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General Chemistry Students' Understanding of Climate Change and the Chemistry Related to Climate Change

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Ⓢ *Supporting Information*

ABSTRACT: While much is known about secondary students' perspectives of climate change, rather less is known about undergraduate students' perspectives. The purpose of this study is to investigate general chemistry students' understanding of the chemistry underlying climate change. Findings that emerged from the analysis of the 24 interviews indicate that students confuse the greenhouse effect, global warming, and the ozone layer. In terms of chemistry concepts, the students lack a particulate-level understanding of greenhouse gases, making it difficult for them to understand the mechanism of the greenhouse effect and corresponding links to the impact of increasing carbon dioxide concentrations and climate change.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Chemical Education Research, Misconceptions/Discrepant Events, Atmospheric Chemistry, Constructivism, Gases*

FEATURE: Chemical Education Research

■ INTRODUCTION

Gilbert has described five problems that chemical education faces including a bloated, overloaded curriculum, curricula that emphasizes isolated facts, a lack of transfer of knowledge across chemistry and STEM, a lack of relevance of the material to students especially nonmajors, and a misplaced emphasis on why chemistry should be studied.[1] He notes that contextualizing the curriculum can be a route to address the challenge of relevance. Given this premise, he notes that contexts used must "resonate with students' present and anticipated interests... (and) engender interest and commitment" such that students become more willing to engage in the material at hand.

The chemistry of climate science is a context that provides meaning for learning new chemistry concepts for many (but not all) students.[2−4] It sets ideas such as the electromagnetic spectrum, chemical bonding, vibrational motion, gases, acids and bases, and a variety of other concepts into a relevant interesting context with a broader perspective than simply mastering the concepts for the next course in the curriculum. Additionally, this context is in good alignment with Education for Sustainable Development (ESD)[5,6] and courses that emphasize sustainability.[7−10] Recently, the impacts of climate change have been reported in the United States as part of the National Climate Assessment.[11] Although the report is written for a general audience, the supplements to the report are filled with scientific data, analyses, graphs, and figures.[12] Chemistry in the context of climate science plays a key role in understanding the report.

Research has shown that students hold fragmented understandings about climate science due to the complexity of climate change models, and the multidisciplinary content knowledge (e.g., earth and atmospheric science, physics, chemistry, and biology) needed to be able to understand and articulate key concepts in climate science.[13,14] Kerr and Walz emphasize that due to the complexity of climate science principles, alternative conceptions occur as a result of inaccurate information provided by the media and lack of climate science curriculum.[13] A deeper understanding of undergraduate students' notions of the chemistry associated with climate science would allow faculty to identify potential barriers to learning which could in turn build insight into planning curriculum and designing instruction that builds on students' existing mental models.[14,15]

Research has been conducted into secondary student beliefs about the causes, consequences, and solutions to the enhanced greenhouse effect.[16−28] This research serves as a foundation for investigating college students' conceptions of the chemistry associated with climate change which has not been studied explicitly. Thus, we seek to explore freshmen undergraduate students' understanding of the chemistry underlying climate science and related climate change concepts through the following research question: What are undergraduate students' conceptions of climate change and the chemistry related to climate science?

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LITERATURE REVIEW

Theoretical frameworks are used in qualitative research to help inform and guide the research study because they suggest the appropriate methods for collecting and analyzing data in order to answer the research questions.[29] Therefore, there are three bodies of literature that informed this study: (1) the learning theory, personal constructivism, (2) students' alternative conceptions of climate science, and (3) students' understanding of the particulate nature of matter. Each of these theoretical frameworks and its implication for this study will be discussed below.

Personal Constructivism

This study is grounded in the educational theory of constructivism which posits that students do not receive knowledge; rather students construct knowledge based upon preexisting ideas and experience.[30−34] Thus, in the context of chemistry education, constructivism is used as a theoretical lens for taking into account that students come into chemistry classrooms with a multitude of preconceptions or alternative conceptions about chemistry and climate science concepts. As a theory of learning, constructivism provides a basis for understanding how students incorporate new knowledge into their existing.[35−38] Research from this perspective seeks to elucidate how learners make sense of phenomena and the world around them. In this case, we aim to understand the meanings constructed by students about climate science and the chemistry underlying climate science. It is important to note that these personal beliefs and ideas are often naïve, incomplete, fragmented, or inaccurate while at the same time strongly entrenched and resistant to change.[39,40]

Students' Alternative Conceptions of Climate Science

Students across all levels struggle to grasp climate science concepts due to the complexity of climate science models, and the multidisciplinary content knowledge (e.g., earth and atmospheric science, physics, chemistry, and biology) needed to be able to understand and articulate key concepts in climate science.[13,14]

Research has shown that secondary students often confuse the greenhouse effect with the depletion of the ozone layer, and also relate the ozone layer depletion with global warming.[20,24,25,27,28,41−43] Secondary students also believe greenhouse gases are responsible for the depletion of the ozone layer and trapping the sun's energy.[27,28,42,44] Along with the belief that greenhouse gases are depleting the ozone layer, secondary students articulate that greenhouse gases form a thin layer in the atmosphere much like a blanket that prevents heat from escaping.[21,28] Recently, research on undergraduate students' understanding of formation of ozone in the atmosphere has demonstrated that they hold beliefs and models that conflate the greenhouse effect, ozone formation, and global warming.[45] Conclusions from this body of research have implications for how students' conceptualize greenhouse gases, the identity of these gases, how they behave, and how they impact the environment.

Along with students' naïve conceptions of the causes of climate change, it has also been documented that students possess very naïve understandings of the impact of climate change on their personal lives and futures.[20,21] Some students do not believe that climate change will impact them other than experiencing warmer summers.[20] Others believe that climate change will impact them by causing skin cancer.[21,26,41,43] Students often indicate that climate change is caused by air pollution.[16,22,25] Therefore, they believe that greenhouse gases are air pollutants; thus, increased greenhouse gases will cause more air pollution, and this problem needs to be addressed in order to resolve climate change.[20,21,23−25,27] Another widespread belief held by secondary students is that recycling and polluting less would help improve the effects caused by climate change.[21,41,43] Students have a very naïve belief that there is nothing people can do to change or stop climate change, and students believe that people would not be willing to change their lifestyles.[20,21]

Students' Understanding of the Particulate Nature of Matter

Research has clearly demonstrated that students struggle with understanding the structure of matter at the particulate level.[46−50] An appropriate understanding of the particulate nature of matter is essential for learning chemistry and thus understanding the chemistry underlying climate science, especially the interaction of electromagnetic radiation and gases in the atmosphere.[51]

An understanding of the particulate nature of matter is critical for understanding how molecules interact with electromagnetic radiation and how they interact with each other in a collisional sense. In order for students to understand the impact of increasing carbon dioxide concentrations, they must be able to conceptualize and model gas molecules at the particulate level and understand the structural properties (e.g., polarity of individual bonds, molecular shape, polarity of an entire molecule, vibrational motion of bonds, and change in dipole moment) that characterize greenhouse gases.

METHODS

The study presented herein is related to a NSF-funded international project, VC3Chem, which seeks to facilitate student learning of chemistry concepts through the rich context of climate change.[3] It used a qualitative approach to develop a rich, context specific description of student understanding of the chemistry related to climate science and climate change. The theoretical frameworks of personal constructivism, students' alternative conceptions of climate science, and students' understanding of the particulate nature of matter align well with our chosen methodological framework, phenomenography.

Methodological Framework: Phenomenography

Phenomenography aims to define the different ways in which people understand and conceptualize a phenomenon.[52−54] It seeks to identify the multiple conceptions or meanings that a particular group of people can have for a particular phenomenon. Orgill articulates that phenomenography is most often employed to explore the variation in students' conceptions of a certain scientific topic.[54] Semistructured interviews can serve as a particularly rich source of data to reveal the variation of students' understanding that we seek in this study. Additionally, the three theoretical frameworks inform the data collection and analysis derived from this methodological framework.

Participants and Setting

Participants for this study were recruited during the first week of the semester from a general chemistry course for engineering and science majors at a large research institution in the United States. From the sample of students who volunteered to participate, 24 freshman students were randomly selected for the study, 12 females and 12 males. The participants were international and domestic students who received a $10 iTunes gift card as compensation for participation. All students were given pseudonyms to protect confidentiality; however, the names accurately reflect the sex of the participant.

Data Collection

Prior to beginning data collection, the Purdue University Institutional Review Board (IRB) approved the study. A semistructured interview protocol was developed based on alternative conceptions identified in the research literature and the essential principles of climate change outlined in the U.S. Climate Change Science Program (CCSP) document which pertain to chemistry.[55] The interview protocol was piloted with two graduate students to generate a revised protocol which is included in the Supporting Information. The interviews were recorded and ranged in length from 10 to 40 min.

Data Analysis

Each interview was transcribed verbatim using the InqScribe program.[56] Some aspects of grounded theory were used as an inductive approach to analyzing the data.[57] For example, open coding was used to analyze each interview to facilitate the exploration of common themes that emerged from the data.[58] A constant comparison method was used to compare emerging codes and themes across all participants.[58,59] The common themes were also matched back to the existing research literature to facilitate interpretation of the data which supported the generation of findings. Inter-rater reliability was conducted with a professor in chemical education once all of the final code categories were established with both the climate science concepts and the chemistry underlying climate science concepts. Disagreements were resolved through discussion and a final code was assigned in these cases by mutual agreement.

FINDINGS AND DISCUSSION

The major themes which emerged from the analysis of the student interviews are confusion between the greenhouse effect, global warming, and the ozone layer, the paucity of connections between greenhouse gases and the particulate nature of matter, sources of carbon dioxide, and impacts of and how to address climate change. Each of these themes is supported by student quotes from the interviews and is connected to the prior research.

Confusion between the Greenhouse Effect, Global Warming, and the Ozone Layer

Students do not exhibit a clear understanding of the definition the greenhouse effect and used the terms "greenhouse effect" and "global warming" interchangeably such as Cailey.

> *Cailey: Uhh, usually when I hear it you think more of the sun rays being trapped in the earth and heating up the earth it is usually akin to global warming.*

In their verbalized definitions of the greenhouse effect, students used the notion of trapping heat such as Susan, Caroline, and Luke.

> *Susan: It's trapping the heat in (laughing) that's about all that I know it's the carbon dioxide that's doing it.*
> *Caroline: Greenhouse effect is where the gases in the atmosphere are trapped umm a lot of the heat from like the sun's rays when it comes down and hits the earth and reflects back up.*
> *Luke: That's when the sun the radiation and solar rays are coming in and the greenhouse gases prevent uhh, most of them from escaping.*

All of the students who used this trapping definition exhibited a macro-level description that is consistent with an object such as a blanket holding in the heat. Additionally, some students substituted the term "global warming" for the "greenhouse effect" using the terms as synonyms.

Seven out of 24 students (29.2%) conflated the greenhouse effect with the depletion of the ozone layer. For example, Mary Beth suggested that the depletion of the ozone layer contributes to global warming, and that greenhouse gases cause the breakdown of the ozone layer: "Greenhouse effect is usually like toxic type things or invading the atmosphere and depleting our ozone."

Although recent research links the depletion of the ozone layer to climate change, in general it appears that students confuse and conflate global warming and the depletion of the ozone layer.[60] Undergraduates in this study hold similar understandings to secondary students who have been shown to conflate the greenhouse effect, global warming, and the depletion of the ozone layer as opposed to possessing and being able to apply an operational definition of each term or concept that would allow them to appropriately understand the phenomenon.[16,22,25,43,45]

Lack of Connections between Greenhouse Gases and the Particulate Nature of Matter

A second theme emerged around greenhouse gases and the particulate nature of matter. Students articulated that greenhouse gases, primarily carbon dioxide, are trapping or absorbing heat and not allowing it to escape the atmosphere. Students discussed and described the buildup of gases such as carbon dioxide in the atmosphere as forming a layer in the atmosphere as Gladys notes (e.g., blanket effect).

> *Gladys: Umm, from the greenhouses gases like to keep the greenhouse effect going like a certain gas is like I think it's like carbon dioxide is created and it's like let out into the air and it forms a layer in the atmosphere.*

Analysis of the interviews demonstrated that students were not able to describe the greenhouse gases at a particulate-level. An understanding of the particulate nature of matter is critical for understanding the structure, behavior, and interactions of molecules.[49] None of the students used a particulate model to discuss the mechanism of the greenhouse effect when asked. They did not describe how electromagnetic radiation (IR in particular) interacts with the vibrational motion of the molecule. In the absence of a particulate model, students use a "blanket" macro-level model that does not invoke the particulate nature of matter. It is important for students to understand the particulate nature of matter in order to describe the mechanism of the greenhouse effect and recognize the structural and dynamic characteristics of molecules that are greenhouse gases.

Nearly all students in this study (22 out of 24; 91.7%) identified carbon dioxide as a greenhouse gas; however only five out of 24 (20.8%) students named water as a greenhouse gas and only two of these identified it as the most abundant greenhouse gas. Eighteen out of 24 students (75%) stated that carbon dioxide is the most abundant greenhouse gas. Students also named carbon monoxide (41.7%) and methane (25%) as greenhouse gases. Three or fewer students named the following gases, some of which are not greenhouse gases: ozone, CFCs, hydrogen, nitrogen, oxygen, and nitrogen dioxide. Given that students lacked definition of the physical characteristics that

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operationally define a greenhouse gas, they defaulted to simple recall as a method identifying such gases.

Prior research shows that some secondary students do not consider carbon dioxide as a greenhouse gas;[20,25,43] however, when students do identify carbon dioxide as a greenhouse gas, they rarely mention other greenhouse gases such as methane, water vapor, or nitrous oxide.[16,24,41,43] On the basis of the interviews from this study, freshmen undergraduates were able to identify carbon dioxide as a greenhouse gas; however, water vapor was rarely mentioned as the most abundant greenhouse gas, and nitrous oxide was not identified as a greenhouse gas by any of the participants.

Sources of CO_2 in the Atmosphere

Given that most students named CO_2 as a greenhouse gas, they were asked to describe the primary source of CO_2 in the atmosphere. Students stated that cars, transportation, factories, or major industries are the primary source of carbon dioxide in the atmosphere contributing to climate change. Several students such as Luke and Mary Beth believe that the primary source of carbon dioxide in the atmosphere is human causes such as the burning of fossil fuels.

Luke: Umm, probably primary source I think the primary source would be a lot of human causes such as burning fossil fuels for energy.

Mary Beth: I feel like maybe it's like umm, when we burn fuels that produces like fossil fuels all produce carbon dioxide when they're burned so that would probably be how you get the most of it.

Ten others stated that the primary source of carbon dioxide in the atmosphere comes from "human respiration". Previous research has also indicated that secondary students believe human respiration causes an increase in atmospheric carbon dioxide levels.[16] A few students believe the primary source of carbon dioxide in the atmosphere is pollution or from pollutants such as greenhouse gases. This is consistent with the prior literature on secondary students who often believe that climate change is caused by air pollution or pollutants from cars and factories.[20,2,23−25,27]

Emergent findings within this theme are consistent with prior research that indicates students believe CO_2 originates from a variety of sources, some of which are supported by evidence (transportation and manufacturing sources), and some of which are not (human respiration and pollutants) as actual contributors to increasing atmospheric CO_2 concentrations.

Impacts of Climate Change and How To Address Climate Change

The final themes that emerged from this study pertain to the impacts of climate change and how they could be addressed. Ten students discussed the major impacts of climate change during their lifetimes as warmer summers or more severe weather patterns such as tornadoes or hurricanes. Prior research has shown that secondary students predict much higher temperature estimations,[27] and they believe the weather will get warmer thus, shorter winters and longer, hotter summers.[16,27] Nearly half the students in this study hold similar views about the major impacts of climate change to secondary students.

However, 14 of 24 students (58%) do not believe that climate change will have an impact on their lives. Prior research has demonstrated that some secondary students do not believe there will be any consequences or changes in their lifetimes.[20,21] In essence, this is a question about the rate and time scale of climate change impacts. For students such as Chris, they believe the rate of climate change will be too slow to be observed.

Chris: On our lifetime I don't think anything major is going to happen in like the next 100 years at the rate we're going at so maybe not in my lifetime.

Others such as Nate associate the impacts of a changing climate with apocalyptic predictions and scaremongering.

Nate: I don't think so just because I feel like there has always been people who say that something is going to happen and it's not even as far back as like the middle ages it's like oh there's going to be kind of like almost the end of the world uhh, scenario where like cultures say that things are going to happen all the time but then they don't so its I don't know it's almost like scientists are going to scare us into oh you really should think this is happening and we have all of this evidence that it is happening but it might not necessarily happen.

Although a majority of the students believe that climate change is occurring and described impacts, five of the 24 (20.8%) students stated they do not believe that climate change is occurring. These students such as Luke cited a lack of "firsthand experience" with climate change. We also found evidence of confusion between weather and climate as Susan's quote illustrates.

Susan: No, because I have not witnessed any large change in weather umm, since one summer they all say said it is the biggest heat wave ever and then the next summer it is cold so to take these fluctuations in weather they average out to create climate I'm not seeing any big change.

Finally, the natural variation of climate with time was used by Gladys as justification for her doubts.

Gladys: Umm, I don't think so I don't really believe in global warming because even though like through all these changes that's happening throughout like even if you see like the statistics like we've had a lot like it's this has happened before in history before like Ice Ages and stuff it's just the fact that this time it's a lot more extreme than the others so I think it's just something that happens periodically.

When asked about resolving or addressing the effects of climate change, many students provided pro-environmentally friendly actions such as "going green" or recycling. Others suggested changing means of transportation by driving less, walking, biking, or carpooling. Students also proposed conserving energy by turning off the lights when leaving a room or changing light bulbs to LEDs or running less water could ameliorate climate change.

Sixteen of 24 (66.7%) students indicated that the effects of climate change can be slowed by stopping the use of or burning less fossil fuel, and by using alternative energy sources or renewable energy sources such as, nuclear, solar, wind, or hydroelectric energy sources. Three other students expressed unique perspectives on ameliorating the effects of climate change. Dave was the only student that described a need to develop technologies that can remove greenhouse gases from the atmosphere as a method of addressing climate change.

Dave: We should research and develop technologies that produce renewable energy, clean energy and develop technology that can remove the excess greenhouse gases from the atmosphere put them away somewhere out of the atmosphere store them somewhere. Wind energy, solar energy, umm, hydroelectric umm, and this one isn't entirely renewable but there's different forms of nuclear energy that could be develop and improved upon.

Finally, Elliot and Karen discussed the impacts that government regulations could have in slowing the effects of climate change.

Elliott: Umm, I think definitely increased governmental influence or focus on those fields and the development of alternative energy resources would help us as a nation and as a world to really shift toward alternative energy I think at the moment umm, it's not going to happen as rapidly as a lot of people would like it to but I think if we definitely work now to develop and research these kind of energy sources that we can gradually umm, decrease and hopefully cease our use of fossil fuels.

Karen: Umm, I think having more regulations and being more strict on what's being put up into the atmosphere that like a lot of countries have already adopted umm, stricter like carbon footprints taxes...umm, factories are required to have filters but not all factories keep up with standards because they're just fined so like sometimes it's cheaper to just except the fine then to actually go through the process of putting a filter in so it's better to have them actually not just be a fine but be something more substantial and be on top of what is being put up into the air.

Undergraduates and secondary students voice similar pro-environmental views when discussing how to ameliorate the impacts of climate change.[16,21,41,43] However, in this study we found evidence that some undergraduates are aware of the possibilities of carbon dioxide sequestration and the role government regulations and policies can have on impacting climate change. Thus, as students enter college, they are beginning to consider methods of addressing climate change that are more substantial than simply "going green".

CONCLUSIONS AND IMPLICATIONS

In harmony with prior literature on secondary students, our findings demonstrate that undergraduates commonly confuse greenhouse effect, global warming, and the depletion of the ozone layer. Additionally, when discussing the greenhouse effect, many students used a macro- level "blanket" description stating that heat is trapped with little idea of the mechanism of interaction between gas phase molecules and electromagnetic radiation. In terms of understanding the greenhouse effect at the molecular level, this suggests a need to help students connect their understanding of the particulate nature of matter and how infrared radiation interacts with molecules to the greenhouse effect. This is a challenge for students as prior research has documented difficulties in understanding matter at the molecular level.[49] Thus, for example, faculty may wish to use materials from the VC3Chem project or The Greenhouse Effect PhET simulation to support student learning.[3,61]

This lack of understanding has an impact on students' ability to consider the causes of climate change, the impacts, and how it can be addressed. Our research suggests that if students do not have a particulate model of matter that can be used to understand the mechanism of the greenhouse effect, it might be difficult for students to link increasing concentrations of carbon dioxide to climate change, and subsequently discuss and consider the impacts and methods of ameliorating the impacts of climate change. Thus, it is important for faculty to explicitly help students learn about the particulate nature of matter and demonstrate the connections between those concepts and climate change.[3,61,62]

Addressing the relevance issue described by Gilbert[1] through contextualization via climate change incorporates the initiatives aligned with sustainability[5,6] and recent initiatives such as VC3Chem.[3] Key to building an informed citizenry that can address our coming climate challenges is education at the university level as well as elementary and secondary levels.[6,11,63] Through an emerging understanding of undergraduate students' conceptions of climate change, faculty can gain important insights into planning curriculum and designing instruction and assessments to better address these concepts in our classrooms.[14,15]

As faculty include context based examples in their courses, it is important to consider student understanding of the underlying chemistry content which may impact the effectiveness of the applications and examples.

ASSOCIATED CONTENT

Supporting Information

The final revised interview protocol used in the study. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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