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RESEARCH ARTICLE

'Out into space?' – Engineering students' understanding of the carbon cycle and challenges they face while solving atmospheric CO_2 accumulation tasks

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ABSTRACT

This study examines the challenges faced by engineering students in understanding atmospheric CO_2 accumulation, a key concept for climate literacy and sustainable engineering. Through qualitative analysis of task-based interviews with third-year engineering-mathematics students from a Swedish university, we identify and categorise cognitive, metacognitive, and affective challenges in conceptualising the carbon cycle and solving CO_2 mass balance tasks. Our findings reveal difficulties in integrating formal mathematical training with real-world environmental issues, underscoring the importance of addressing these multidimensional challenges in engineering education. The study highlights the need for pedagogical strategies – for mathematical modelling and climate education – that not only impart cognitive knowledge but also foster metacognitive skills and address affective factors related to climate change and problem-solving. By integrating sustainability-themed real-world problems into curricula, this research advocates for a holistic educational approach, preparing engineers to effectively contribute to climate change mitigation and sustainability efforts.

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KEYWORDS
Stock-flow failure; Engineering Education; misconceptions; carbon cycle; real-world problem solving; mathematical modelling

1. Introduction

Despite clear signs like record temperatures, coral bleaching, droughts, and wildfires, the world is failing to meet global climate targets such as the Paris Agreement's goal of limiting global temperature increase to well below 2°C (United Nations 2015). In presenting safe Earth system boundaries, Rockström et al. (2023) argue that we have already exceeded the threshold for climate change. The contrast between the emission reductions required to meet climate targets and the current peak level of emissions is stark (Friedlingstein et al. 2023). Yet climate policy packages face political and social contestation. In the European Union, the green transition has raised concerns about distributional effects, short-term costs, and sectoral disruption, creating risks that climate action be delayed, weakened, or rejected if these social challenges are not addressed (Council of the European Union 2024). Other major actors, such as the United States, are rolling back climate policy and redirecting federal support towards fossil energy, including through executive action to eliminate wind and

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solar subsidies and Department of Energy funding to expand the coal industry (The White House 2025; U.S. Department of Energy 2025).

Engineers play a key role in developing sustainable solutions and phasing out systems that contribute to climate change. However, just as for society at large, the transformation towards carbon neutrality requires widespread acceptance and motivation to change, also among engineers. Gifford (2011) argues that such acceptance and motivation is – at the individual level – challenged by psychological 'dragons of inaction', listing factors ranging from cognitive limitations to ideological and economic barriers. One of the suggested barriers to climate action is ignorance: not appreciating the existence or scale of the challenge or not knowing how to respond to this challenge. While lack of public understanding has long been proposed as a key obstacle to climate action, early studies (e.g. Kahan et al. 2012; Kellstedt et al. 2008) showed little evidence for general scientific literacy leading to stronger climate policy support, instead emphasising the role of worldviews and political factors. However, a string of studies has established that climate change knowledge (at least in some domains) is indeed correlated with attitudes towards climate change (Hornsey et al. 2016; Shi et al. 2016), and even simple interventions can improve understanding (Clark, Ranney, and Felipe 2013). Studies also show that knowledge attenuates the negative association between individualism and climate skepticism (Guy et al. 2014; Stevenson et al. 2014), supporting Wibeck's (2014) conclusion that lack of knowledge interacts with other factors like worldviews and social norms in hampering engagement with climate change.

Because of their key roles, engineers need to have a sufficient understanding of key mechanisms, such as how CO_2 emissions cause climate change. It is appropriate that many engineering schools have invested in integrating sustainable development into their curricula; see Lemkowitz et al. (1996), Thürer et al. (2018), and that journals focus on the topic - for instance through the special issue 'Sustainability in Engineering Education' in the European Journal of Engineering Education (2024). We argue that in order to design instruction that effectively addresses common misconceptions, a nuanced appreciation of how engineering students reason when solving tasks on atmospheric CO_2 accumulation is needed.

One area with a noticeable knowledge gap in the general public – and hence a potential leverage point for climate change engagement – concerns the understanding[1] of the carbon cycle and the processes governing atmospheric accumulation of CO_2 (Dryden et al. 2018; McCaffrey and Buhr 2008).

It is worth noting that public awareness and understanding of the carbon cycle vary greatly between countries (Lee et al. 2015). In Sweden, where this study was conducted, the carbon cycle is incorporated into primary and secondary school curricula[2] (Skolverket 2022), and climate change has been a prominent topic of public debate for about three decades (Olausson 2009) – entering into the policy debate five decades ago (Ekberg and Hultman 2023). As such, Sweden is likely among the countries with the highest levels of public knowledge about the carbon cycle, and the levels of challenges found in this study could therefore be seen as a conservative measure of the level and types of challenges to be expected in other countries. Yet, several studies have shown that even well-educated people have considerable difficulty in disentangling the fundamental relationship between stocks and flows of CO_2 in the carbon cycle (Cronin, Gonzalez, and Sterman 2009; Dutt and Gonzalez 2009; Sterman and Sweeney 2007). This is known commonly as 'stock-flow failure' and shows that there may be merit in studying even highly educated people from a country with high climate awareness. Considerable effort has gone into investigating the reasons for this failure (Fischer, Degen, and Funke 2015; Guy et al. 2013; Newell et al. 2016) and measures for rectifying it (Dutt and Gonzalez 2011, 2012a, 2012b; Moxnes and Saysel 2009).

Relatively little is known about how students conceptualise the active carbon cycle[3] and what difficulties the students experience as they solve seemingly simple CO_2 mass balance tasks. While earlier studies have mainly sought explanations for stock-flow failure in what Jonassen (2017) calls the problem's *external factors* (e.g. task format, context), Sterner et al. (2019) and Covitt et al. (2021) started to unravel the multitude of ways in which people misunderstand atmospheric CO_2

accumulation. To better understand the multifaceted nature of these challenges, we draw on two well-established frameworks in the learning sciences. The mentioned framework by Jonassen (2000, 2017) distinguishes between external factors, such as problem formulation and complexity, and internal factors related to the problem solver's personal characteristics, including prior experience and strategies. Complementing this theoretical lens, Schoenfeld's (1983, 1992) framework for mathematical thinking theorises that problem-solving performance is influenced by four domains: two cognitive (factual and procedural knowledge as well as heuristics), one metacognitive (monitoring and control of cognitive processes), and one for belief systems (affective and social determinants). These frameworks are appropriate for this study as they move beyond a 'purely cognitive' view to account for how a student's identity and their reaction to an experimental setting can make them underperform in problem-solving situations. This is particularly prevalent for 'real-world' environmental issues – often present as 'ill-structured' problems, which, unlike well-defined textbook exercises, require the integration of knowledge and skills from multiple domains and often the navigation of conflicting goals.

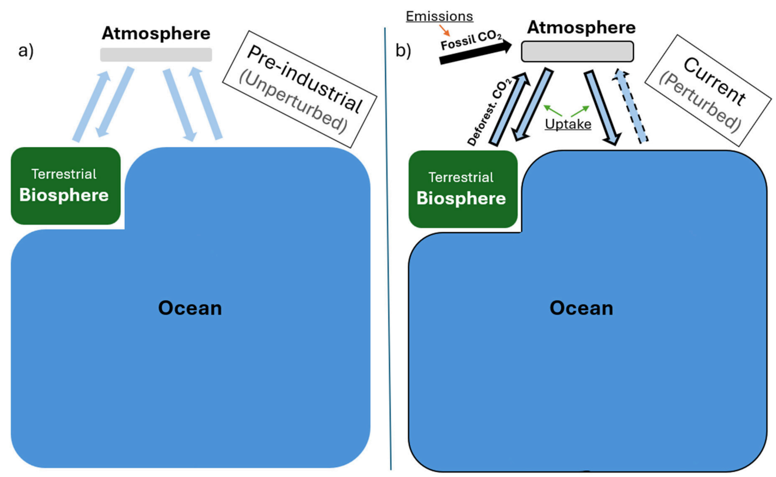
Prior research has successfully utilised these two lenses to unpack the specific mechanisms underlying student failure in complex (climate-related) tasks. For instance, Aşık and Küçük (2021) employed think-aloud protocols to reveal that stock-flow failure is frequently a result of metacognitive underperformance, particularly in the monitoring and checking phases, rather than a simple lack of mathematical skill. Similarly, Cox, Elen, and Steegen (2019) demonstrated the value of externalising mental representations through 'causal diagrams', identifying specific cognitive strategies that novices use to organise information about complex systems. Applying the frameworks by Schoenfeld (1983, 1992) and Jonassen (2000, 2017) to the carbon cycle, this study explores the role of external vs. internal factors and identifies whether engineering students' difficulties stem from limited cognitive resources, a failure of metacognitive control, or the influence of affective beliefs related to the climate context.

Furthermore, by explicitly studying engineering-mathematics students, we expand on the work by Covitt et al. (2021) that mainly studied high school students. While Covitt et al. (2021) have a slightly more narrow focus on exploring one type of emission scenario, it is an important scenario, and its result – students often defaulting to informal 'good versus bad' logic or correlation heuristics – and their discussion on how this underscores the necessity of scaffolding to move learners towards sophisticated model-based stock-flow reasoning is a highly relevant reference point for our study. Taking a purely qualitative approach, we here dig even deeper than previous studies to explore how engineering students construct their understanding of the carbon cycle (CO_2 emissions, uptake, accumulation, and stocks). For the convenience of the reader, Box B1 explains the active parts of a simplified carbon cycle conceptual model and its stock-flow balance.

Box B1.

Simplified active carbon cycle – unperturbed and perturbed stocks and flows

In pre-industrial times, there was an approximate balance between the amount of CO_2 in the atmosphere, the oceans, and the biosphere. This means that each year, the flows between each pair of carbon stocks cancelled out (see the two pairs of arrows in panel a). The balance is now perturbed, mainly due to human emissions of fossil-based CO_2 and deforestation. In response to this, the system seeks to regain balance between these three main stocks. This means that emitting fossil carbon into the atmosphere enlarges each stock (for human and climate-relevant timescales), but deforestation has kept the biospheric carbon constant. Fossil emissions since the industrial revolution have most noticeably raised the carbon content of the atmosphere. Today, the net change in Ocean and Biosphere stocks – which is referred to as the *uptake*– is driven chiefly by the rate of human CO_2 emissions.[4]



Each box represents carbon stored in the three stocks of the simplified active carbon cycle. The arrows represent annual flows between the stocks in the pre-industrial unperturbed state (B1a) and the perturbed current state (B1b), indicating the main changes to the system following human emissions of CO_2 (i.e. increased stocks and flows, indicated by the outlining of the arrows which have been slightly enlarged to signal increase in size).

Against this background, the present study focuses on the carbon cycle because it sits at the intersection of climate literacy, sustainability education, and mathematical modelling: it is central to understanding why net-zero emissions are required (to reach politically set targets), while also being formalizable as a stock-flow problem involving accumulation and rates of change. This makes atmospheric CO_2 accumulation a particularly revealing case for examining how students interpret climate-framed, real-world problems that are both mathematically tractable and conceptually demanding. Engineering-mathematics students are an analytically useful group in this regard: if students with strong formal mathematical training struggle with these tasks, the challenges are unlikely to be reducible to a lack of calculus skills alone. Rather, their reasoning can illuminate how conceptual, metacognitive, and affective factors shape the use of mathematical knowledge and skills in sustainability-related engineering problems. The aim of this study is therefore to identify and describe challenges that can support university teachers in designing learning activities[5] for engineering students that address common misconceptions about the carbon cycle and strengthen the metacognitive skills needed for real-world problem-solving.

The following research questions (RQ) are addressed in this paper:

1. How do engineering students conceptualise the active carbon cycle and its components?
2. What cognitive, metacognitive and affective challenges do engineering students experience when reasoning about and solving atmospheric CO_2 accumulation tasks?

2. Methodology and methods

2.1. Study setting and sample

The setting for this study is a research-intensive Swedish university of technology, targeting third-year students studying engineering mathematics[6] who, at the time of the study, were taking a course on environmental mathematical modelling (see Supplementary material for the full program plan). As a point of reference, this program is considered academically demanding and consistently ranks among the highest in Sweden in terms of entry requirements for STEM education programs

(Antagningsportalen.se, accessed April 10, 2025). At the time of the study, the university required each of its engineering programs to include at least one 7.5 ECTS (200h) sustainability-focused course[7]. The course had three focus areas: (1) introduction to sustainable development and the three dimensions; enviromental, social and economical, (2) population dynamics and ecosystem resilience, and (3) climate change. The purpose of the course was to inspire and stimulate the student to reflect on what sustainable development means, both in their everyday life and in their future professional role.

A purposive (rather than random) sampling strategy was used, which is based on the notion that 'certain categories of individuals may have a unique, different or important perspective on the phenomenon in question and their presence in the sample should be ensured' (Robinson 2014, 32). To this end, all students ($N = 35$) were asked to complete an online survey (see Supplementary material Selection Survey), carried out at the very beginning of the course, designed to probe how they fared on a set of real-world themed problem-solving tasks and to assess different aspects of their understanding of and reasoning about atmospheric CO_2 accumulation. The survey contained both multiple-choice questions, drawing, tasks and open-ended questions of different types, including asking students to motivate their answers. Based on an analysis of the students' success rate on the tasks in the survey and striving for a variation in both performance and ways of reasoning about CO_2 accumulation, thirteen students were invited via e-mail to participate in the study. In the invitation (sent out two weeks into the ten-week course), the purpose of the study was described, and it was made clear that participating in the study would not affect the students' grades in any way. Ten students (5 males and 5 females) – who ranged from low- to high-performing students – accepted the invitation and provided consent to data collection. Note that, by the time of the survey and interviews, the students had not received any university-level training on the carbon cycle. Consequently, the knowledge being tested reflected a combination of mathematics- and physics-oriented problem-solving skills and any prior understanding of the carbon cycle acquired through earlier education or from sources outside the formal educational context.

2.2. Data collection

Data were collected through semi-structured interviews, allowing each student 'to express meaning in his or her own words and to give direction to the interview process' (Brenner 2012, 357). The interview protocol was designed to gain a deep understanding of how the students reasoned and applied their mathematical thinking skills when solving real-world tasks about atmospheric CO_2 accumulation, with the aim of identifying prior knowledge of the carbon cycle and different types of challenges to solving the tasks. By this design, the interview followed the main characteristics of a task-based interview (Goldin 2012), which is an interview method for educational research where understanding the thought processes and problem-solving strategies of learners is central.

The interview questions and tasks were divided into four groups. Following good interview practice, the first task (1a) was designed to be a 'grand tour' question (Brenner 2012, 358), asking students to 'give a broad description about a particular topic' and to 'give the researcher the "native" language of the [student] and the identification of significant topics within the cultural framework of the [students]. Grand tour questions are followed by minitour questions that probe each of the topics that have been identified' (Brenner 2012, 358). Here follow the main topics explored, with short, paraphrased versions of the most important interview tasks (see Supplementary Material for a full recount of interview questions and task material):

1. The carbon cycle and the atmospheric CO_2 amount
   a. What is important for the amount of CO_2 in the atmosphere? Please create a conceptual model of this.
2. Scenarios of CO_2 emissions (i.e. human-caused inflow to the atmosphere) and uptake (i.e. outflow

from the atmosphere as an induced effect of the emissions)
   a. What could the emissions and uptake curves look like if they were to produce the atmospheric amount illustrated in the scenario of Figure 1(b)?
3. Mathematical expression of CO_2 accumulation[8]
   a. If you were to write a mathematical expression that describes how the amount of CO_2 in the atmosphere is related to the emissions and uptake of CO_2, what would it look like?
   b. You have now written an expression in differential (integral) form. Could you write an expression in integral (differential) form instead that expresses how much CO_2 is in the atmosphere at any given point in time (how the amount of CO_2 changes over time)?
4. What is CO_2 uptake's long-term behaviour?
   a. How do you think the uptake would develop in the following emission scenarios (see Figure SM4 in Supplementary Material)? Assume we start today and that the scenarios last a long time.

We did not assume that all participants would come with practical knowledge of the terms 'emission' and 'uptake'. Rather, the first question was designed to explore the students' un-primed mental representation of the carbon cycle as well as potential ideas related to the role and significance of atmospheric carbon in general. After this exploration, we purposefully embedded brief, in-task definitions of each term (for example, 'uptake by oceans, plants, and trees') in Question 2, so that any remaining difficulty would reflect the relationship between those concepts (stock vs. flow), the format of the task, or the application of their mathematical reasoning – not mere unfamiliarity with jargon. This approach follows prior stock-flow research showing that novices often conflate stocks with flows unless they are cued explicitly (e.g. Cronin et al. 2009; Sterman 2008), and it allowed us to isolate whether students' challenges arose from conceptual misunderstandings rather than simple terminological gaps.

Questions of clarification or follow-up questions to enable deeper analysis when students' reasoning seemed particularly interesting, for example when a new type of challenge to correct reasoning appeared, were formulated following the interviewer's judgment from case to case. The judgment was based on taking the particular subject topic being discussed, the whole interview situation, and the accounts from the previous interviews into account, with the aim of exploring both shared and unique meanings for the different interview subjects (Krauss 2005).

In addition to the interview protocol, material was designed to help the students reflect or move on during the interview if they got completely stuck. For example, the students were frequently (but not always) asked to compare their answers with, or comment on, the correct answer or an answer reflecting a common misconception. These materials also served to assist the exploration of variation in, nuances of, and the confidence in the students' problem-solving reasoning around the tasks.

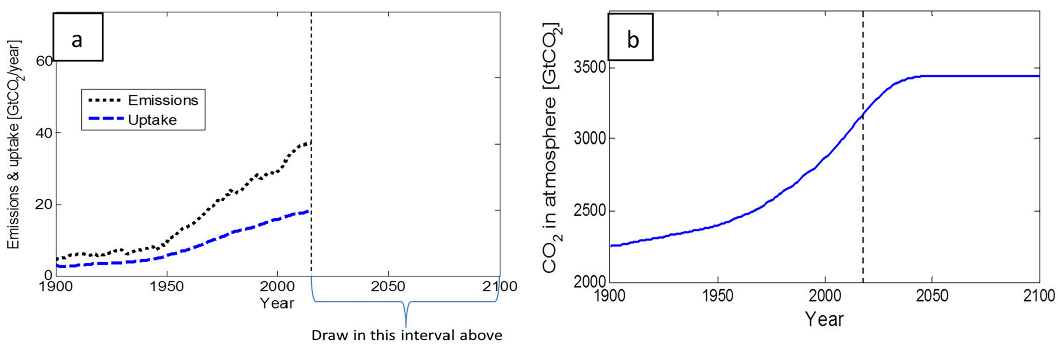


Figure 1. Graphs in task 2a: CO_2 emissions (i.e. inflow to the atmosphere) and uptake (i.e. outflow from the atmosphere) scenario (a) and amount of CO_2 in the atmosphere (b).

The interviews lasted on average 70 minutes and were audio-recorded. In addition, the written and drawn solutions to the tasks were saved as additional data for analysis. The interviews were transcribed verbatim in Swedish, and a determined effort was made to include non-verbal sounds (such as groans, sighs, and laughter) and longer pauses. This quality of the transcripts facilitates an analysis of the affective dimension of problem-solving, such as frustration, engagement and uncertainty. All quotes presented in the manuscript have been translated to English, staying as close as possible to the original utterances.

2.3. Data analysis

The interview transcripts, together with the drawings and diagrams produced by the students, were analysed using an inductive thematic analysis (Braun and Clarke 2006). This qualitative analysis involves reading each transcript several times, coding the transcripts, and constantly comparing codes across transcripts to validate ideas for themes or develop new themes. The transcripts were coded manually for ways of reasoning about atmospheric CO_2 accumulation, with a focus on identifying challenges to correct reasoning in relation to the tasks. To guide the analysis, we used Schoenfeld's (1983, 1992) framework for mathematical thinking. According to this framework, 'belief systems, interactions with social or experimental environments, and skills at the "control" level in decision-making shape people's behavior as they solve problems' (Schoenfeld 1983, 329). To put it differently, we looked beyond the purely cognitive to identify challenges when reasoning about atmospheric CO_2 accumulation while attempting to be mindful of the influence of the social and experimental setting, as described by Schoenfeld (1983, 329), in which the task-based interview (Goldin 2012) took place. Using this framework, we categorised the identified challenges into four categories (see Table 1; for a complete list of all identified challenges, see Table SM2 in the Supplementary Material). Finally, we used a second theoretical lens by Jonassen (2000, 2017) to interpret our findings in relation to the context of *real-world problem-solving* and so-called *internal factors*. This is an attempt to make a second round of reflections on the first level analysis, with the aim of contributing with insights of direct didactical value for engineering educators.

Table 1. Summary of findings: domain, categories of challenges, and challenges.

Domain	Challenge category	Challenges (selection)
Cognitive	1. Identifying and conceptualising components of the carbon cycle	Role of CO_2 uptake and oceans
		Emissions going out into space
		CO_2 breaking down
		Role of the ozone layer
	2. Physics of carbon cycle	
	(2.1) Applying principle of mass balance	Pattern matching (i.e. correlation heuristic)
		Formulating a symbolic expression
		Mixing up stocks and flows (incl. their units)
	(2.2) Uptake's dependence on emissions pathway	Uptake being a function of emissions pathway
		What happens at zero emissions?
Metacognitive	3. Being aware of and regulating thought processes	Articulating, testing and if necessary updating internal problem representation
		Checking answers and implications of used model against given data and common knowledge
		Regulating allocation of effort between parts of the problem-solving process
Affective	4. Beliefs, attitudes & affections	
	(4.1) Climate-specific	Apocalyptic narratives
		Discarding logical models for wishes and concerns about climate change
	(4.2) Disciplinary identity	Self-doubt and perceived lack of 'real-world'modelling identity
		Believing in the 'five-minute rule' (belief that understanding = speed)

3. Results

We identified four categories of challenges to correct reasoning about atmospheric CO_2 accumulation, ranging from the purely cognitive (Challenge Categories 1–2), to both metacognitive (Challenge Category 3) and affective (Challenge Category 4), see Table 1. In this section, these categories (1–4) are described and supported with illustrative quotes, drawings, and diagrams from the interviews. The third column of the table provides selected examples of the different challenge categories.

3.1. Challenge category 1: identifying and conceptualising components of the carbon cycle (RQ1)

This Challenge Category focuses on whether the students are able to identify salient components of the carbon cycle as well as how they conceptualise these components for the given task. Figure 2 summarises what components the students included in their conceptual models of the carbon cycle (RQ1) when asked to make an illustration or mind map of important factors affecting the amount of CO_2 in the atmosphere (Task 1a).

As indicated in Figure 2, only three (out of 10) students explicitly included the oceans in the uptake (i.e. outflow from the atmosphere), and overall there was a larger focus on emission (i.e. inflow to the atmosphere) sources than on the uptake: all ten students mentioned emissions, while seven students mentioned uptake. S9, for example, did not mention uptake at all in his/her conceptual model of the carbon cycle (see Figure 3(A)). When the notion of uptake was introduced later in the interview, S9 became unsure of 'whether the uptake will add to the amount like the emissions or not' and was therefore 'not sure about the sign in front of the uptake' when asked to write a

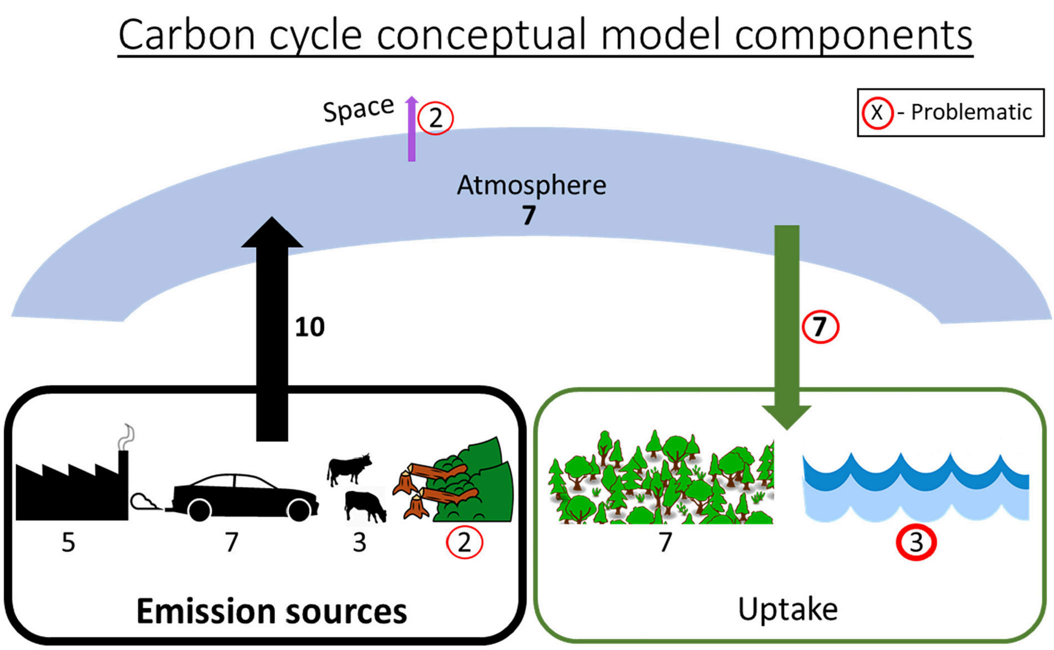


Figure 2. A summary of the conceptual models of the carbon cycle produced by the students, indicating what components they included. All parts are correct except the arrow indicating losses to space. The numbers show how many students (out of ten) included each component. Red circles highlight the components that were most challenging for the students in terms of incorrectly omitting them or incorrectly including them as in the case of losses to space.

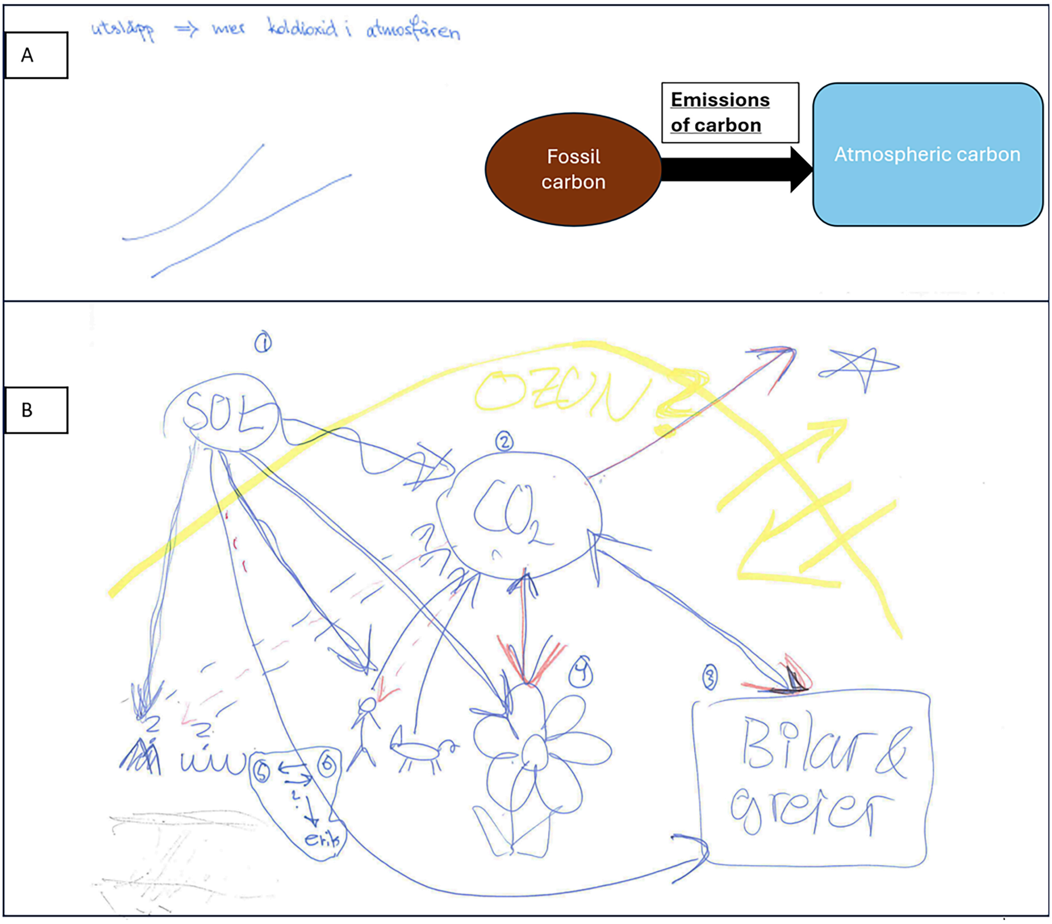


Figure 3. (A) On the left is the conceptual model of the carbon cycle drawn by S9, dictating that emissions give rise to more CO_2 in the atmosphere, with two curves of unknown meaning. On the right is an idealised 'carbon system' which lacks an uptake component, which S9 confirms corresponds to his/her own idea of the system. (B) The conceptual model of the carbon cycle drawn by S1, where 'sol' is 'sun', 'ozon' is 'ozone', and 'bilar and grejer' is 'cars and stuff'.

mathematical expression (Task 3) for the relationship between emissions, uptake, and the amount of CO_2 in the atmosphere.

Even when students used correct scientific terms for key components of the carbon cycle and included them in their conceptual models, they did not always conceptualise these terms in a correct way. In fact, most students struggled with one or more of the following key concepts: 'emissions', 'uptake', 'gas' and 'atmosphere'. Consider, for example, how S1 modelled the carbon cycle (Figure 3(B)). S1 reasoned that CO_2 'emissions are going out into space' and that 'uptake is the part of the emissions that the atmosphere takes up'. S1 also included the ozone layer in his/her conceptual model of the carbon cycle: 'The ozone layer does something – I guess it keeps things in [the atmosphere] and reduces the amount of emissions being sent out into space'. Related to this, S1 mentioned that CO_2, as a gas, is not going to weigh much (if anything?), and became very surprised when she learned that it is billions of tons of CO_2 that are being emitted: 'You don't think a gas can weigh a ton, it's like you can't imagine a ton of cotton'. Moreover, three of the students believed that the atmosphere is a layer some distance above the ground.

Another student reasoned,

Then there are natural, eh, carbon dioxides in nature. Eh, but that doesn't contribute, what should you say … But it is not something that has like an impact on the climate system, but it is primarily like the humans that [contribute].

which is yet another example of how the physical properties of the carbon cycle and the climate system are not a part of the students' main expertise.

On a more fundamental level, several students were not able to distinguish between *stocks* and *flows*, drawing stocks and flows in the same diagram without noting the difference in units (e.g. tons and tons/year, respectively).

3.2. Challenge category 2: physics of carbon cycle

The challenges concerning understanding the physics of the carbon cycle are divided into two subcategories, i.e. how to apply the principle of mass balance and the uptake's dependence on the emissions pathway.

3.2.1. Challenge category 2.1: applying the principle of mass balance

The Challenge Category 2.1 concerns the ability to apply the principle of mass balance to *understand* how emissions (i.e. the human-caused inflow to the atmosphere) and uptake (i.e. the outflow from the atmosphere induced by the human emissions) affect the amount of CO_2 in the atmosphere. This understanding was tested in a number of tasks: scenarios for CO_2 stabilisation (Task 2a, based on Sterner et al. (2019) following Sterman and Sweeney (2007), see Figure 1 in this paper) and a hypothetical scenario where the amount of CO_2 (i.e. the concentrations) increase, stabilise and then fall (Task 2d, Supplementary Material), as well as tasks asking the students to write mathematical expressions for (changes in) the amount of CO_2 in the atmosphere (Tasks 3a–b).

The most basic level of understanding displayed by most students is based on recognizing that changes in the atmospheric amount of CO_2 (A) is equal to the emissions (E) minus the uptake (U), according to:

$$\dot{A}(t) = E(t) - U(t) \tag{1}$$

This expression can be applied to solve several of the tasks in a mathematically correct way. This relationship can be used to judge how the relationship between emissions and uptake make atmospheric CO_2 increase, remain stable, or decrease.

Most students had no problem applying the principle of mass balance at this level of complexity. In Task 2a (see Figure 1), only two students (S10 and S9) did not manage to apply the principle of mass balance and drew emission curves that were higher than the uptake (see Figure 4), which would lead to an increased amount of CO_2 in the atmosphere. Both students S9 and S10 drew curves that look approximately the same as the curve in the task description for the amount of CO_2 in the atmosphere (see Figure 4 in comparison to Figure 1(b)), which is an indication of the incorrect reasoning of pattern matching that has been identified also in other studies (Cronin, Gonzalez, and Sterman 2009; Korzilius et al. 2014; Sterner et al. 2019).

S10: The emissions will increase*[expressing uncertainty]. Can compare a little with carbon dioxide … carbon dioxide present in the atmosphere, that it has increased.

I: So it's the slope you're looking at?
S10: Yes. Pattern matching reasoning by S10.

S10: One way is that the emissions increase, but then the uptake must also increase … And if it's going to level off, the uptake got to be much, much more, so it'll find an equilibrium. No accumulation reasoning by S10

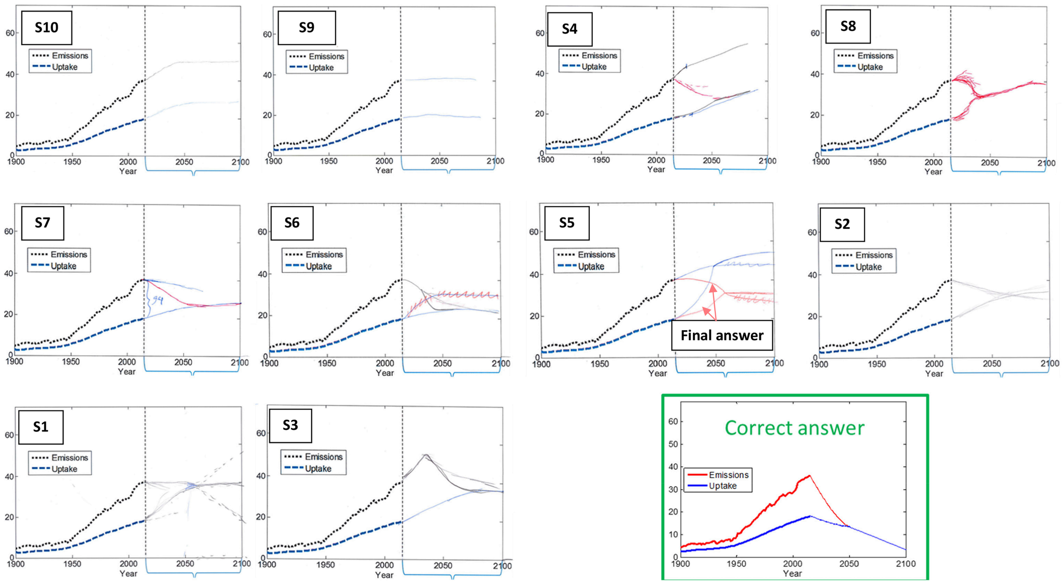


Figure 4. Students' answers to Task 2a. On the upper row (from left): 2 pattern matchers of which one also reasons $A = E$-U and 2 that have emissions and uptake meeting and then growing together. Second row: 4 that have emissions going down noticeably before stabilising together with the uptake (uptake still grows during this period). Lower row: 2 that follow various emissions and uptake scenarios with only one that has emissions and uptake slowly decreasing and finally the correct answer at the bottom right.

While in the end, the rest of the students applied the mass balance principle in a sound way, it should be noted that the students were not always consistent in their reasoning and two of them changed their reasoning from pattern matching or 'no accumulation' reasoning to the correct (mass balance) reasoning just prior[9] to or during the interview. Most students also had difficulties with the task of writing a mathematical expression to express their understanding in symbolic form (Task 3a). For example: being able to apply the principle of mass balance may be interpreted as being comfortable in one's knowledge about what the fate of CO_2 emissions is, but two of the students who managed Challenge Category 2.1 (S1 and S4) momentarily expressed ideas of CO_2 breaking down or being sent out into space (i.e. misunderstandings belonging to the first category of challenges).

> S4: The hell I know if I'm completely sure how it works. But that is, I think it's … things must be sent out from the atmosphere as well. That is, in some … or type broken down [laughter] or somehow …

The same student used multiple different models but finally understood that emissions and uptake need to be equal according to the principle of mass balance.

One of the tasks (see 2d in the Supplementary Material), in which the students were asked to construct emissions and uptake scenarios that would have the amount of CO_2 in the atmosphere go through three phases (increase, be stable, and decrease), allowed for a more complete assessment of the skill to apply the principle of mass balance. This was done by reducing the priming from historic data (that might provide hints of a natural starting point for the emissions and uptake trajectories) and by testing if the students would get all three phases right. Figure SM7 (Supplementary Material) shows that for this group the general results from the CO_2 stabilisation task (i.e. task 2a, see Figure 1) were confirmed (i.e. those who reasoned in line with pattern matching in the earlier task did so also in the latter task).

3.2.2. Application of mathematical skills to real-world problem-solving

The mathematical expression tasks (Task 3) were approached in various ways by the students. In Task 3a, which asked for an expression describing how the amount of CO_2 in the atmosphere is related to emissions and uptake, most students succeeded in formulating a differential expression (Equation (1)) representing how the amount of CO_2 changes as a function of these flows. This demonstrates that they possessed the procedural knowledge necessary to conceptualise and formalise how the system's flows influence the rate of change (i.e. the derivative) of the amount of CO_2 in the atmosphere. However, this was not exactly what was asked for, and when prompted in Task 3b to instead formulate an expression in integral form, only a few students were able to produce the correct integral expression representing the amount of CO_2 at any point in time (Equation (2)). This indicates a lack of conditional knowledge, as they failed to recognise which knowledge was appropriate to apply, despite having practiced the relevant calculus skills for years.

$$A(t) = A_0 + \int_0^t E(t) - U(t)dt \tag{2}$$

It seemed to be a challenge for the students to realise how they could integrate the differential form of the equation when they didn't know what types of mathematical functions the emissions and uptake functions could be described by.

3.2.3. Challenge category 2.2: uptake's dependence on emissions pathway

Another set of cognitive challenges is connected to knowing or figuring out the dependence of the CO_2 uptake on the CO_2 emissions pathway. All students had a more or less limited understanding of what uptake is (category 1 challenges) and how – mathematically speaking – estimates of it together with estimates of the emissions give us the change in the amount of CO_2 in the atmosphere (Challenge Category 2.1).

A couple of example quotes to support this sub-category of challenges are:

> Yes, I realized that. I don't know … it [the uptake] probably won't go down later. The uptake capacity there. (S5)

> If there is more to eat, then maybe they want to eat more [laughter] … Nature itself has found a way to take up more carbon dioxide. (S10)

> The oceans are already quite saturated with carbon dioxide, so they have no room … for more carbon dioxide.

These utterances illustrate how students resort to informal, often metaphorical, reasoning to navigate a system for which they lack a clear mechanistic understanding. This reliance on intuitive heuristics – whether anthropomorphizing uptake or conceptualising sinks as static reservoirs – serves as an attempt to bridge significant gaps in their internal problem representations. In particular, only a few of the students were familiar with the oceans playing a key part in the uptake, and none was acquainted with how the oceans determine the uptake's dynamics both on the short and long timescales (the oceans account for about half of the carbon uptake on a short time horizon and more over a longer time horizon). It is then no wonder that the dynamics of the uptake were a mystery to the students. A mystery that is not made easier to uncover due to the difficulties the other challenges provide. The result of this is that not a single student answers the 'Sterman type question' (Task 2a, see Figure 1) in a physically sound way that exhibits an appreciation for how uptake depends on the emissions pathway in an even close to accurate way (see Figure 4). Despite the priming that the historic data provides, two students (S1 and S8) even declared that 'as long as they [emissions and uptake] are equal it doesn't matter [for the amount] where they go'. Yet the answers are nevertheless mathematically correct.

Many students confused natural and human-caused carbon emissions in their understanding, including processes like respiration and decomposition. This confusion extended to tasks where some speculated that CO_2 would vanish from the atmosphere after halting emissions, highlighting a mix-up between anthropogenic and natural carbon processes. The Supplementary Material provides a more elaborate analysis of this Challenge Category 2.2 on the uptake's dependence on the emissions pathway.

3.3. Challenge category 3: being aware of and regulating thought processes

This category of challenges involves the metacognitive challenges that affect the students' reasoning while dealing with the atmospheric CO_2 accumulation tasks. All students experienced metacognitive challenges related to problem-solving, and these are linked to the cognitive challenges mentioned in the previous categories. These plentiful metacognitive challenges related to the previously discussed cognitive challenges are to be expected according to Schoenfeld (1983, 1992), which provide a theoretical foundation for understanding how students regulate their thought processes and how these processes are connected to their cognitive challenges. Insufficient reflections related to key concepts for the tasks at hand, problem-solving skills, and assessing what models predict in relation to what the data tell are central aspects of this Challenge Category.

A selection of quotes to underpin this challenge category:

> No, not 'dt', am I stupid or something. X. Yes okay, x, like that maybe. (drumming and writing). or lambda A and B.

> Something made the logic behind my thinking fail, and so I had to find something else … realized it was wrong.

> Yeah, my god, this feels … yeah, now when you sit and draw like this … Yeah, I simply have to decrease [emissions] more drastically.

These rare utterances provide evidence of students attempting to monitor the legitimacy of their mathematical tools and assess their progress in real-time. Such conscious metacognitive acts – ranging from symbolic self-correction to the retrospective recognition of logical failures – demonstrate the 'checking' and 'assessment' behaviors that Schoenfeld (1983, 1992) identifies as critical driving forces in intellectual performance. While these instances capture the students' attempts at regulation, they also highlight the inherent difficulty of maintaining consistent control throughout the entire problem-solving process, especially when dealing with the unfamiliar dynamics of a real-world system.

Most or all the students could have benefited from reflecting more on what the tasks were asking for and whether the solutions they came up with were physically sound and consistent with the data presented. The need for enhanced reflection varied quite considerably, however, from being a minor challenge to an overwhelming challenge. Most students noticed that they had difficulties (i.e. they were able to monitor their thought processes) and clearly expressed that they felt uncertain about their reasoning or that they didn't know. There were also instances when the students reflected on new data or new thoughts and put their old answers and thoughts to the test, sometimes discarding them and sometimes being mostly puzzled by what was probably seen as some kind of earlier mistake or inconsistency. An example comes from when one of the pattern-matching students (S10) reasons around Task 4a. Thinking aloud about the, task, the student reflects on input from a question that S10 does not seem to have been able to reconcile with his/her way of reasoning S10 said:

> We have learnt that it [referring to the atmospheric amount of CO_2] can go up while emissions is going down … this is kind of a funny and tough nut to crack.

3.3.1. Missed opportunities

Having insufficient metacognitive skills led to missed opportunities to reject or revise potentially problematic mental representations. Such opportunities included:

Using previous information presented in the sampling survey to answer the tasks;
Carefully considering the information, graphs, and units presented in the tasks (mainly Task 2a) to describe the carbon cycle, including data on emissions, uptake, the amount of CO_2 in the atmosphere (Figure 1), and how they all relate to each other. This allows for a comparison with and fact-checking of their own model.

The data in Task 2a can be used to draw conclusions about the relationship between emissions, uptake, and the atmospheric amount (i.e. the core relationship explored throughout the interview). A careful look at these data would tell the observant student that Equation (1) holds (see Section 3.2). At least the two pattern-matching students (S10 and S9) missed a chance here to correct their mental representation. A couple of the students did express being surprised about the absolute and relative sizes of the flows and the stocks.

Students grappling with CO_2 accumulation tasks need to understand two key facts: the pre-industrial carbon cycle was in balance, and the physics of the cycle strives to maintain this balance, meaning not all added emissions are absorbed on a human-relevant timescale. Most students recognised a stable pre-industrial CO_2 level but struggled with the fact that not all emissions are offset by natural uptake. This was a recurrent obstacle leading to several misses, including failing to question the feasibility of the assumption of large-scale uptake in scenarios like Task 2e, indicating a lack of comprehension about the overall dynamics of the carbon cycle and its disturbed state due to human activities (see Supplementary Material for more on this).

3.3.2. Mathematical modelling – mathematical expression

Few students took the opportunity to use the data available to them about the variables they identified to check for the physical soundness of the mathematical model they constructed, even though the material needed was still lying on the table (i.e. they missed opportunity 2). For example, missing to include a starting level for the amount of CO_2 in the atmosphere (in the integral form of the mathematical expression) could have been avoided after a quick look[10] at the data. S10, for example, incorrectly answered that Equation (3) is a reasonable mathematical expression for the amount of CO_2 in the atmosphere. Similarly, reflecting on the implications that could be made by combining their reasoning from different tasks was sometimes lacking. For example, in a couple of tasks some students created scenarios in which at times the emissions were much larger than uptake ($E > U$) while for some period they were equal ($E = U$), yet in the mathematical-expression task they could suggest that the amount was dependent on a term with $(E(t) - U(t))$ *t (see Equation (5)). But this $(E(t) - U(t))$ would then vary dramatically in magnitude between the time periods they had just described in their earlier reasoning (see Figure 4). However, when disconnecting the variables from the physical entities they represent, assuming them to be constants and thinking in purely mathematical terms for a limited time-period of interest, Equation (5b) holds to describe the principle of mass balance mathematically. Such an abstraction and simplification of the system is, however, so rough that in using it, the students likely lose aspects of the connection to the physical system they are asked to describe. When the interviewer explored to guide the students who reasoned this way to think about what this type of mathematical expression would imply for a scenario that varied a lot in the relative sizes of E and U, the students were, however, fairly quick to realise the limited usefulness of the expression they had provided. By this, they showed signs of not having followed the abstraction of the reasoning too far away from the physical real-world problem they were attempting to solve.

$$A(t) = E(t) - U(t) \tag{3}$$

$$A(t) = A_0 + E(t) - U(t) \tag{4}$$

$$A(t) = (E(t) - U(t)) * t \tag{5a}$$

$$A(t) = A_{now} + (E(t) - U(t)) * t \tag{5b}$$

All in all, the level of metacognitive awareness and self-regulation varies among students. Some students exhibit a fairly strong ability to monitor their problem-solving process, assess their progress, and adjust their strategies accordingly. Others seem to lack this self-regulatory capacity, persisting in ineffective strategies despite evidence of lack of progress.

Finally, we note that since this metacognitive Challenge Category is to a large extent about what the students didn't do or at the least didn't say or give a sign of having done, it is harder to find and explore the different challenges belonging to it. Failed or misdirected reflections give a hint of what reflections were close at hand for the students to have, but to some extent this category is an inferred one, in which the students' reasoning was compared to how an expert in the area would have reasoned.

According to the framework that guided the data analysis (Schoenfeld 1983, 1992), this category of challenges, focusing on students' metacognitive skills, can be seen as a level above the cognitive level (Figure 5). But while the metacognitive level controls cognitive processes, Schoenfeld (1983) argues that there is yet another level involved in mathematical thinking – the affective level – which in turn controls both metacognitive and cognitive processes. Figure 5 illustrates this hierarchy and leads us to the next and final category of challenges.

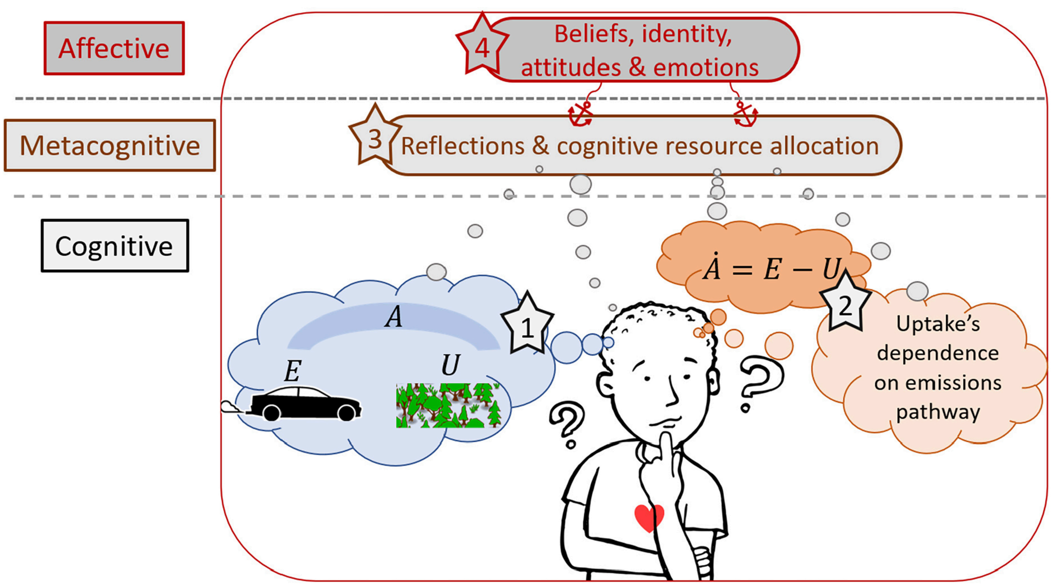


Figure 5. Illustration of the categories of challenges and the hierarchical relationship between them.

3.4. Challenge category 4: beliefs, attitudes, and affective challenges for CO_2 problem-solving

Students face a multitude of challenges that are not of a directly cognitive or metacognitive nature but instead belong to an affective or beliefs-focused level of mental processes. Schoenfeld (1992) interprets beliefs as 'an individual's understanding and feelings that shape the ways that the individual conceptualizes and engages in mathematical behavior', and the data and findings of this study are in line with this reasoning. For instance, the students' beliefs and affects seem to have a major impact on what the students end up reasoning about and how they feel while doing it. The students' attitudes towards, and emotional response to, answering the tasks under the given circumstances could, at worst, increase the risk of affective and/or cognitive overload and stop the student's problem-solving attempts and at best encourage curiosity, and an inspired problem-solving approach.

This category of challenges is divided into two sub-categories: one which is related to the climate context (4.1) and one that is related to respondents' disciplinary identity and beliefs (4.2).

3.4.1. Challenge 'beliefs, wishes and concerns about the climate change issue' – the result of a context too rich for clarity

In approaching and solving the tasks, the students are noticeably influenced by expectations, emotions, beliefs, attitudes, and prior knowledge about the climate change topic. The overarching context of the tasks, i.e. climate change or global warming, is not mentioned once by the interviewer and is not necessary to be considered in solving the tasks, yet a large share of the students' reasoning is strongly influenced by and related to aspects of climate change. One example is that all of the students, to a smaller or larger extent, expressed what they feel *needs to happen* or what they think *will happen* as if asked explicitly about it, when they were not.

The students talked at length about the greenhouse effect, the ozone layer, or the need to change our lifestyles and hence showed environmental concern when asked to solve the tasks. In the light of Schoenfeld's (1983) arguments on the effect of the experimental setting, it seems likely that the students felt expected to express environmental concern. But it is also plausible that they simply wanted to express environmental concern or thought that it was part of solving the tasks. For instance, half of the students declared that atmospheric CO_2 needs to be limited as the first or one of the first things when answering Task 1a: what is the first thing you come to think of regarding what is important for the amount of carbon in the atmosphere?[11].

Notably, Student S10 employed the greenhouse effect as an analogy, stating: 'it gets warmer and in the beginning most plants like it and grow more but in the end it can also get too warm in the greenhouse so that the plants die … '. This student's approach, while creative, lacked critical reflection on the suitability of this analogy for the specific task. This excerpt highlights a common challenge in engineering education: balancing the use of analogies, which can simplify complex concepts, with reviewing their applicability. Jones et al. (2011) observed that analogies are often used to explain phenomena that are not directly perceivable, citing Rickheit and Sichelschmidt (1999), who documented this technique as commonly practiced. However, in engineering education, it is crucial to foster not just the use of analogies but also the metacognitive ability to evaluate their relevance and limitations in specific contexts.

There are two interesting cases in which the climate change context characterising challenge sub-category 4.1 clearly affects what lines of reasoning get higher priority and consequently what lines of reasoning are discarded. The first one is exemplified by a quote by S8: 'It is weird/ (strange in a natural system) that uptake would/could go up so much (relative to emissions), but I don't see any other way since emissions will continue to increase'. Expectations of what will happen determine which scenarios are explored and which are left with little or no consideration. Similarly, S4 questions and becomes uncertain in what way to reason about and answer Task 2c : 'Based on this model? What I feel is realistic? Or what I hope for?' The quote by S4[12] exemplifies nicely how rational logical reasoning meets the beliefs about the world and the emotional wishes for a better future. A meeting that illustrates the mental space in which the CO_2 accumulation problem-solving takes place.

On the opposite end of the scale, there is one student who does not allow himself to be affected by emotions or expectations on attitudes that cloud the image of many of the others. S8 instead is to the point and focuses on modelling the system in a largely successful way. This in turn stands in contrast to a couple of the students commenting on a possible apocalypse approaching as a consequence of climate change. And although it is not our field of expertise, it seems likely that reasoning 'I don't know when the world will end' as part of solving tasks with scenarios of the future is not a good starting point for rational reasoning and problem-solving in any domain.

3.4.2. Challenge 'Beliefs, identity and attitudes as a mathematical engineering student and problem solver'

Challenge sub-category 4.2 has two sides to it: (1) the identity part about *who I am as a problem solver* and (2) the belief part about *what's needed to be able to solve these problems*. It may come as a surprise to some that even people who are highly trained in mathematics question their problem-solving skills. This questioning takes a few different forms but often seems to come down to a kind of mantra about the belief that: 'if only I knew my calculus better' (as expressed by S1) or in terms of identity: 'I'm not the kind of person who knows how to connect math's to real-world systems' (S8). The large number[13] of 'I'm uncertain' or 'I don't know', nervous laughter[14], mid-sentence hesitations, and inconsistencies in reasoning add to the impression that for most of the interviewed students regularly feel insecure in the problem-solving processes observed here. Considering the entirety of the interview data and the interviewer's overall experience, we ask ourselves whether this only signals a difficulty with the tasks at hand or with real-world problems in general. Alternatively, could it indicate a low to moderate self-confidence in both their mathematical content knowledge and in their competence to apply those skills? Beliefs of the kind; 'more information is needed' (S9), or 'if only I had studied more pure math's courses the last year' (S8) are expressed despite the limited level and complexity of the mathematics involved in the problem-solving performed. These and other beliefs may, together with a classroom culture of not asking questions 'because you don't want to appear stupid or unknowing', [15] contribute to forming attitudes and expectations that in turn affect the emotional response to the problem-solving experience during the interviews.

Another challenge observed instead relates to the students' understanding of the nature of mathematical problem-solving. The observations this builds on are that we note that a few of the interviewees did not want to make multiple attempts at the mathematics expression task but instead seemed to be somewhat uncomfortable with being observed while trying to work out the mathematics or being used to give up quickly. Underlying this could be the belief or problem-solving identity that one does not know enough mathematics – a finding in line with the belief[16] 'Students who have understood the mathematics they have studied will be able to solve any assigned problem in five minutes or less' by Schoenfeld (1992, 27).

4. Discussion

4.1. A typology of challenges to correct reasoning about atmospheric CO_2 accumulation

Understanding the accumulation of CO_2 in the atmosphere is central to understanding the fundamental dynamics of climate change. However, as we have seen, although the carbon cycle may at first glance appear simpler than many other complex problems and systems that engineering students encounter in their courses, students face a multitude of challenges in modelling and reasoning about this stock and flow problem. Drawing on Schoenfeld's framework for mathematical thinking

(1983, 1992), we have categorised the challenges identified into three types or levels: cognitive, metacognitive, and affective. Table 1 above summarises our classification of the challenges that the students experienced when dealing with tasks related to the accumulation of CO_2 in the atmosphere. Given the multifaceted nature of the challenges, their interconnectedness, and the significant influence they exert on students' problem-solving abilities, it is understandable that prior research has yet to pinpoint a definitive primary cause for the typically modest performance observed in the CO_2 category of stock-flow tasks.

As expected, the students experienced a series of *cognitive* challenges, such as not being aware of oceans' role in the uptake of CO_2, believing that CO_2 breaks down or goes out into space, and believing that if emissions of CO_2 stabilise, so will the atmospheric amount of CO_2. Much like Schoenfeld (1983, 1992), we found that the students also experienced *metacognitive* challenges: they spent a significant amount of time talking beside the point of the question, or started out using the first mathematical problem-solving approach that came to mind without reflecting on whether it was an appropriate approach to use. Finally, like Schoenfeld (1983, 1992), we found the students experienced *affective* challenges – provoked by either the climate context or by their own disciplinary identity or beliefs – which sometimes stopped them all together from attempting to answer a question, and on other occasions they just dropped a thought and moved on if they felt uncertain about pursuing it.

To discuss and dig deeper into these findings, we will raise two points for which the findings and the interpretations of the data made a special impression on the educators with a climate science background among the co-authors. These were the influence of internal factors and the role of a functioning internal problem representation for any task addressed, both of which are topics studied by Jonassen (2000), who makes the point that creating an appropriate internal representation of the problem is the most critical step in problem-solving.

4.2. Internal factors shaping problem solving

Using terminology from Jonassen (2017) for analysing what makes problem-solving difficult, we find the classification of aspects into external- and internal factors in line with our findings. While the influence of external factors on people's understanding of CO_2 accumulation has been raised before (e.g. Dutt and Gonzalez 2011; Fischer et al. 2015), our study highlights internal factors, which are 'related to the personal characteristics of the problem solver' (Jonassen 2017). This is particularly true for metacognitive and affective challenges, which to a large extent are deeply personal.

We have shown that the degree of metacognitive skills needed to solve the tasks was high[17]– given that the mathematically skilled students had significant difficulties in solving the tasks. This primarily revolved around the physical soundness of the models or answers produced (i.e. proficiency in problem-solving). And while our impression is that the students did their best in dealing with the tasks, there is clearly room for improvement, as most students did not apply their background knowledge consistently, nor were they able to use data presented to them to check the answers they provided. An explanation for this could be a lack of experience working with real-world problems (Jonassen, Strobel, and Lee 2006), as several of the students brought in experiences or opinions into their reasoning in a way that seemed to cloud the central issues of the tasks.

Experience is an important internal factor in problem-solving, and it is noted that 'experiences are phenomenological and are normally conveyed through stories' (Jonassen 2017). At the same time, such 'stories' or dominant narratives can also hamper problem-solving, as demonstrated by sub-category 4.1. This sub-category describes how the tasks triggered different types of 'stories' related to climate change, resulting in lengthy discussions of system details or what needs to happen, rather than a focus on the data provided and the relationships between emissions, uptake, and the atmospheric amount of CO_2. This tendency was dubbed *phenomenological* reasoning in Sterner et al. (2019).

While some of the affective challenges, like feeling stupid for not being able to directly solve the tasks, may pertain to the nature of the interview situation and the group of students, others, like apocalyptic narratives, are documented to exist more generally, and under other social circumstances as well (Hickman et al.2021). To sum up, commonly held beliefs (not necessarily consciously held) about what is useful in solving a problem and negative to mildly negative attitudes and feelings around their problem-solving capacity (or possibly identity) significantly influence their approach and performance in problem-solving situations, with this echoing the findings of Schoenfeld (1992). The self-doubt dimension of this clearly dominates challenge sub-category 4.2, but occasional positive affective responses exist among a few students who express interest in the subject. Even with a generally positive attitude to taking part in the interviews (all but one was positive to extending the duration of the interview), the problem-solving situation was to some degree emotionally challenging for the interviewees.

4.3. Internal problem representation and inconsistent reasoning about CO_2 accumulation

Most of the students struggled in various ways with their conceptual model (or mind map) of what affects the amount of CO_2 in the atmosphere (Task 1a). We interpret this struggle as being connected to students not having constructed a clear internal representation of the problem. The students' ability to present a correct and coherent mental model in Task 1a is a strong indicator of their consistency (or lack thereof) in their wider reasoning around CO_2 accumulation in the later tasks, including their ability to use analogies and solve the mathematical expression tasks. This finding aligns with the foundational principle that problem-solving necessitates the conversion of a problem statement into a robust internal representation (Chi et al. 1989, 165) and is consistent with Covitt et al. (2021), who found that learners lacking such models frequently default to informal 'good versus bad' logic or simplified correlation heuristics (which we refer to as pattern matching). Identifying what the core components of the CO_2 accumulation tasks are (i.e. locating the key components of the problem) was found challenging and was classified as Challenge Category 1, while grasping the relationship between the components in an unambiguous and correct way was categorised as Challenge Category 2.

It was striking to observe that only a few students were consistent in their reasoning on the various tasks, and that these students were not necessarily the students that demonstrated most content knowledge of the subject, but rather students who were more certain of their mathematical modelling skills and chose to rely on them to guide their interpretation and meaning making process (i.e. students with a structured approach to real-world problem-solving). As an example of this, one of the students (S3), who reasoned most consistently throughout the tasks and who produced a concise and easily interpretable conceptual model, based his/her reasoning on a bathtub analogy. Interesting to note is however, that from his/her conceptualisation of the system, he/she drew the conclusion that the amount of emissions must increase in order for the uptake to (by some argument of increased pressure within the atmosphere – a kin to the increased pressure in the drain of a bathtub with more water in it) also increase so that they may become equal. It is hence important that mental representations of systems and problems are based on analogies or interpretations of systems that keep the risk of internalising misunderstandings low. At the opposite end of the problem-solving skills spectrum, we find student (S9), who barely produced a conceptual model at all (Figure 3(a)), was also one of the two students who used pattern matching (Figure 4) and thus performed poorly on most tasks.

Summing up, it seems that these students have mainly experienced working with problems for which the mathematics needed to solve the problems is easily discerned. When faced with tasks that have unclear goals, or for which the solution can be evaluated in several ways (mathematically vs. physically sound), the students experienced substantial difficulties, in line with previous findings (Jonassen 2017). However, the majority of the students ended up partially solving the problem by turning it into a mathematical problem and without reflecting much about the consistency of the model used, the solution generated, or the problem background (context and data) within which it was presented. Schoenfeld (1992) summarised his observations on mathematical problem-solving as: 'Most students spend time "doing the maths" – not planning, analysing, or questioning their process (regularly), and evaluating their results'. Our findings align well with this description; at the same time, an overarching impression from the interviews and the analysis is that the students would like to master the subject as well as the application of their mathematical modelling competence to a higher degree. This suggests opportunities for meaningful engagement in learning activities on the topic of CO_2 accumulation, as well as highlighting the need to take internal factors into account in mathematical modelling education generally.

4.4. Limitations

While our study intentionally seeks to uncover a range of challenges in students' reasoning rather than provide generalizable results, we acknowledge certain limitations. Because all participants were Swedish engineering-mathematics students from a single university, the sample is quite homogeneous and therefore unlikely to reflect the full spectrum of ways of reasoning and challenges that a more diverse cohort would encounter when tackling these tasks. Sweden's strong tradition of environmental consciousness and its long-standing inclusion of the environment in the national primary and secondary school curriculum likely skews the perceived prevalence and types of climate-related challenges. The sample size of ten students, although purposive with the aim to capture a breadth in ways of reasoning (when solving the main tasks), limits the breadth of challenges identified. Additionally, the first author's climate science expertise may have inadvertently biased the analysis towards subject-specific challenges over more general problem-solving obstacles. While the study comprehensively addresses cognitive, metacognitive, and affective challenges in understanding CO_2 accumulation, it does not encompass all possible facets of this complex issue.

5. Conclusions

The difficulties encountered by the engineering students suggest that their training in formal mathematics is sufficient, but they underperform when faced with a real-world problem like CO_2 accumulation, which does not come with a clear roadmap on what mathematics skills to apply. The students seem to either be overwhelmed by the details of the context or to simplify away the essence of the problem at hand, i.e. to the extent that the understanding of the physical system needed to address the task accurately is lost. Consequently, no student in our sample managed to derive a mental representation of the carbon cycle that is physically sound in the sense of it describing the main characteristics of the system in a qualitatively correct way.

This study provides several distinct contributions that address the gaps identified in our introduction regarding the nature of stock-flow (SF) failure and sustainability reasoning. While earlier research has extensively documented the prevalence of SF failure, it has primarily sought explanations in what Jonassen (2017) terms external factors, such as task format or contextual cues. Our study extends this literature by shifting the analytical focus to internal factors – specifically the metacognitive and affective dimensions that govern how engineering students select and employ their cognitive resources.

Our findings also refine the current understanding of climate literacy - e.g. documenting the misconception that some CO_2 goes out into space. Additionally we build on Covitt et al. (2021) who identified that non-science students frequently default to informal 'good versus bad' logic or correlation heuristics. We expand on this work by demonstrating that even mathematically proficient engineering students, who possess the formal calculus skills to solve these tasks, revert to similar informal 'pattern matching' when their internal problem representations are fragile. This highlights a critical lack of conditional knowledge – the ability to determine which mathematical tools are appropriate for ill-structured, real-world problems – which is a general indication of a lack of experience with professional engineering practice rather than a lack of mathematical proficiency. Beyond climate literacy, these findings suggest a broader implication for mathematical modelling education: students may need more opportunities to practice identifying when, why, and how particular mathematical tools and skills should be applied to ill-structured real-world problems, sometimes even without carrying out the calculations themselves.

Methodologically, we contribute a nuanced qualitative approach to a field often dominated by quantitative assessments. By utilising think-aloud protocols across conceptual, symbolic, and graphical formats, we were able to capture the 'pathological' behaviors described by Schoenfeld (1983, 1992), such as the 'five-minute rule' or the 'doing the maths' phenomenon. These behaviors demonstrate how a student's identity and reaction to an experimental setting can induce underperformance, a dimension that remained largely invisible in prior answer-based studies. We also believe that a small methodological contribution of this study was the interdisciplinary nature of the work, which involved both climate and education scientists.

Finally, our study contributes to the literature on sustainability in engineering education by positioning the carbon cycle as a foundational case for developing professional sense-making. We argue that the specific cognitive hurdles of CO_2 accumulation – such as conceptualising gas as an entity with mass and understanding dynamic uptake – embedded within the publicly debated and affectively charged context of climate change, make the carbon cycle a valuable case for preparing engineers to navigate the complexity and uncertainty of 'wicked' sustainability challenges in their future careers (Lönngren, Adawi, and Svanström 2019).

The nature and range of the challenges were, from a climate scientist's perspective noteworthy and from a teacher's perspective, instructive. All of these challenges need to be addressed to help students to successfully create and be able to apply a physically sound mental representation of atmospheric CO_2 accumulation.

Turning to practical implications, we suggest that educators in climate-related courses[18] should be aware of the complexity of bringing clarity to what is needed of the global CO_2 emissions trajectory ahead in order for it to be aligned with politically agreed-upon targets and plan learning activities that assist students in facing and overcoming the key challenges addressed here. The public debates around the climate challenge vary between countries, but because of the Paris agreement and the nationally determined contributions it includes, most countries have some form of public discourse (often politicised) about what reaching a given climate target requires in terms of emissions ahead (i.e. net-zero emissions) [19]. This means that engineering students will come to the classroom with both preconceived notions of the carbon cycle and, in some cases, intense emotions connected to the issue of climate change.

While classical problem-solving challenges, such as lack of prior content knowledge and metacognitive skills, have been forefronted in this study, it also shows that the context of climate change affects most students significantly by invoking certain beliefs, attitudes, and emotions that in turn affect the problem-solving process. The identification of several affective challenges suggests that an especially promising path for subsequent research is the creation and evaluation of emotional support frameworks. These frameworks would encompass methodologies and tools aimed at assisting students in navigating the emotional, attitudinal, and belief-based barriers that could obstruct their problem-solving capabilities and educational progress in areas markedly influenced by emotional and identity considerations, like the domain of climate change. As engineering educators, we suggest that (1) a student-centered approach to leverage the students' problem-solving competencies would focus more on (mis-)understandings (as a part of students' prior knowledge), metacognitive skills and affective dimensions (echoing Schoenfeld 1992) and (2) that some integration of well-chosen sustainability-themed real-world problems into engineering education training can prepare students better for the tasks that awaits them in their future professions.

Notes

1. *Understanding the carbon cycle* here refers to the ability to account for the three main components of the active carbon cycle, the flows between them as well as the resulting accumulating nature of CO_2 emissions from fossil-fuel sources and finally the resulting need for net-zero emissions for a stabilisation of the climate.
2. Chemistry core content, Years 7–9: 'The properties and cycles of the carbon atom in nature, society and the human body' (Skolverket 2022).
3. Active carbon cycle is here a pedagogical shorthand for the atmosphere–land–ocean carbon system that exchanges carbon on climate relevant/human-to-centennial timescales, including anthropogenic emissions from fossil fuels, cement production, and land-use change.
4. For a more complete description of the carbon cycle and its response to human perturbation see for instance Ch 5 in IPCC AR6 (Canadell et al. 2021).
5. An example of a lesson plan and learning materials that exemplifies how CO_2 accumulation tasks can be integrated as a learning activity into engineering curricula: https://doi.org/10.5281/zenodo.20745877
6. Without having the exact information about the age of these students we can – as teachers in the course – estimate the age of these students to be 22–24 years old with limited variation, which is representative for the program. See the supplementary material section 1 for the program plan and prior courses studied by the students.
7. In addition to this, there is also a mandate to have a 7.5 ECTS course classified as 'Human, Technology, Society'.
8. Tasks 3.a–3.c (see Supplementary Material) were accompanied by clarification questions of the type: 'Could you write what the different variables mean? Could you explain to me term by term what the expression says?'
9. The student described how he/she changed his/her reasoning between the survey and the interview.
10. An alternative metacognitive strategy that could have avoided the mistake of not including A_0 would have been for the student to ask him-/herself any of the questions: *what do I know since before about CO_2in the atmosphere or what do I know about the flows of CO_2?* This would likely lead to a reflection about the plants' need for CO_2 etc.
11. Note however that the exact formulation (in Swedish) of the question can be translated to English using formulations that involve the words 'significant' or 'what matters' instead of 'important'.
12. We note that S4 was one of the students who voiced most pro-environmental attitudes.
13. The ten interviewees in total produced >100 'I don't know', >200 laughters (most often as a sign of uncertainty) and >1500 hesitations.
14. This happens despite the interviewer instructing the interviewees that some of the tasks are difficult and may be hard to solve.
15. As a former student in a program very similar to the students' own program and from having evaluated the classroom culture as a teacher, in the course which ran parallel to this study, the main author has on multiple occasions witnessed people expressing this, for example as an explanation for the limited interaction between students and teachers.
16. The beliefs 'mathematics is a solitary activity, done by individuals in isolation' and possibly also 'mathematics problems have one and only one right answer' may also be playing a role here, Schoenfeld (1992, 27).
17. A reflection from the authors is that challenges were expected to arise, yet the authors were surprised by the degree of metacognitive skills needed.
18. Courses that relate to climate change directly or indirectly (e.g. on technologies, business models, etc. that have a direct or indirect effect on climate change). Example of learning activity that can be used athttps://doi.org/10.5281/zenodo.20745877.
19. This assumes no other changes in climate forcings from other climate forcers such as emissions of other greenhouse gases or land use change that alter the reflectivity of Earth's surface. Which is a fairly strong assumption, but here serves a pedagogical point.

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