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Secondary students' ideas about scientific concepts underlying climate change

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ABSTRACT

We present ideas about concepts underlying climate change, held by students in years 9 and 10. Misconceptions about climate change are common among students, and may be due to misconceptions about underlying concepts. To investigate this, we developed the Climate Change Concept Inventory (CCCI), and trialed it with 229 students; corroborating findings through focus group interviews. Our interview method and data analysis methods are described. Findings included overestimation of human contributions to atmospheric carbon inputs, ultra violet radiation in sunlight, and greenhouse gases in the atmosphere. Students were unaware that CO_2 dissolves in water, and of the role of oceans in the carbon cycle. Greenhouse gases other than CO_2 were rarely known. Earth's energy balance and black body radiation were not well understood. There were misconceptions about interactions between electromagnetic radiation and atmospheric gases; and limited understanding of carbon chemistry. The CCCI is available from the corresponding author.

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1. Background

1.1. Introduction

1.1.1. The importance of education about climate change

Climate change is a significant issue for students as future decision makers and voters (Intergovernmental Panel on Climate Change 2014; Schreiner, Henriksen, and Hansen 2005). To respond effectively, students must understand the basic science: 'Effective public education on global warming … is essential.' (Bord, O'Connor, and Fisher 2000, 216). Schreiner, Henriksen, and Hansen (2005, 8) claim 'empowerment is a prerequisite for action and includes content-specific knowledge'. Mason and Santi (1998, 68) assert that accurate knowledge is a 'fundamental component' of responses to environmental issues. McNeill and Vaughn (2012, 2) state that strong conceptual understanding increases desire to take action, and recommend that learning activities address common misconceptions: 'if … education is to improve citizens' understandings about … climate change, students must develop mental models … more closely aligned with scientific models'. According to Shepardson et al. (2011), we must understand how students conceptualize the topic, to design appropriate curricula and learning experiences. Regarding the common conflation of climate change and ozone depletion,

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Gowda, Fox, and Magelky (1997, 2234) comment, 'This mistake is significant because peoples' perceptions regarding causes help dictate their responses … they may have the false impression that they are doing a significant amount to prevent global warming'. Bord, O'Connor, and Fisher (2000, 216) assert 'Those believing that aerosols and insecticides cause global warming are not likely to make wise choices on referenda questions for government policies.'

Our study employs constructivist learning theory, which posits that learning involves active construction of knowledge by students when new information interacts with existing ideas (Bodner 1986). Pre-existing ideas thus play a crucial role in knowledge construction. Ausubel (1963) asserts that the most important principle in educational psychology is 'what the learner already knows'. Learners' pre-existing ideas about concepts are often remarkably consistent across age groups and nationalities, and tend to persist following traditional educational practices.

Given the importance of accurate knowledge about climate change in shaping attitudes and responses, and the centrality of learners' existing ideas to knowledge construction, it is essential to understand students' existing ideas so that effective learning experiences can be designed. Therefore, our research aims to identify learners' existing ideas about key scientific concepts underlying climate change and suggest possible reasons for these. To do this, we developed the Climate Change Concept Inventory (CCCI) and conducted semi-structured focus group interviews.

1.1.2. Previous research on learners' ideas about climate change

Over 30 years of research into learners' ideas about climate change shows that misconceptions are widespread, consistent, and persistent; chiefly conflation of climate change and ozone depletion (Boyes and Stanisstreet 1993; Dove, 1996; Gowda, Fox, and Magelky 1997; Rye, Rubba, and Wiesenmayer, 1997; Mason and Santi 1998; Koulaidis and Christidou 1999; Andersson and Wallin, 2000; Shepardson et al. 2009; Hansen 2010; Arslan, Cigdemoglu, and Moseley, 2012; Lambert, Lindgren, and Bleicher 2012; Ratinen, Viiri, and Lehesvuori, 2012; Versprille and Towns 2015; Chang and Pascua, 2016; Varela, Sesto, and García-Rodeja, 2018). Some of these researchers suggested possible underlying reasons for observed misconceptions. These include the complexity of the topic (Hansen 2010; Andersson and Wallin 2000; Mason and Santi 1998); applying 'environmentally friendly' ideas in a general way (Boyes and Stanisstreet 1993; Hansen 2010; Gowda, Fox, and Magelky 1997); conceptual difficulties with energy exchanges between the earth's surface and atmosphere (Rye, Rubba, and Wiesenmayer 1997; Koulaidis and Christidou 1999; Andersson and Wallin 2000; Mason and Santi 1998; Meadows and Wiesenmayer 1999), and difficulties applying knowledge learned in other contexts (Österlind 2005).

However, none of the authors tested these hypothesized explanations directly, and interventions to address misconceptions need to be based on well-established understanding of their causes. Also, most research on learners' ideas about climate change has investigated the topic as a whole, limiting the extent to which underlying causes of misconceptions can be investigated. Therefore, our study sought to address the ways in which misconceptions about essential underlying concepts (e.g. energy exchanges as noted above) may contribute to miconceptions about the science of climate change. Our research questions were as follows:

1. What scientific concepts students do students need to understand, to make sense of a basic explanation of the mechanism of climate change?
2. What do year 9 and 10 students understand about these underlying scientific concepts?

The methods for our first research question were described in detail in Jarrett, Takacs, and Ferry (2011) and are summarized in Sections 1.1.3 to 1.2.2. The rest of this article reports on the second question.

1.1.3. Scientific concepts underlying the mechanism of climate change

Understanding the mechanism of climate change involves applying and integrating conceptual areas including the carbon cycle, energy emitted by the Sun and Earth, and interactions between the electromagnetic spectrum and the Earth's atmosphere. The first stage in development of the CCCI involved identifying concepts essential for a basic understanding of climate change, by combining findings of a literature review and a Delphi study to generate a ranked list of 10 conceptual areas. The methods and findings for this stage are described in Jarrett, Takacs, and Ferry (2011). The ranked list is given in Section 1.2.2.

Other researchers have proposed similar lists of essential concepts (Shepardson et al. 2012; Lambert, Lindgren, and Bleicher 2012; McCaffrey and Buhr 2008; Climate Literacy Network 2009; Gautier, Deutsch, and Rebich 2006). These studies either have a broader focus than ours or apply to different groups of learners such as pre-service teachers or undergraduate scientists. However, taking account of these differences, their findings are broadly in agreement with ours and were used for corroboration.

1.1.4. Students' understanding of the concepts underlying climate change

Learners' ideas about some of the concepts in our list have been studied (Jarrett, Takacs, and Ferry 2011). We compared our findings with those of other researchers; these are discussed in Section 3. The literature shows that misconceptions about underlying concepts are common, giving credibility to the idea that difficulties with underlying concepts are a factor in students' misconceptions about climate change.

1.1.5. Critique of data collection methods and rationale for the CCCI

Our unpublished pilot study used concept maps and semi-structured interviews. Participants produced limited concept maps but articulated more extensive ideas during interviews, suggesting that in the time available, they had not mastered the skills to express their ideas fully in a concept map. Novak (1990) discusses the need for learners to practice the skill of concept mapping. We therefore decided to use a different large-scale data collection method.

The conceptual models articulated by Koulaidis and Christadou's (1999) participants, while being no more correct than those of Rye, Rubba, and Wiesenmayer's (1997) participants, were more detailed, suggesting that stimulus material may help activate participants' knowledge. In semi-structured interviews, questions and probes act as stimulus; however, they are not suitable for large-scale data collection.

Many of the studies cited in Section 1.1.2 used 'agree/disagree' surveys. While some invited students to explain their reasoning, there is no guarantee that a participant can, or will, do so. Boyes and Stanisstreet (1993) acknowledged that this method could give misleading results. Furthermore, most surveys included only a small number of questions about the mechanism of climate change and it is impossible to validate responses to a single question. Concept Inventories (CIs) overcome these weaknesses while allowing large participant numbers. First, they require students to choose one of the several options, offering more insight than 'true/false' questions. Second, two or more items test each concept, so responses to items addressing the same concept can be compared, allowing validation. Finally, CIs provide participants with pre-prepared responses to choose from, which may help overcome difficulty in expressing ideas. Students are familiar with the multiple-choice format so no time is required to learn the method, minimizing disruption to schools.

CIs cannot explore reasons behind responses, and lack the capacity of concept mapping to investigate perceived relationships among concepts. However we considered the advantages outlined above to outweigh these limitations. We combined our CI with semi-structured focus groups for a subset of participants, to validate CI findings and explore reasons for CI responses in more depth, overcoming one limitation of a closed-response survey. We chose focus groups because research suggests that students are likely to feel less intimidated about expressing their thoughts in the company of their peers, and that focus groups generate more ideas than individual interviews (Rabiee 2004). Focus groups also maximize the time available for participants to talk; and allow topics to be covered in more depth in the available time; minimizing inconvenience to schools. To allow for natural conversation flow, focus group participants were not asked to give their name each time they spoke. Also, participants often interrupted, finished each other's sentences, or offered ideas due to their high level of engagement (Lederman 1990). This meant that it was rarely possible to reliably compare participants' verbal responses on audio recordings, with their CI responses. However, we felt that this disadvantage was outweighed by the advantages described.

1.2. Concept Inventories

1.2.1. CIs in science, technology, engineering, and mathematics education research

CIs are validated multiple-choice tests designed to assess conceptual understanding of a topic. They contain distractors based on known misconceptions (Bardar, Prather, and Slater 2006; Evans et al. 2003), providing insight into the prevalence of these ideas. CIs originated in physics education with the Force Concept Inventory (Hestenes, Wells, and Swackhamer 1992) but have since been developed for other STEM areas (e.g. Herman 2011; Stone 2006).

1.2.2. The CCCI: a brief description

The first version of the CCCI, used in this study, is a 27-item multiple-choice instrument addressing seven conceptual areas underlying the mechanism of climate change. Our Delphi study and literature review (Jarrett, Takacs, and Ferry 2011) identified the 10 conceptual areas shown in Table 1.

Three conceptual areas were not included because pre-trial focus groups revealed either no ideas, or no variability in ideas about these concepts; so, we could not write appropriate items for them Jarrett, Ferry, and Takacs (2012). We applied rigorous methodology to development and statistical evaluation of the CCCI to enhance quality and validity (Jarrett, Ferry, and Takacs 2012).

1.2.3. Other recently developed conceptual tests for climate change science

Lambert, Lindgren, and Bleicher (2012), Arslan, Cigdemoglu, and Moseley (2012), and Lombardi, Sinatra, and Nussbaum (2013) developed conceptual tests for climate change, concurrently with our research. These differ from the CCCI in several ways. The first two focus on different groups of learners and address a wider range of concepts. Lambert, Lindgren, and Bleicher's (2012) instrument contains both multiple-choice and extended-response items while Lombardi, Sinatra, and Nussbaum's (2013) instrument uses Likert-response to probe understanding. It also takes a broad view, while probing the mechanism in less detail. However, the parallels between these instruments and the CCCI emphasize the importance of assessing conceptual understanding of the topic.

2. Methods

2.1. Sources of information about participants' ideas

Table 2 summarizes the key authors whose work informed the development of our methods for the research reported here.

Table 1. Ten conceptual areas identified through literature review and Delphi study.

Conceptual area	Number of CCCI items
Carbon cycle and fossil fuels: There is a fixed amount of carbon on Earth: it is cycled among the atmosphere, biosphere, soils, ocean, and rocks. There are both natural and human-induced sources and sinks of greenhouse gases. Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere–ocean–biosphere cycle. Burning fossil fuels returns this carbon to the cycle.	8
Electromagnetic spectrum: There is IR and UV radiation beyond the visible spectrum: these are all related forms of electromagnetic energy. The Sun emits mostly visible radiation and the Earth emits mostly IR.	3
Interactions between greenhouse (GH) gases and electromagnetic radiation: Most of the gases that make up the atmosphere are transparent to visible light. Non-GH gases are transparent to IR but GH gases absorb IR: this is the cause of the greenhouse effect. GH gases allow the Sun's visible light in but absorb IR emitted by Earth. This is re-emitted in all directions – down as well as up.	6
Natural climate variability in the past and relationship to CO2 levels: The climate has been different in the past (e.g. carboniferous period and ice ages) due to changes in energy emitted by the Sun, the distance between the Earth and Sun or CO2 released from volcanoes during periods of high levels of volcanism. Prehistoric climate changes correlate with changes in CO2 levels, providing evidence for the link between CO2 levels and global temperatures.	None
Difference between weather and climate: Weather is short-term, day-to-day climatic conditions, while climate is the longer-term average conditions.	None
Proportions of greenhouse and non-greenhouse gases in the atmosphere: Over 96% of the atmosphere consists of non-greenhouse gases. The atmosphere also contains small amounts of CO2, CH4, O3, N2O and H2O, and CFCs—all of which are greenhouse gases. Water vapor is a variable component of the atmosphere and is the most abundant greenhouse gas. GH gases are not in a distinct atmospheric layer.	4
Radiative forcing capacity: Some greenhouse gases have more radiative forcing capacity than others, that is, a given amount of a 'stronger' greenhouse gas would result in more radiative forcing than the same amount of 'weaker' greenhouse gas.	None
Feedback: Changing one parameter can have an effect on another parameter, which causes a change in the original parameter. Feedbacks can be negative (i.e. tends to return the parameter to its original value) or positive (i.e. tends to drive the parameter further away from its original value), for example, increasing CO2 raises surface temperatures causing more water to vaporize, which further raises temperatures.	3
Equilibrium of energy: There is a balance of energy into and out of the Earth/atmosphere system. A net flow of energy into or out of the Earth/atmosphere system leads to temperature change over time.	2
Conservation of energy: Energy can change from one form to another but the total amount of all forms of energy remains constant.	1

Bogdan and Biklen (2002), Cohen, Manion, and Morrison (2007), and Conrad and Serlin (2006) discuss the importance of triangulation and corroboration, through the comparison of data from miultiple sources. Our methods involved comparing three sources of information about participants' ideas:

- Responses to individual CCCI items. Item response analysis involves analyzing what participants' option choices imply about their understanding of the concepts (Bodzin 2011). We grouped items according to conceptual areas addressed. For each item, we calculated the percentage of participants choosing each option. To facilitate comparison with interview data, each finding was expressed as a statement, based on the item stem and option chosen. This was compared with codes derived from interview data.
- Contingency tables to determine whether participants reasoned consistently about concepts. CIs typically contain multiple items per concept. Students with a strongly held idea about a concept would be expected to answer such items consistently. For example, items 11 and 16 include the idea of greenhouse gases damaging the ozone layer. A student who strongly believes this idea would be expected to choose the corresponding options for both items. To test for evidence of consistent reasoning, we generated contingency tables for pairs of items that included a concept in common. These show frequency distribution of responses.

Table 2. Key authors for methods reported in this article.

Authors	Summary of contribution to research methods for this study
Bogdan and Biklen (2002); Cohen, Manion, and Morrison (2007); Conrad and Serlin (2006)	Application of multiple methods to enable triangulation and enhance credibility in qualitative research; overall research design.
White and Gunstone (1992)	Use of multiple modes of communication to enhance mode validity.
Treagust (1988)	Use of diagnostic tests with distractors based on known student misconceptions, as a tool for education research.
Lederman (1990); Kidd and Parshall (2000); Osborne and Collins (2001)	Use of focus group interviews in preference to individual interviews in order to gain deeper insight into participants' ideas. This is because participants can respond to, challenge, confront and criticize each other's ideas, allowing participants to re-evaluate their own ideas; and because less interviewer talking-time is needed.
Rabiee (2004); Gibbs (1997); Kidd and Parshall (2000)	Design of focus group interview protocols, including recommended group size of 4 to 12 participants; participants of similar age and experience; use of interview guides that evolve over a series of interviews; and the role of the interviewer in focus groups.
Cohen, Manion, and Morrison (2007)	Sampling considerations for CI and focus group interviews.
Bodzin (2011)	Item response analysis for CCCI items.
Everitt (1992)	Use of contingency tables.
Koulaidis and Christidou (1999)	Use of activities such as diagram completion in focus group interviews to help activate participants' knowledge.
Marton (1981)	Use of phenomenography in analysis of focus group interview data.
Braun et al. (2019)	Application of thematic analysis to focus group interview data.

Table 3. Focus group interview participants.

Location	Participants	Discussion time	Additional activities
Suburban	9 (all boys)	26 min (part 1) 32 min (part 2) Parts 1 and 2 took place on two consecutive days	Completing table of atmosphere/ sunlight interactions Completing drawing of carbon flows Open-ended drawing activity
Urban	13 (4 girls, 9 boys)	52 min	None
Urban	5 (all girls)	1 h 28 min	Completing drawings of carbon stocks and flows
Rural	6 (3 girls, 3 boys)	47 min	Completing drawings of carbon stocks and flows

- Focus groups to compare verbally expressed ideas with CCCI responses and explore reasoning. Focus group data analysis methods are described in Section 2.2.

The process of comparing these three sources is detailed in Section 3. We compared percentages of participants choosing CI options with percentages of focus group interviewees expressing phenomenologically equivalent ideas to these options. We used contingency table data to determine whether participants had reasoned consistently about a concept, suggesting that the idea was strongly held. We used direct quotes from focus group interviews to provide evidence for reasons behind students' CI choice, and to illustrate their thought processes.

2.1. Data collection

We trialed the CCCI in (date to be re-inserted after review), with 229 students aged between 13 and 16 years in six schools (region to be re-inserted after review). Details are summarized in Table 3. We used an interview guide based on the CCCI item stems in open-ended format (Rabiee 2004), allowing participants to express ideas in their own words; and follow-up questions to clarify responses and reasons behind them. This interview guide was revised for each focus group (Kidd and Parshall 2000). To help activate their knowledge, participants worked together to complete diagrams of carbon reservoirs and fluxes, and a table summarizing interactions between atmospheric gases and bands of the electromagnetic spectrum, and whether or not the gases were greenhouse gases (Koulaidis and Christidou 1999).

The moderator was guided by Gibbs' (1997) advice to clearly explain the purpose of the interview; put participants at ease; ask open questions, challenge participants, and probe for details; keep the conversation relevant; ensure that everyone has a chance to contribute; and avoid showing too much approval or giving personal opinions. We audio-recorded the interviews and took field-notes.

2.2. Data analysis methods for post-trial focus group interviews

Data analysis comprised six stages:

1. Transcription of audio recordings in full within 1 week.
2. Data reduction: removing utterances not related to conceptual knowledge; collating responses from different focus groups.
3. Thematically coding transcripts with inductively derived codes using an open-source text analysis tool (Diment 2010). We tagged each statement with one or more codes, then grouped phenomenographically (Marton 1981) equivalent statements to give a list of participants' ideas about each conceptual area.
4. Mapping thematic codes to CCCI findings following analysis of the CI data.
5. Grouping coded transcript sections to produce a set of transcript segments for each CCCI finding.
6. Counting phenomenographically (Marton 1981) equivalent responses to indicate prevalence of ideas, summarizing transcript segments, and illustrating each summary with quotations.

We used thematic analysis to derive and analyze codes for the focus group interview data (Braun et al. 2019). According to the authors, thematic analysis is a flexible method compatible with a range of theoretical and epistemological approaches; although this flexibility may make it difficult to know what aspects of the data to focus on. However, in our case, CI findings and the focus group interview guide provided focus, while the method allowed unexpected insights to be generated (Braun et al. 2019). These authors generated a 15-point checklist for good thematic analysis which we used to guide and evaluate our data analysis. To minimize delay, we completed analysis of focus group interview data before analysis of CI data, so we derived codes inductively rather than pre-determining them to match the format of the CI data. These codes were then compared phenomenographically with the statements summarizing the CI findings. All interview data were assigned a code and all utterances that addressed conceptual understanding of the topics were compared with CI findings.

3. Results and discussion

CCCI findings that were corroborated by interview data are discussed below. Focus group data that corroborates and elaborates on these findings are discussed. Our most significant findings are summarized in Table 4.

In this section, our findings are compared with those of other researchers who investigated learners' ideas about the same concepts (except where we could identify no such studies). The literature we reviewed is summarized in Table 5. For futher details on this literature review, see Jarrett (2013).

Table 4. Summary of CCCI findings corroborated by focus group interviews.

Relevant CCCI items	Finding and estimated prevalence
8	Overestimation of contribution of fossil fuel burning to carbon flows 90%
6	Overestimation of proportion of UV in Solar energy incident on Earth, 86%
1,8	Lack of awareness of solubility of CO_2 (81%) and water bodies as carbon reservoirs 46%
10	Confusion about greenhouse gases: carbon monoxide (70%) but not water vapor (80%), was thought to be a greenhouse gas
7, 14,24	Incomplete understanding of Earth's energy balance and black body radiation—responses strongly context-dependent 19%–90%
9,19	Overestimation of proportion of greenhouse gases in the atmosphere 17%–76%
2, 3,5, 13, 22	Incomplete understanding of the carbon cycle and fossil fuel formation including the role of atmospheric carbon 30%–75%.
25, 26, 27	Feedback was a new concept but most participants successfully applied it. 59%–66%
11,15,23 16,23, 18	Various incorrect ideas about interactions between electromagnetic radiation and atmospheric gases. No student could describe the interaction. 100%
1	Limited awareness of carbon compounds. 40%

3.1. Overestimation of quantities and proportions

Overestimation of quantities and proportions was a common theme. We observed overestimation of human contributions to carbon flows; the proportion of ultra violet (UV) radiation in sunlight; and the proportion of greenhouse gases in the atmosphere.

The 90% of CI respondents and 9 of 11 focus group participants (82%) overestimated the role of fossil fuel burning in global carbon flows. Seven focus group participants thought they exceeded those from natural sources. However, none could explain their reasoning. Two participants contradicted the idea, but neither gave an explanation. One student explained that they had initially chosen the correct answer based on 'climate sceptic' information, rather than a full understanding of how small but inputs can destroy equilibrium if they are not balanced by outputs:

> 'I should have thought about it relative to the others but you hear those big scare campaigns against the carbon tax that our percentage of carbon is tiny compared with cows farting and burping'.

This illustrates how 'climate sceptic' arguments encourage incorrect conclusions by providing partial information.

Overestimation of carbon flows from fossil fuels may have two sources. First, human activities may be mentioned in education and media more frequently than natural processes. Second, students who do not understand the concept of equilibrium, may conclude that human outputs can only cause problems if they are large compared with natural flows. Such students may be persuaded by 'climate sceptic' arguments such as the one described above. We did not identify any previous research findings on students' ideas about this concept, so it may be a new addition to the body of knowledge.

Of the CI participants, 89% overestimated the proportion of UV in Solar energy incident on Earth and 63% of these thought that UV comprises the largest proportion of solar energy. Focus group data closely reflected this. Twelve of nineteen focus group participants (63%) thought that UV comprised the greatest proportion of solar energy; only two (10%) chose the correct proportions. Two groups expressed astonishment when told the actual proportions. 'Sun safety' messages appear to be behind the focus on UV.

> 'You see TV ads 'put sunscreen on or you'll die in 15 min' … they make a big deal as if it's mostly UV'.

Only one focus group recalled learning about the topic, but no-one in this group used their knowledge to answer the question. We identified little prior research on high school students' ideas about the electromagnetic spectrum. Most of our participants, unlike those of the American Institute of Physics (1998), were familiar with the idea that different bands of the electromagnetic spectrum are related. We identified no prior research on students' ideas about the proportion of UV in sunlight, so again, this finding may be a new addition to the body of

Table 5. Summary of literature reviewed on learners' ideas about underlying concepts.

Authors	Concepts	Key findings
American Institute of Physics (1998)		Bands of the electromagnetic spectrum were thought to be unrelated.
Bodzin (2011)	Energy resources	Few participants knew that fossil fuels originate from living things; or that they are non-renewable.
Browne and Laws (2003)	Electromagnetic radiation	Difficulties understanding similarities and differences between visible light and IR radiation.
Comins (2003)	Electromagnetic radiation	All electromagnetic radiation was thought to pass through Earth's atmosphere.
Daniel, Stanisstreet, and Boyes (2004)	Greenhouse gases	Few participants were aware of the variety of greenhouse gases; their sources; or the concept of radiative forcing capacity.
Dove (1996)	Greenhouse gases	Greenhouse gases were thought to trap solar (not terrestrial) radiation. Methane and water vapor were not identified as greenhouse gases, but carbon monoxide was.
Ebert-May, Batzli, and Lim (2003)	Carbon cycle and photosynthesis	Biomass was thought to come from dissolved substances in soil; or from particles in soil. Decomposition was thought to destroy matter; and photosynthesis was seen only as a source of energy (rather than matter) for plants. Land and living things were thought to contain the largest pools of carbon; and carbon was thought to move between all pools at the same rate.
Gautier, Deutsch, and Rebich (2006)	Electromagnetic radiation and the greenhouse effect	Inappropriate mental models of radiation; trouble differentiating between shortwave and long-wave radiation. Few understood that the earth emits radiation. Most believed that it reflects the Sun's energy directly. The greenhouse effect was thought to be due to trapping of reflected solar energy.
Goldring and Osborne (1994)	Energy	Few participants understood basic energy concepts; some could recite the law of conservation of energy but not apply it.
Henriques et al. (2002)	Atmosphere, weather and climate	Participants thought that IR is the only band of radiation that causes objects to heat up.
Lambert, Lindgren, and Bleicher (2012)	Electromagnetic radiation and climate change	The sun's energy was thought to turn into CO_2 when trapped in the atmosphere. Lack of knowledge of carbon cycle processes. Very limited understanding of chemistry concepts or the role of fossil fuels in climate change. Few participants differentiated between different bands of solar radiation and very few knew that the Earth emits radiation.
Lambert (2005)	Electromagnetic radiation	Participants struggled to put bands of the electromagnetic spectrum in the correct order. Many thought that the Sun heats the Earth's interior.
Madsen, Gerhman, and Ford (2007)	Carbon cycle	Burning fossil fuels was thought to destroy carbon; lack of understanding of movement of carbon between reservoirs. Conflation of carbon and water cycles.
Mohan, Chen, and Anderson (2009)	Carbon cycle	Learners did not apply the principle of conservation of matter; gases were seen as not having mass; lack of understanding of chemical reactions; matter thought to be turned into energy; difficulties with large (global) and small (molecular) scales.
Österlind (2005)		Difficulty in recognizing the same phenomenon when discussed in different contexts or when given different names (e.g. IR or thermal radiation).
Pompea et al. (2007)	Light	Many participants believed that all radiation is harmful.
Rule (2005)	Fossil fuels	Fossil fuels were thought to have existed as long as the Earth; that they can form in a short time; that oil comes from soil or molten metal; and that coal comes from rock.
Shepardson et al. (2009)		Most participants did not distinguish between the different forms of radiation involved in the greenhouse effect. Methane was not identified as a greenhouse gas.
Sibley et al. (2007)	Carbon cycle	Difficulties with abstract or non-visible concepts e.g. chemical species or groundwater. The authors concluded that knowledge of chemistry is essential for understanding the carbon cycle.
Smith and Anderson (1986)	Photosynthesis and carbon cycle	Matter thought to be created and destroyed in the carbon cycle; plants were believed to turn CO2 into oxygen. Carbon cycle seen as separate, unrelated events; and plants and animals seen as fundamentally different types of matter.
Stavy, Eisen, and Yaakobi (1987)	Photosynthesis	Difficulty with the idea that CO2 is a major source of biomass for plants. Confusion between terms such as 'element' and 'compound'. Evidence that formulas were rote-memorized but not understood. The authors concluded photosynthesis is a very difficult topic for students.
Wandersee (1986)	Photosynthesis	Atmospheric CO_2 was not seen as a major raw ingredient for photosynthesis.

knowledge for this topic. Few of Lambert, Lindgren, and Bleicher's (2012) pre-service teacher participants differentiated between types of radiation from the Sun.

Conflation of ozone depletion and climate change is the most commonly reported finding of research into learners' ideas about climate change. Our finding offers insight into this: students may believe that more UV reaching the Earth's surface significantly increases incident solar energy, causing heating. This supports Rye, Rubba, and Wiesenmayer's (1997) suggestion that students' existing experience of sunlight as being 'hot' could interact with new information, resulting in the idea that 'the the extra sunlight or ultraviolet radiation, coming through the 'hole' in the ozone layer, heats up the planet' (p. 530).

Of the CI participants, 56% thought greenhouse gases comprise 5% to 30% of the atmosphere and 22% thought they comprise over 30%. When asked in another item whether a small proportion ($<$5%) of greenhouse gases can have a significant effect, 17% responded, 'it ca not'. Contingency table data for these two items showed that participants reasoned consistently, suggesting this is a firmly held idea.

Focus group data mirrored these findings. Of the 26 participants who responded, 13 (50%) thought the atmosphere comprised over 5% greenhouse gases, and four (15%) thought 30% or more. Some thought 5% *was* a small amount. Nine thought the atmosphere comprised less than 5% greenhouse gases. Of these, three based their reasoning on knowledge of other atmospheric gases. Thirteen students expressed surprise when told the actual concentration.

> 'That's shocking'.
>
> 'I thought it would be a lot more - they're talking about how they're destroying our atmosphere, so I assumed it would be at least 25% if not more because that's what they're focusing on in the news'.

Gowda, Fox, and Magelky (1997) observed the idea that the atmosphere is too large for small amounts of CO_2 to have any significant impact. Students clearly struggle to believe that a tiny percentage of greenhouse gases could be significant. Again, this may lead them to accept 'climate sceptic' arguments based on greenhouse gas concentrations. As with the proportion of UV in Solar radiation, media and scientific concern may have been misinterpreted to mean a large quantity rather than significant potential for harm.

3.2. Difficulties with carbon chemistry and the properties of carbon compounds; the source of carbon in fossil fuels, fossil fuel formation, and the carbon cycle

We observed difficulties with the origin of carbon in fossil fuels, and the origin and age of fossil fuels. Of the CI participants, 49% thought carbon in fossil fuels originated in soil or rock. Knowledge that fossil fuels originate from living things was observed in all focus groups; however, some students were unfamiliar or unhappy with this idea:

> 'How's oil or gas made out of dead things? That's weird'.
>
> 'I don't really know what a fossil fuel is'.
>
> '[coal originated from] Diamonds, ashes, volcanoes, charcoal, when the Earth formed, igneous rocks, heat in the middle of the Earth'.

A common idea was that burning fossil fuels creates carbon, increasing the amount of carbon on Earth (71% of CI participants):

> [Researcher] 'Plants growing, dying, getting buried, how would that affect carbon in the atmosphere?'
>
> '[Student] More fossil fuels so more carbon'.
>
> '[Researcher] When you dig up coal, is the carbon in the coal then?'
>
> '[2 students] Yes'.

'[3 students] No, it's when you burn it, because it reacts'.

'[Student] Maybe [total carbon] has increased because when the Earth began there wasn't anything living but there is now. All living things have carbon'.

'[Researcher] Do they create it, or get it from somewhere else?'

'[Student] Get it from the ground?'

'[Student 1] Over time, the total amount of carbon has increased [all agree]'.

'[Student 2] Because of forests getting destroyed and factories being built [several agree]'.

'[Researcher] Where does that carbon come from?'

'[Student 2] Factories, cars, burning fossil fuels, human activity'.

Some students, while understanding the stages of fossil fuel formation as separate events, had not consciously reasoned before that carbon in fossil fuels originated in the atmosphere:

'That's where I'm stuck, [living things] would get [carbon] from the atmosphere or their food source which would have had to get it from somewhere'.

Smith and Anderson (1986), Madsen, Gerhman, and Ford (2007), and Mohan, Chen, and Anderson (2009) observed the idea among their participants that matter can be created and destroyed, concluding that students might think photosynthesis involves plants turning CO2 into oxygen. These learners would not understand plants' role as a sink for atmospheric CO2, or that carbon in fossil fuels was once in the atmosphere. Only one focus group knew that carbon in fossil fuels came from the atmosphere, and named photosynthesis and respiration as the processes by which carbon moves between the atmosphere and living things.

Previous research shows high rates of misconceptions about fossil fuel formation. Lambert, Lindgren, and Bleicher (2012) found little evidence of understanding of the role of fossil fuels in climate change. We found the knowledge that fossil fuels originate from living things to be more widespread than did Bodzin (2011); only 17% of his Grade eight participants knew that coal formed from swamp plants. 19% of Rule's (2005) primary-aged participants thought coal comes from dirt or soil, while 36% thought coal is the same thing as charcoal and comes from wood. However, only one of our focus group members thought coal comes from rock. Of the CI participants, 45% thought fossil fuel formation increased atmospheric carbon, further suggesting a lack of understanding that carbon in fossil fuels originated in the atmosphere, and of the carbon cycle. Students may not have engaged with this concept before, and while they may possess elements of knowledge, they have not tried to synthesize them:

'You just have to think about it. I actually probably learned more on that test'.

'[Researcher] Is that something that you think about when people talk about fossil fuels being burned?'

'[2 students] Not really'.

Of the CI participants, 39% thought plants get carbon from air; 39% thought they get from it from soil, and 22% thought plants convert the Sun's energy into new carbon atoms. Therefore, 61% of students may not appreciate that plants remove carbon from the atmosphere. Wandersee's (1986), Stavy, Eisen, and Yaakobi's (1987) and Ebert-May, Batzli, and Lim's (2003) participants also thought plants get carbon from soil. Focus groups expressed these ideas at similar rates, but expressed a wider range of ideas, including that carbon came from more than one source. Conversations suggest tentative conceptual models about the role of sunlight in photosynthesis and the ability of energy to create atoms.

'[Researcher] And what do they do with [the Sun's] energy?'

'[Student] Use it through photosynthesis'.

'[Researcher] What do they turn it into?'

'[Student] Nutrients and stuff so they can grow'.

'[Researcher] Can you turn energy into chemicals?'

'[Student] Good question. Using energy you can make chemicals'.

'[Student] Is there energy *in* chemicals?'

Fourteen (29%) focus group participants thought carbon came from either the air and, the Sun and soil or the Sun and water. None explained their reasoning. All groups, even the one most proficient at chemistry, expressed misconceptions about photosynthesis. The comments below suggest that even students who can recite the reactants and products may be confused about where reactants come from, and may believe plants obtain carbon from the Sun. Students strongly believe that plants need *something* from the Sun, but are unsure what:

'[Student 1] They absorb Sun's rays and turn them into energy'.

'[Student 2] Water and glucose, carbon dioxide and the waste is oxygen'.

'[Student 3] They're taking in CO_2, glucose'.

'[Student 4] Glucose what's formed - don't they take water and things from the Sun?'

'[Student 5] Photosynthesis takes in carbon and releases oxygen'.

Of the CI participants, 40% thought carbon is found almost exclusively in the atmosphere, unlike Ebert-May et al.'s (2004) students, who thought carbon is mainly on land and in living things. This may reflect media focus on atmospheric carbon pollution, or conceptual difficulties with carbon chemistry of living things. Despite most focus group participants knowing that CO_2 dissolves in water (in part due to information in the CCCI), 5 of 10 focus group participants who commented, named the atmosphere as the largest carbon reservoir, including a student who had watched a video on the topic. This suggests the idea is strongly held.

To gain more insight into how participants conceptualized carbon, we asked focus group participants what words they associated with 'carbon'; what compounds contained it; whether it was found in living things and if so, what form(s) it was in. Table 6 summarizes the results. Responses suggest that students struggle with the idea of carbon in the tissues of living things. Of the 9 words, 8 associated with carbon focused on CO_2 or other combustion products. With the second question, fossil fuels and products of combustion again dominated, with only one mention of an organic compound. Responses to the third question again showed limited understanding of carbon chemistry, a tendency to focus on CO_2 and misconceptions of the process and products of photosynthesis.

Our findings reflect those of other researchers. Stavy, Eisen, and Yaakobi (1987) found confusion about the concepts 'element' and 'compound' and 'carbon' and 'carbon dioxide' among junior high school students. They could recite the formula for glucose but could not say which chemical elements it contained, suggesting that chemical formulae were rote-memorized rather than understood. Lambert's (2005) students struggled to recognize equations for photosynthesis and respiration, even after instruction. Sibley et al.'s (2007) undergraduate students' errors nearly all related to chemical reactions as carbon move between reservoirs. This suggests that Stage 5 students are unlikely to appropriately conceptualize greenhouse gas molecules or understand their link to greenhouse gas sources and sinks. Furthermore, they may not understand the origin and chemical composition of fossil fuels or their products of combustion. Ratinen, Viiri, and Lehesvuori (2012, 1813) found 'Students did not know enough about combustion and its relation to climate change'. According to Shepardson et al. (2012), little research has been carried out into students' understanding of the carbon cycle's link to the greenhouse effect. Of our participants, 7 thought water was plants' carbon source; two apparently mistook it for a product of photosynthesis. We were surprised water was not mentioned more often: students would be very familiar with the importance of water to plants. This may be due to a lack of knowledge that CO2 dissolves in water.

Table 6. Responses to questions about carbon.

Question	Responses	Categories of response
What could you associate with the word 'carbon'?	Smoke	General pollution (5 students)
	Emissions	Greenhouse gases (3 students)
	Factories	Do not know (3 students)
	Cars	Other (1 student)
	Gas	
	CO_2	
	Greenhouse gases [2 students]	
	Nothing/do not know [3 students]	
	Carbon fibre	
Can anyone name any chemical compounds that contain carbon?	CO2 [5 students]	Chemical species with 'carbon' in the name (9 students)
	Carbon monoxide [3 students]	Fossil fuels (2 students)
	Carbon pentoxide	Pollution (2 students)
	Coal	Organic compounds (1 student)
	Non-renewable sources	Inorganic compounds containing carbon (3 students)
	Vehicle Emissions [2 students]	Water (1 student)
	Is not it in glucose?	Do not know (2 students)
	Graphite	
	Diamonds	
	Steel	
	It's in water? like in the other question it dissolves it. The equation's H_2O. There might be an H_2OC sometimes.	
	I do not remember [2 students].	
Do living things contain carbon?	Yes, probably. I do not know what form it's in [4 students].	Yes – but do not know what form (5 students)
	In our blood. Air's in our blood, CO2 would be in our blood.	Response references CO2 (3 students)
	Yes but not that much. Dioxide. When you breathe it out, that's the waste.	Response references an organic molecule (1 student)
	Not just CO_2. It's hard to explain because it's mixed through with everything because not everything is pure like diamonds - they're all compounds.	
	I kind of know about trees, how they take in stuff and give out oxygen	
	Is not there a C in the glucose formula somewhere, plants have glucose in them and when you eat them they have not probably completed their photosynthesis so you would probably get it through that. And then your meat would do the same thing.	

3.3. Solubility of CO2, and the role of oceans in the global carbon cycle

Oceans are major CO2 sinks. The CCCI contained two items addressing solubility of CO_2 in water. Of the CI participants, 83% thought that oceans contain little if any carbon. When asked about flows, 47% chose the option that showed very little carbon entering and leaving oceans. Focus group data demonstrated participants' difficulties with the idea that CO2 dissolves in water:

> 'Oceans is smallest, in comparison [with living things and atmosphere]'.

No focus group participants disagreed that CO_2 dissolves in water. We expected this because the CCCI gave this information (two groups claimed they had first learned this while completing the CCCI). Two more groups had previously learned the information in school. Some focus group participants could apply their knowledge correctly; however the following conversation suggests difficulty with the concept of substances dissolving; in particular, that when a chemical species dissolves, it is no longer present:

> '[Student 1] Does carbon dissolve in the ocean, does it [the process of dissolving] completely get rid of it [the carbon], or is it still in the ocean?'
>
> [Student 2] there's carbon in living things, and living things in the ocean so it probably doesn't get rid of it completely, algae and stuff'.
>
> '[Student 3] if it dissolves it, it removes it'.
>
> [Student 4] Where does it remove it to? The equation's H_2O. Might be an H_2OC sometimes'.

3.4. Earth's energy balance, electromagnetic radiation, and black body radiation

Two CCCI items asked about energy absorbed and emitted by the earth; these gave very inconsistent results. Of the CI participants, 81% thought that if Earth emitted less energy than it receives from the Sun, it would heat up. However, 68% thought some of the Sun's energy incident on the Earth is used up, for example, in photosynthesis. The contingency table showed evidence of inconsistent thinking: 55% chose the following combination of responses: 'if Earth emitted less energy than it receives it would get hotter', and 'Earth emits less energy than it receives, because energy is used up, e.g.in photosynthesis'. This suggests students do not have firm mental models about Earth's energy balance, and their responses depend on contextual cues.

Focus groups reflected these inconsistencies. When asked whether Earth emits the same amount of energy as it receives from the Sun, no student agreed; 12 said it emits less, five of whom thought the retained energy was used in photosynthesis. However, when asked what would happen if Earth emitted less energy than it receives, 14 of the 20 students (70%) thought it would get hotter. Again, responses suggest confusion about photosynthesis, matter, and energy; reflecting findings of Smith and Anderson (1986), Madsen, Gerhman, and Ford (2007) and Mohan, Chen, and Anderson (2009):

> '[Researcher] does energy get used up in photosynthesis?'
>
> '[Student 1] that's what I thought'.
>
> '[Student 2] not used up, just converted [1 student agrees] into glucose'.
>
> '[Student 3] it's energy, not matter, you need UV/light energy to go into photosynthesis'.

To probe understanding about conservation of energy in a familiar context, one CCCI item asked what happens to the energy when a hot bath goes cold. Of the students, 56% said the total amount of energy is unchanged. Focus group responses were almost identical in frequency: Of the 33 students, 13 thought the amount of energy was unchanged; 15 said the energy had changed form or moved into the air (55% in total), consistent with conservation of energy. However, five focus group members thought some or all of the energy had disappeared, or 'dissolved'. The response below suggests difficulty understanding that energy can change form or that heat energy is conserved when an object is not hot:

'I thought if it was hot to start with then went cold something must have happened. It can't be the same energy if it's changed. Because if it was the same energy you'd have the same heat'.

One group claimed this apparently simple question was very difficult to answer. Other groups identified that the law of conservation of energy applied. However, some students could recite the law but struggled to apply it.

'[Student 1] It's impossible for energy to vanish - you can't destroy energy '.

'[Student 2] Or create it'.

'[Student 3] It has to be converted from one form into another'.

'[Student 1] Yes that's a law [all agree]. We learned it in Year 8'.

'[Researcher, to another group] What about 'energy can be created or destroyed'?'

'[Student 1] It can be created'.

'[Student 2] No, just changed or transformed'.

'[Student 1] You can create energy - friction, that's creating energy'.

Goldring and Osborne's (1994) year 6 students had similar difficulties with this law.

Of the CI participants, 50% thought most heat leaving Earth's surface is the Sun's heat reflected. Focus group data corroborated this, and revealed considerable confusion about what was meant by 'heat naturally emitted from the Earth'. Focus group participants thought this included the 'radioactive core', volcanoes, bacteria, plants, and mulch. Some questioned whether Earth emits heat at all. Contingency table data showed 20% of students, the largest proportion, thought that heat leaving the Earth's surface, and energy absorbed by greenhouse gases, are both the Sun's energy reflected from Earth's surface. This implies a mental model where heat from the Sun is reflected from Earth rather than being absorbed and re-emitted. This is significant because greenhouse gases mostly interact with the longer-wavelength emitted radiation. Gautier, Deutsch, and Rebich (2006) considered this concept fundamental, and suggested that students who have believe that radiation is reflected rather than absorbed and re-emitted, may draw wrong conclusions about what will happen as concentrations of greenhouse gases increase.

Our findings concur with those of several researchers. Few Lambert, Lindgren, and Bleicher's (2012) adult participants mentioned radiation emitted by Earth. Few of Chang and Pascua's (2016) participants mentioned infra-red radiation, and all who did thought it came directly from the sun. Gautier, Deutsch, and Rebich's (2006) undergraduate participants had inappropriate conceptual models of shortwave radiative processes, and struggled to differentiate between shortwave and longwave radiation. Browne and Laws' (2003) undergraduate participants struggled with the electromagnetic spectrum, especially similarities and differences between visible light and infrared (IR) radiation. Ratinen, Viiri, and Lehesvuori's (2012) participants found electromagnetic waves the most difficult concept. Shepardson et al.'s (2009) literature review showed that many high school students do not distinguish between different radiation bands involved in the greenhouse effect. Henriques' (2002, 214) participants thought 'Infrared is the only type of light that, when absorbed, causes objects to heat', that is, they did not understand that visible light causes heating when absorbed. This concept is central to understanding the greenhouse effect.

Of the CI participants, 46% thought that only warm or living things emit IR radiation. Even groups who had experienced the concept, found it difficult. Only one student could explain:

'Everything emits IR, nothing's at absolute zero - no molecules are perfectly still'.

3.5. Greenhouse and non-greenhouse gases

Only 11% of CCCI participants identified water vapor as the most common greenhouse gas: 80% thought that it is not a greenhouse gas. Of 13 focus group participants, three (23%) disagreed that water vapor was a greenhouse gas despite the fact that the CCCI contained this information. Two students provided reasons:

> '[Water vapour isn't a GHG] because it doesn't have carbon on it'.

> 'It couldn't have a bad effect because water wouldn't have any harmful aspects'.

Of the 10 focus group participants who named water vapor as a greenhouse gas, three recalled it from the CCCI, and two had completed research on it at school. None of Dove's (1996) participants listed water vapor as a greenhouse gas, and according to Daniel, Stanisstreet, and Boyes (2004), most children are unaware of the variety of greenhouse gases. None of Chang and Pascua's (2016) participants mentioned water vapor and only 20% of Versprille and Towns' (2015) chemistry undergraduates named it. Lack of awareness of water vapor as a greenhouse gas has implications for understanding feedback mechanisms, and may lead to acceptance of 'climate sceptic' arguments based on the small concentration of CO2 relative to water vapor.

Of the CI participants, 70% thought carbon monoxide is a greenhouse gas, but only 20% of focus group participants did so. However, several reported learning about carbon monoxide during the CCCI. Twenty-seven percent of Dove's (1996) participants, 42% of Versprille and Towns' (2015) participants thought carbon monoxide was a greenhouse gas; Chang and Pascua (2016) also reported this idea. Carbon monoxide is a greenhouse gas, but 'makes no significant contribution to the greenhouse effect' (Box and Box 2015, 92). We suggest that students citing carbon monoxide are probably employing a generalized concept of pollution rather than knowledge of atmospheric chemistry.

3.6. Interactions between greenhouse gases and electromagnetic radiation

Of the CI participants, 45% thought energy absorbed by greenhouse gases is mostly the Sun's energy, either direct or reflected from Earth. Of the 18 focus group participants, 15 (83%) agreed, expressing mechanisms including trapping of UV radiation; absorption of heat; greenhouse gases reflecting the Sun's rays back to Earth; and the idea that all of the Sun's energy interacts with greenhouse gases.

Gautier, Deutsch, and Rebich's (2006) participants thought the greenhouse effect is caused by trapping of reflected solar energy by greenhouse gases or clouds. Of the Dove's (1996) participants, 45% thought greenhouse gases absorb solar radiation. Versprille and Towns' (2015) participants thought greenhouse gases stop heat escaping the atmosphere, but could not describe them at a particulate level, which the authors claim is essential to understanding interactions between greenhouse gases and electromagnetic radiation.

The CCCI included three items addressing conflation of the greenhouse effect and ozone depletion. Of the CI participants, 49% thought greenhouse gases cause warming by damaging the ozone layer, allowing ultraviolet rays to warm the Earth. When asked why oxygen and nitrogen are *not* greenhouse gases, 38% said that they do not damage the ozone layer. When asked what happens when a greenhouse gas molecule absorbs heat, 37% said it rises into the ozone layer.

Contingency tables for items addressing ozone show consistent reasoning, suggesting the idea that greenhouse gases damage ozone, is strongly held. The largest proportion (23%) chose 'ozone damage' options for items 11 and 16, and 18% (again, the largest proportion) chose 'ozone layer' responses to items 11 and 23. Only 1% chose correct responses for both these items, suggesting significant difficulties with this concept.

Of the 17 focus group participants, 6 (35%) mentioned the ozone layer, or agreed with others' comments:

> 'Greenhouse gases burn the hole through, which means sunlight - I thought it didn't directly come to Earth, but through the ozone layer' [3 students agree]'.

'The gases form a protective blanket, lets stuff in but doesn't let heat out'.

'[Researcher] Why do GHGs cause the Earth to warm up?'

'[Student 1] The ozone layer - traps gases. Like a greenhouse, keeps it warm, traps it in some area'.

'[Student 2] Earth gets hotter because IR rays aren't being reflected. They're staying in the atmosphere because of the ozone layer'.

No focus group participant explained the mechanism by which greenhouse gases warm the atmosphere. Groups cited unrelated wave properties, ozone depletion, or thought infra-red radiation was reflected from greenhouse gases. The idea that radiation can get in but not out was known to some students, but appears to have been rote memorized because they could not explain it.

'[Researcher] Have you been taught how greenhouse gases trap heat?'

'[Student] Just diagrams with arrows. Nothing chemical or anything'.

According to Meadows and Wiesenmayer (1999), students learn that the ozone hole allows UV to reach the Earth's surface and experience the Sun's rays as hot; so conclude that the ozone hole allows more heat through.

4. Recommendations

This section briefly outlines some recommendations for learning and teaching strategies to address misconceptions. These will be elaborated on in a future publication.

Students assume that significant concern about a substance implies a large quantity of the substance. We suggest that learning activities explicitly address proportions and quantities, and explain how small proportions and quantities can cause significant effects. The concept of equilibrium is central to understanding both the impact of small net changes in flows, and of the Earth's energy balance; and should be taught explicitly. We also recommend experimental measurement of biomass in growing plants, and the use of infra-red detectors to 'see' infra-red radiation.

It is important for students to understand the role of water vapor as a greenhouse gas, and the possibility of positive feedback as higher temperatures cause more water vapor to enter the atmosphere. Similarly, the belief that carbon monoxide is a key greenhouse gas, is suggestive of a generalized conceptual model of pollution. One student thought that water vapor could not be a greenhouse gas because it does not contain carbon. While rote-learning lists of gases are unsatisfactory, the mechanism of energy storage in bonds is too complex for Stage 5. However, students could identify common characteristics in the molecular structure of greenhouse and non-greenhouse gases, and derive simple rules to classify them. Such an activity would reinforce learning of chemical elements and compounds.

According to Sibley et al. (2007), 'students must have some understanding of chemistry to understand the global carbon cycle' (p.145). We suggest that our participants' lack of awareness of the diversity of carbon compounds may be linked to the fact that the NSW Science syllabus at the time (New South Wales Board of Studies 2003) only required students to use word equations. No participant could name a carbon compound whose name did not contain the word 'carbon'. The National Curriculum (Australian Curriculum, Assessment, and Reporting Authority 2012) reproduces the problem. In year 9, students are required to learn only word equations. In year 10, the option exists for using word or symbol equations; however, this remains only an option. We recommend the use of symbol equations as well as the use of chemical model-making kits, simulations and animations to help students visualize how elements combine to make molecules in the different stages of the carbon cycle.

Participants' understanding of interactions between atmospheric gases and electromagnetic radiation was also extremely limited. A wide range of incorrect ideas was voiced, and no participant was able to correctly explain the interaction between greenhouse gases and infra-red radiation. Again, these concepts are central to understanding climate change.

Solubility of CO2 in water was very poorly understood; however, students are very familiar with carbonated drinks. These could provide an introduction to the concept. Again, model-building kits, animations and symbol equations could be used to help students visualize the processes.

None of our participants reported learning about feedback in climate change. However, this concept is both central to understanding climate change and was readily grasped by our participants. We recommend explicitly including it.

The concepts required to understand climate change are often learned in other contexts. Participants were rarely successful in applying their knowledge correctly in the context of climate change. We suggest that learning activities for climate change should draw on students' knowledge from other contexts, and provide scaffolding to help them apply their knowledge successfully in the new context.

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