CONCEPTUAL CHALLENGES IN LEARNING OZONE FORMATION FOR COLLEGIATE STUDENTS

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FORMATION FOR COLLEGIATE STUDENTS

Abstract

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Collegiate students have a low conceptual understanding of atmospheric chemistry in general and tropospheric ozone formation in particular, both of which are complex processes that to be understood require students to learn several interrelated concepts. These systems are particularly difficult to grasp as they are inherently nonlinear and because they are abstract- students do not have an obvious tangible model for how gases behave in an unbounded atmosphere. In order to extract student understanding and conceptions of ozone formation, qualitative interview and analysis methodologies were implemented. Our results indicate that students comprehend individual concepts within the ozone production cycle to some extent. However, there were very few students who were able to link together overlapping ideas, especially when it came to piecing together a process model for ozone formation. Four conceptual difficulties were identified which led to the inability of students to form correct and coherent models regarding ozone formation. These conceptual difficulties conflated the process being studied (tropospheric ozone formation) with two other atmospheric processes that receive extensive public attention: stratospheric ozone destruction and greenhouse gas-induced global warming. The results of this study have implications for teaching, such as integrating concept mapping into the curriculum, and can be applied to other atmospheric chemistry disciplines.

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DEDICATION

This thesis is dedicated to my family for their support throughout my degree. I would like to extend enormous gratitude to my parents, brother and husband Alex for their unlimited love and continuous emotional support.

CHAPTER ONE: Introduction

I. APPLICATION OF CONCEPTUAL CHANGE FRAMEWORK

Human beings are complex individuals that cannot be categorized into simplistic learning environments. The infinite combinations and variations of genetics and personal life experiences that define each person make it impossible for any individual to think or learn in an identical manner as another person. Aside from people's individual learning styles (auditory, visual, kinesthetic), every person thinks differently about how the world works and therefore incorporates and organizes knowledge differently, even when information is presented consistently (such as in a classroom setting).

A mental model can be defined as an individual's thought process that describes how a system operates. It includes the user's logic and justifications, and connects various pieces of knowledge in order to form a model that is coherent to the user. If the user is not an expert in a subject, their mental model will often be incomplete and unstable, causing rules and reasoning within their personal representation to become contradictory and erroneous. When students maintain a strong understanding of only pieces of knowledge, the unexplained gaps will frequently be justified with logic that appears to work but isn't really rational or consistent to the rest of their model (Norman, 1983). For example, many students have differing mental models of Newtonian mechanics, specifically of force and motion, which may be due to their own perceptions of how to move objects around based on their experiences in the world (Clement, 1983). Larkin (1983) compared novice-expert mental models of force and work-energy, noting that novices created models that strongly incorporated aspects of the "real world" whereas experts were also able to include fictitious or imagined entities. The varying amounts of information that students integrate into their mental models can create multiple pathways to arrive at an applied concept, some of which may omit critical knowledge or incorporate unnecessary information. These pathways may or may not lead students to correct concepts, as they can include contradicting pieces of knowledge, and thus may ultimately lower their conceptual understanding.

Complex material can be difficult to successfully teach when students enter classroom environments with an already low conceptual understanding. The knowledge obtained through the integration of an established research framework may aid in effectively teaching difficult material, such as the process of ozone formation. Conceptual change is a research framework and learning theory that aids in determining and changing how students think and learn about information across multi-disciplinary fields of study through collaborative efforts by scientists, educators and curriculum developers. It has a progressive structure that encompasses three main aspects:

1. Extract level of conceptual understanding of the subject through the use of concept inventories and/or interviews.
2. Determine existing student misconceptions (incorrect knowledge) inhibiting conceptual understanding as well as why they exist in order to eradicate them through the process of conceptual change.
3. Investigate the deeper causes that misconceptions and low conceptual understanding stem from considering students' epistemological beliefs, etc.

In order to undertake the first stage of conceptual change, it is crucial to establish how students learn. Conceptual understanding often refers to students' abilities to associate and understand the significance behind rote calculations and textbook knowledge they are taught. Simply having the ability to regurgitate knowledge does not signify a deep understanding; students with true comprehension of material will be able to apply it to unfamiliar situations across contexts outside of which it was learnt (Stephanou, 1999).

There has been a great deal of student physics misconception research conducted at the collegiate level, much of which has provided beneficial teaching implications toward the process of conceptual change. One of the earliest research efforts conducted by Lillian McDermott toward the physics education front was on students' understanding of kinematics. The investigation of students' interactions with kinematic diagrams indicated that students had difficulty connecting motion, velocity, and acceleration graphs to physical concepts as well as the real world, and were unable to interrelate the different kinematic graphs (McDermott et al., 1987). The suggested teaching implications to help remedy these student difficulties included assisting students to gain familiarity and practice with motion, velocity and acceleration graphs by providing multiple opportunities which stress the differences amongst the kinematic topics. Showing students all three kinematic graphs at once can help demonstrate the different ways identical information can be presented. Students may also comprehend these graphical differences if they are required to obtain information from all three kinematic graphs (going back and forth between them) in order to successfully complete a problem. Finally, utilizing an outside context to incorporate similar graphs (such as another physics topic or from another subject entirely) into a lesson plan can allow students to practice and apply their knowledge to a familiar learning format.

Another field of physics previously investigated was light and optics. Goldberg and McDermott (1987) conducted a study on students' understanding of the real image formed by a converging lens or concave mirror. Students were evaluated throughout the investigation on their ability to predict and explain image formation by actual lens and mirrors using ray diagrams. Similar to the kinematic research results, students failed to understand the concept of a light ray and its graphical representations. Furthermore, they failed to grasp the functions of the optical system, including a lens, mirror, screen, and the relationship between the individual components. It was suggested that instructors employ an active intervention in order to help students learn how to connect geometrical optics with real world phenomena and address the above difficulties. Integrating a laboratory approach into the curriculum may assist students in understanding the appropriate relationship between light rays and the position of an image. For example, the instructor might incorporate a demonstration in which students observe the effects on an image when different parts of a lens and mirror are covered. The concept of an open-ended or "hands on" learning approach was also introduced and advised. Suggesting students "explore the relationship between the location of an image and the placement of a screen" (Goldberg and McDermott, 1987, pg. 119) during a laboratory investigation could help them understand the existence of an aerial image and that the screen must be at a specific position in order to view an image.

In a series of papers, McDermott and Shaffer conducted a thorough investigation of student difficulties with simple electric circuits and used the results as a guide for the development of an inquiry-based curriculum. They discovered that the students' interviewed had an inability to apply formal concepts to electric circuits, relate formal representations and numerical measurements to electrical circuits, and reason qualitatively about the behavior of DC electric circuits. The students were unable to understand the concept of resistance or distinguish between current and potential difference as well as equivalent resistance and the resistance of an individual component. Furthermore, students lacked the conceptual model necessary to predict and explain the behavior of dc circuits (McDermott and Shaffer, 1992). "Curriculum development by the Physics Education Group is based on the premise that meaningful learning will not occur unless students are engaged at a sufficiently deep intellectual level," (Shaffer and McDermott, 1992, pg. 1004). Therefore, both the laboratory-based instructional modules and tutorial materials developed to address the student difficulties associated with electric circuits involved a "hands on" learning approach.

The instructional modules, eventually included in McDermott's "Physics by Inquiry"(McDermott and Physics Education Group at the University of Washington, 1996a) laboratory-based book, integrated two main strategies. The first instructional tactic was for students to experimentally learn material based on a spectrum that initially introduced basic concepts qualitatively and slowly added difficulty as well as quantitative aspects (Shaffer and McDermott, 1992). For example, students would first connect a light bulb with a battery and single wire, eventually adding another bulb and battery sources. Through the process of slowly incorporating new variables and different combinations of apparatus configurations, students were able to learn and observe first hand key concepts such as current, a complete circuit, and equivalent resistance. The gradual introduction of an ammeter and voltmeter aided students in eventually defining these concepts and incorporating an algebraic relationship into their model. The increased use of quantitative measurements was intended to ultimately help students comprehend and formulate Kirchhoff's rules and Ohm's law.

Multiple methods were incorporated into the Physics Group's curriculum development in order to address the treatment of specific difficulties, such as those associated with reasoning, diagrammatic representations and concepts. However, the second major instructional strategy implemented focused on deeply-rooted difficulties (Shaffer and McDermott, 1992). In order to explicitly address these difficulties and actively engage students in the learning process, students were purposefully presented (through guided instruction) with a conceptual conflict to resolve by exposing typical student errors. Moreover, to help students successfully overcome their predispositions and initiate the process of conceptual change, they were presented with multiple opportunities "to apply the same concepts in different contexts," (Shaffer and McDermott, 1992, pg. 1009).

Finally, the tutorial materials implemented helped deepen students' conceptual understanding and develop their scientific reasoning skills by continuing to emphasize qualitative learning. Although the tutorial materials target smaller class sizes, it can also be utilized during an interactive lecture. Regardless of the setting that integrates these materials, the instructor's role should take on that of a facilitator, guiding students to arrive at their own conclusions. Instructor-based questions can help stimulate group discussions and enhance an interactive learning environment. Similar conceptual difficulties were integrated into the developed tutorial materials as in the laboratory modules. However, due to the time constraints of a standard lecture, demonstrations replaced any “hands on” activities. Structured worksheets help students utilize predictions, observations, and graphical interpretations in order to stress scientific problem solving and maintain an inquiry frame of mind. Finally, pretests and course examinations were included to accompany the tutorial material which would help focus students’ attention on the critical concepts (Shaffer and McDermott, 1992).

One of the final considerations to investigate in the process of conceptual change is how students approach knowledge and learning. The following learning/teaching sections have surfaced in the realm of education largely due to the research on conceptual understanding. These particular methods of learning provide supportive teaching implementations to facilitate conceptual change.

Ontological Training

Many researchers have proposed the notion of students organizing concepts into hierarchy categories. Slotta’s (1995) example discussed people categorizing an unfamiliar object as a bird if it contains common “bird” attributes such as flying, having a beak and laying eggs. An example of how this classification process (that defines unfamiliar objects based on shared attributions) can result in hierarchy categories is the instance of all varieties of sparrows falling into the sparrow category as well as the higher categories of birds, and then animals. At some level, categories become ontologically distinct such as the living versus non-living attribute of a dog versus a rock. A recent addition to the vast conceptual change research has been the investigation of ontological categories, including processes (e.g., osmosis), abstract ideas (e.g., freedom) (Slotta et al., 1995) and material substances (e.g., animals) and their correlation to student science-based misconceptions. Chi's research proposed that student difficulties with physics subjects may be attributed to students' incorrect application of ontological categories (2005). Additionally, Chi (2005) discovered that many students were attributing a material-substance ontology to heat transfer and electricity topics rather than appropriately committing to a process ontology. It is extremely difficult to change established ontologies, especially when those students are unaware of how to correctly apply them to science content. Chi (1992, 1997) describes emergent processes as robust misconceptions that are resilient to change because they occur at the ontological level. Further research determined that students have exceptional difficulty understanding emergent processes due to their inability to correctly attribute a concept's ontological nature.

Slotta and Chi's (2006) research not only support students' tendencies to classify science concepts according to distinct ontological categories but help establish the importance of shifting students' ontological nature in regards to science curricula. When students assign a fundamental characteristic to a concept that isn't consistent with the scientifically normative view, they establish an incorrect knowledge base that carries into future learning endeavors. For example, while the scientifically normative view associates the concept of heat with a process ontology due to the transfer of kinetic energy between molecules, many students apply a material substance ontology. This may be due to the familiar phrase, "close the door, you're letting all the heat out," (Slotta et al., 1995). Regardless, this incorrect ontology could be the foundation of existing misconceptions regarding the concept of heat as well as future misconceptions which utilize their conception of heat as a foundation for learning. Slotta and Chi (2006) then proceeded to test the implementation and impact of training students on the appropriate ontology prior to instruction as a means of facilitating conceptual change.

Slotta and Chi (2006) set up a training study that tested students’ understanding of electricity. The control and experimental undergraduate groups both received the same instructional text about electric current; in addition, the experimental group was provided with direct training regarding the emergent process ontology while the control group was not. Slotta’s (1995) previous research established an inventory of verbal predicates that students used to describe electric current with a material substance ontology. Identical pre- and post-tests were then administered during the experiment as a means of measuring any changes in verbal predication to indicate whether the experimental group demonstrated conceptual change. As predicted, providing the experimental group with direct instruction on an ontological class changed the manner that the students thought and discussed electric current, using fundamentally different terms in comparison to the control group. These results suggest that particular lecture material content doesn’t necessarily have to be altered in order to obtain positive results toward conceptual change.

Inquiry Based Learning

While Slotta, Chi and Joram (1995) attributed misconceptions of heat to an incorrect ontology and proposed ontological training as a possible solution, McDermott and the Physics Education Group at the University of Washington outlined inquiry lab assignments as a means of addressing these misconceptions through active mental engagement, or a process of inquiry. The heat and heat transfer modules step students through a combination of narrative elements, experiments, exercises, and supplementary problems. One exercise references a previous temperature experiment that students were to conduct. They were prompted to mix various amounts of water at hot and cold temperatures using simple ratios with the intention of investigating how the final temperature of a water sample is affected by masses of individual samples. After reading a short introduction to heat and heat transfer, the exercise then has the students reflect back upon what they learned throughout their experiment and apply it to a hypothetical scenario considering the application of heat transfer to different mass ratios of hot to cold water (McDermott and Physics Education Group at the University of Washington, 1996a).

Inquiry-based learning occurs when a teacher creates situations in which students take the role of scientists. Students are able to ask the questions and learn from their own experimental design procedures (Center For Inquiry-Based Learning). Learning situations are open-ended in the sense that there is not necessarily a single correct answer for students to find. Rather, they learn through scientific exploration and gain knowledge through their own mistakes and findings. Inquiry learning is the type of learning that is generally associated with science-based labs; however, in order for teaching to be truly inquiry-based, the instructor has to take a hands-off approach. This includes guiding students to find their own answers instead of explaining to them how to do a certain procedure so that they will obtain successful results. “Inquiry-based laboratory instruction has been a cornerstone of the curricular reforms proposed for improving the recruitment and retention of undergraduate science majors,” (Bransford and Donovan, 2005).

Research conducted in the Department of Biological Science at California State University, Fullerton, evaluated and compared students who were implemented into a first time inquiry-based lab curriculum that was instilled over a three year period (Casem, 2006). Student responses were tracked over the three years, and it was found that the responses improved along with the quality of graduate teaching assistants and clarity of lab manuals. Student perceptions of lab-related skills were strongly associated with those variables. This supports the notion that in order to run a successful inquiry lab, there are many factors that must be considered. One of the main concerns affecting an inquiry lab is the adjoining curriculum, for, in this type of setting where the instructor is mainly hands off, the assignment or project must be able to stand alone as a teaching aid.

Previous extensive misconception research conducted by the Physics Education Group segued into writing three “Physics by Inquiry” lab manuals, the third of which is under preparation. Examples of the incorporated subjects are: properties of matter, light and color, magnets, (McDermott and Physics Education Group at the University of Washington, 1996a), electric circuits, light and optics, kinematics and astronomy by sight (McDermott and Physics Education Group at the University of Washington, 1996b). Modules were appropriately tailored to their intended student audiences through an iterative process of designing, testing and modifying the inquiry curriculum. One major goal is “to help students think of physics not as an established body of knowledge, but rather as an active process of inquiry in which they can participate,” (McDermott and Physics Education Group at the University of Washington, 1996b, pg. iv).

POGIL

Process Oriented Guided Inquiry Learning (POGIL) is a newer type of inquiry learning initiated in the 1990's as a way to improve chemistry education techniques. This learning environment has been used on the following chemistry topics: general, organic, biochemistry, physical and analytical. Students are broken into groups of four to five and given roles of manager, reporter, spokesman and reflector. The teacher also takes on four roles of leading the learning process, monitoring progress, facilitating learning and understanding and evaluating the learning processes in order to stress both content and process to their students (Hanson, 2006). This learning environment is strongly based on research linked to constructivism, guided inquiry and cooperative learning (POGIL, 2011) and has been implemented into over 42 colleges since 2007. POGIL assignments include a set of questions that lead students to learn a new concept or build upon an idea based on their prior knowledge. Each student receives a group grade based on their POGIL activities and an individual grade based on their test scores. Comparative studies on students involved in POGIL activities versus traditional lecture teaching found that POGIL students made higher grades and had higher levels of mastery (POGIL, 2011).

The Iowa State University of Science and Technology implemented POGIL strategies into their introduction to organic chemistry course as they had found students were unable to provide reaction mechanisms of organic reactions despite perfect scores on their lab reports that required them to do so (Schroeder and Greenbowe, 2008). The organic chemistry course was traditionally taught for the control group and the experimental group incorporated POGIL activities and strategies into their lectures and labs. An organic chemistry book was used throughout each class along with a guided-inquiry book in the experimental class to supplement POGIL activities. In the experimental class, each lab manual was also converted into an inquiry-based manual. Each lecture for the experimental group was laid out into three twenty minute blocks. During the first block, students were handed out a group activity on new material and given a brief introduction on what was discussed and learned in their previous lecture in order to branch and explain how the new material built upon it. A new activity was given out approximately every other lecture. The instructor acted as a facilitator throughout the second block checking on the progress of each group and looking for major difficulties the collaborative groups had. During the final block of time, the class gathered as a whole as the instructor led a guided discussion on the common misconceptions and difficulties experienced by all groups and addressed the major concepts in the activity. Each lab had a similar inquiry, collaborative group set-up. Students would collaboratively produce lab questions to answer prior to entering the lab and used class data tables to draw conclusions as a class, which was facilitated through guided discussions by the lab T.A.

Both the control and experimental class were given a final exam at the conclusion of the course. One of the questions required students to sketch the complete mechanism that showed the formation of both products involved in nucleophilic substitution and elimination. The study found that 75% of the students in the traditional course did not even attempt to solve th problem while every student attempted from the experimental class. Furthermore, 11/23 of those students drew the major and minor elimination production correctly, 8/23 sketched the completed mechanism and 9/23 correctly explained why the more substituted Alkene was produced. Finally, through pre and post course surveys, it was determine that the experimental lab helped students understand topics discussed in lecture even though many times lab topics were introduced before learning them in lecture. This finding suggests that exploring new concepts in a laboratory setting may help prepare students for an activity-based lecture.

Metacognition

Metacognition is defined as "cognition about cognition", or "knowing about knowing.” According to J. H. Flavell, “metacognition refers to one’s knowledge concerning one’s own cognitive processes or anything related to them” (1976, pg. 232). The process of metacognition is similar to the scientific procedure; however, people use it subconsciously on a daily basis. Each time someone thinks before they act, they are using a form of metacognitive thinking: considering an option or dilemma and creating a plan that will create optimum results. The key to successful metacognition is to include the step of reevaluating one’s progress along the way.

While there are different kinds of metacognitive knowledge, three general types are of particular importance. Strategic knowledge refers to the knowledge of strategies for learning and thinking. Although there are a large number of different strategic learning strategies, they can be grouped into three general categories: rehearsal, elaboration, and organizational (Weinstein and Mayer, 1986). Rehearsal strategies refer to the strategy of repeating words or terms to be remembered repeatedly to oneself. This is generally not the most effective strategy for learning more complex cognitive processes. Elaboration strategies include strategies such as summarizing, paraphrasing, and selecting main ideas from texts. These strategies usually result in deeper processing of the material and result in better comprehension and learning than rehearsal strategies do. Finally, organizational strategies include various forms of outlining, concept mapping, and note taking. Similar to elaboration strategies, organizational strategies usually result in better comprehension and learning in comparison to rehearsal strategies (Pintrich, 2002). Knowledge of tasks represents knowledge about different types of cognitive tasks as well as classroom and cultural norms. Lastly, self-knowledge is a critically important component of metacognitive knowledge. Self-knowledge includes all the information one already has prior to attempting to learn anything new or creating a plan of action (Pintrich, 2002).

Metacognitive knowledge can play an important role in student learning and, by implication, in the ways students are taught and assessed in the classroom (National Research Council, 1999). Science teachers, for example, can teach general scientific methods and procedures, but “learning will likely be more effective when it is tied to specific science content, not taught in the abstract,” (Pintrich, 2002, pg. 223). As students have more opportunities to reflect on their own learning, they will develop more self-knowledge that can be helpful to them. Metacognitive thinking can help students develop the ability to take control of their own learning, consciously define learning goals, and monitor their progress in achieving them (National Research Council, 2000).

According to the Strategic Teaching and Reading Project Guidebook, metacognition consists of constantly searching for answers and evaluations before, during and after a given plan, such as those found in Table 1.

TABLE 1. SUGGESTED METACOGNITION QUESTIONS EXCERPTED FROM STRATEGIC TEACHING AND READING PROJECT GUIDEBOOK (Kujawa and Huske, 1995)

During the development of plan, consider:
What in my prior knowledge will help me with this particular task? In what direction do I want my thinking to take me? What should I do first? Why am I reading this selection? How much time do I have to complete the task?
During the monitoring of plan, consider:
How am I doing? Am I on the right track? How should I proceed? What information is important to remember? Should I move in a different direction? Should I adjust the pace depending on the difficulty? What do I need to do if I do not understand?
After the completion of plan, consider:
How well did I do? Did my particular course of thinking produce more or less than I had expected? What could I have done differently? How might I apply this line of thinking to other problems? Do I need to go back through the task to fill in any “blanks” in my understanding?

Some metacognitive strategies of interest in the scientific fields are metamemory, metacomprehension, and self-regulation. Metamemory is the learners’ awareness of knowledge about their own memory as well as the strategies to effectively use it. Metacomprehension is the learners’ ability to monitor to what degree they comprehend the information that is being communicated to them as well as the strategies to repair the failure of comprehension. Self-regulation refers to the learners’ ability to evaluate their progress based on feedback and re-adjust their learning process to create a better outcome in the future (Livingston, 1997). Some other strategies that may aid in developing metacognitive behaviors are: 1) identifying “what you know” and “what you don’t know”, 2) talking about thinking, 3) keeping a thinking journal, 4) debriefing the thinking process, and 5) self evaluation. These strategies in particular can be directly related to the scientific method, as they are all logical step by step procedures. Metacognition has been linked with intelligence and it is supported that those with greater metacognitive abilities tend to be more “successful thinkers” (Holistic Education Network, 2004).

Hypothesis Testing

Similar to Inquiry-based learning, discovery learning, according to Wouter van Joolingen (1999), is a “type of learning where learners construct their own knowledge by experimenting with a domain, and inferring rules from the results of these experiments.” Research indicates that pure inquiry-based learning is not always successful and does not always lead to learning (Klahr and Nigam, 2004); the main difference between these two methods of learning is the domain. In order for discovery learning to be successful, students need to be able to create hypotheses, experimental designs, and data analysis. Van Joolingen used a SimQuest hypothesis editor to aid students in constructing, testing and analyzing their predictions for physics-based modeling software. Joolingen noted that this hypothesis tool especially helps those students who contain little to no experience with hypothesis testing, as “learners very often do not know what the basic elements of a hypothesis are,” (pg. 390, as cited in Joolingen and Jong, 1991). Students set up design procedures for a particular hypothesis and receive feedback which is directly connected to a particular assignment. This type of design curriculum could prove to be a helpful tool for atmospheric chemistry concepts, as the only atmospheric models currently readily available for student use are not user friendly and do not have assignments attached to them.

The teaching implications gathered from these studies indicate that not do science-based misconceptions exist but there is an expectation that research in related science-based fields would provide beneficial teaching implications, if not similar recommendations. The investigation of how students learn atmospheric chemistry subject matter is applicable to the above described conceptual change model as it involves complex material that is difficult for students to correctly comprehend.

II. ATMOSPHERIC CHEMISTRY

Atmospheric chemistry is important for students to learn because the scientific composition of our earth system incorporates multidisciplinary fields of study, including the exploration of the atmosphere, biosphere and geosphere. Some of the current environmental concerns included in this field of research are stratospheric ozone depletion, acid rain, photochemical smog, and climate change. Many of the environmental topics associated with atmospheric chemistry involve overlapping material and interrelated concepts, atmospheric scientists are constantly striving to determine how the environmental topics interact and affect one another. There is an ongoing search for answers and further explanations to observations of our continuously changing earth system in order to understand the problems as well as prpose solutions. Environmental decisions are further complicated by the conflicting opinions from politicians, environmentalists, economists, etc. which also amplify the non-linear quality of many atmospheric chemistry topics. These factors increase the difficulty of predicting atmospheric trends and of acquiring the necessary knowledge for our societal decisions to ultimately better our environment.

Ozone is one of the prominent atmospheric gases incorporated into current media and political discussions. As a secondary pollutant in the troposphere, ozone is difficult to control and poses great concern to human respiratory health, making it necessary for air quality engineers to monitor its short and long-term concentrations. In the stratosphere the ozone molecule maintains a significant role of absorbing harmful UV radiation before it reaches the surface and has an association with the “ozone hole” affecting climate change. With two separate atmospheric roles within the troposphere and stratosphere (and two distinct mechanisms of formation), ozone chemistry is an excellent example of the complexity and non-linear abstract concepts that are the norm within atmospheric chemistry research.

The conceptual intricacies associated with the ozone molecule in the atmosphere suggest that collegiate students would exhibit a low conceptual understanding of the ozone formation process. It is also likely that students with little experience with atmospheric science topics would have incorrect mental models in regards to the ozone molecule. Therefore, it is of interest to study how students learn and organize the various aspects of ozone in order to initiate the process of conceptual change. Such a study is the focus of this thesis.

CHAPTER TWO: Conceptual Understanding of O_3 Formation Research Investigation

I. INTRODUCTION

The competitive advantage of the United States in a global economy requires that the U.S workforce be productive and innovative. Innovative capability is more than the ability to solve equations and develop procedural understandings, it requires students to be able to understand and apply science and engineering fundamentals in a variety of contexts. High graduation rates combined with low performance on assessments of conceptual understanding (concept inventories) suggests that students are often applying equations that they do not understand (Gray et al., 2005; Hake, 1998; Halloun and Hestenes, 1985; Lawson and McDermott, 1986; Steif, 2003; Steif et al., 2005; Streveler et al., 2006; 2004). The lack of a deep understanding of key concepts provides a weak foundation to build upon, which can inhibit positive progress toward more advanced courses and career paths. Conceptual understanding can prepare students with the tools necessary for a successful and innovative work force.

Conceptual understanding is a learning framework that aids in determining how students understand concepts or ideas related to a topic. Conceptual change is a related learning framework that focuses on student's prior knowledge and incorporates the difficulties involved with changing it. These frameworks are relevant for science-based subject matter as they 1) focus on concepts and ideas and 2) are practical when students are likely to have preconceptions about pertinent topics. Research in student learning in the science and engineering disciplines during the past twenty years has revealed that students don’t understand fundamental concepts, including heat, energy, velocity, statistics and electricity. For example, in physics, research has shown that although students can calculate velocity and acceleration, they lack a fundamental comprehension of these concepts, frequently confusing the same velocity to mean the same acceleration for two objects (Trowbridge and McDermott, 1981b).

Atmospheric chemistry is considered by most to be a very challenging subject in which students likely have had previous interactions with these concepts through prior chemistry and physics courses as well as through the media. The foundation of many atmospheric chemistry topics is based on content derived from courses in which conceptual understanding has been shown to be low. Thus, it is reasonable to expect that atmospheric chemistry students exhibit a similar behavior as those researched in previous subjects. For example, a chemical concepts inventory indicates that general chemistry students have difficulties understanding fundamental chemistry concepts, including the properties and behavior of atoms and molecules (Journal of Chemical Education). Atmospheric chemistry includes many abstract concepts that are intangible, hard to visualize and difficult to comprehend. This paper explores students’ understanding of ozone’s formation and role in the atmosphere.

Ozone and Atmospheric Chemistry

Ozone is a major atmospheric oxidant that is formed primarily through mechanisms involving photolysis- the decomposition of a chemical compound by means of light energy or photons. The specific photolytic interactions between atmospheric gases and incoming solar radiation lead to ozone production that is primarily focused in two different regions of the atmosphere, the stratosphere and troposphere.

Stratospheric ozone is produced through the photolysis of oxygen molecules by ultraviolet light. Due to large-scale atmospheric dynamics, ozone formed in the stratosphere tends not to mix with the rest of the atmosphere and accumulates to form an ozone layer concentrated 10-50 km above the Earth's surface. Within the stratosphere, ozone plays a primarily beneficial role by absorbing harmful UV radiation before it reaches the surface. When chemical mechanisms reduce this layer to form an ozone "hole", negative human and environmental impacts such as skin cancer can occur.

Ozone formed in the troposphere is driven by separate and largely independent mechanisms from those that operate in the stratosphere. Because of the predominant dynamic separation of the stratosphere and troposphere, ozone levels in these two atmospheric layers are generally decoupled from each other. In contrast to the beneficial role of stratospheric ozone, elevated ozone concentrations near the Earth's surface can cause severely negative impacts that include aggravation to human cardio-respiratory systems as well as damage to agricultural systems and other plant life.

The formation of ozone in the troposphere can be described with the general reaction: [ ]. The key step for tropospheric ozone formation is the photolysis of an NO_2 molecule, which leads to the formation of an O_3 molecule. This photochemical process is driven by photons in the visible and near-UV portions of the electromagnetic spectrum ($\lambda < 0.39$ μm). However, while the photolysis of NO_2 is the most direct way of forming ozone, by itself this reaction cannot cause O_3 to accumulate to harmful levels. The net reaction for the formation of O_3 via NO_2 photolysis is: [ ]. In the absence of other compounds (such as VOCs), an equilibrium is established for this reaction such that the amount of ozone is fixed by the amount of NO and NO_2 initially present in the system.

For ozone accumulation to occur in the troposphere there must be a pathway for NO_2 to be regenerated without destroying O_3 in the process. The highly reactive hydroxyl radical ($HO^•$) provides a mechanism for this to occur via the chemical HO_x cycle. The HO_x cycle involves the formation of the hydroperoxyl radical ($HO_2^•$) through the reaction of $HO^•$ and VOC's. $HO_2^•$ can then react with NO to regenerate NO_2, which can in turn photolyze to form O_3. Critically, the reaction between $HO_2^•$ and NO that regenerates NO_2 also regenerates $HO^•$; this key step allows the HO_x cycle to propagate allowing continued ozone production to occur. Ozone's production due to the HO_x cycle, therefore, is essentially a negative byproduct of $HO^•$ cleansing of atmospheric VOCs. Ozone concentrations are in a constant state of flux as the destruction and production of ozone are directly affected by the availability of NO and NO_2, respectfully. Therefore, any hydrocarbons that assist the conversion of NO to NO_2 will also increase the production of ozone.

Tropospheric ozone production relies on the interaction of the NO_x and HO_x cycles. Because these complex cycles depend on the availability of NO_x and VOC's, which are in constant competition for $HO^•$ oxidation, there is not a simple, uncomplicated way to predict the amount of potential ozone production. Computer models are necessary which can quickly analyze numerous combinations of NO_x and VOC pollution levels in order to assess their potential to form ozone. These results are often plotted as ozone isopleth diagrams, a useful tool for interpreting the model results to aid air quality management decisions. By examining the plots, managers can determine whether ozone could be most effectively controlled by reducing NO_x, VOCs, or some combination of the two. Understanding this information is essential in the career preparation of an environmental engineering student since it is necessary to first comprehend how the individual atmospheric cycles overlap and interact in order to truly grasp the technical reasoning and decision making behind government standards, regulations, and ultimately execute appropriate managerial decisions for the future of our environment.

II. RESEARCH FRAMEWORK

Because there are so many intersecting concepts involved in ozone production, and because students frequently demonstrate difficulty in mastering related physics and chemistry concepts, there is good reason to study the learning process to determine which particular components give students the most difficulty. Like many other topics in atmospheric chemistry, ozone formation is complex, abstract, and involves numerous interconnected concepts. Moreover, the subject of ozone in the atmosphere is connected to several significant individual societal issues, including the loss of stratospheric ozone (the ozone "hole"), tropospheric ozone pollution, and climate change. These societal connections mean that many different pathways exist for students to encounter the target subject material. In order to determine how students' identify with and comprehend ozone formation, it is necessary to investigate student knowledge using in-depth qualitative techniques and multiple contexts.

Conceptual Understanding and Conceptual Change

Conceptual understanding is an individual's representation of a concept or set of concepts at a point in time. Conceptual change is the process of modifying conceptual understanding, and is more broadly a research framework and learning theory focused on students' integration of existing knowledge with new knowledge (Schunk, 2004), and particularly, aspects of existing knowledge that are incorrect and very difficult to change (misconceptions) (Chi, 2005; Chi and Roscoe, 2002). This approach is differentiated from other kinds of learning theories where modification of existing knowledge is relatively easy or when learning does not significantly interact with existing knowledge.

Conceptual change is based on theories of constructivism (Wadsworth, 1996), which suggest that learning is a process of change, and that people use their life experiences and existing knowledge as a foundation for building new knowledge and understanding how the world works. Conceptual change is largely focused on the structure and organization of knowledge and how these characteristics make some concepts much harder to learn than others. When confronted with knowledge that does not agree with existing knowledge, individuals have been shown to "change" the newly obtained information rather than alter their existing knowledge (Montfort et al., 2007). Additionally, Lising and Elby (2005) argue that students have difficulty applying their experiences and "real life" knowledge to a classroom environment. Others have shown that conceptual change is a long and difficult process, and "the *continuum of understanding* ranges from naïve to sophisticated, and from simplistic to complex," (Stephanou, 1999). Depending on the severity of a student's misconstrued assimilation of new knowledge, an individual's conceptual understanding in a subject can vary substantially from an expert's. In summary, students enter classroom environments with preconceived notions (preconceptions) of how the world works and isolated pieces of knowledge within specific subject areas. If student's preconceived notions are not activated, "they may fail to grasp the new concept and information, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom," (Donovan and Bransford, 2005). Additionally, in order for instruction to revise or replace inaccurate knowledge with correct information, students' preconceptions must be explicitly addressed (Bransford and Donovan, 2005; National Research Council, 2000).

A substantial amount of work in conceptual change research has focused on the development and implementation of concept inventories (CI). CIs are multiple choice assessment instruments with one correct answer and three to four incorrect answers based on typical incorrect student answers, or misconceptions. Halloun and Hestenes (1985) formulated the first of these inventories, the Force Concept Inventory (FCI), which assessed students on Newtonian mechanics through multiple choice questions that focused on their intuitive comprehension. There are currently concept inventories available in diverse fields, including chemistry (Krause et al., 2004; Pavelich et al., 2004), circuits (Evans et al., 2003), electronics (Simoni et al., 2004) and thermodynamics (Evans and Hestenes, 2001; Midkiff et al., 2001; Olds et al., 2004). The results from these inventories help assess students' level of conceptual understanding as well as to identify misconceptions. Concept inventory development includes efforts to determine student misconceptions, but lacks the rich detail necessary to fully understand student thinking and reasoning about core science and engineering concepts. However, conducting interview-based qualitative research can help develop detailed accounts of students' mental representations of these concepts and how they relate.

Figure 1 represents a summary of extensive interview-based qualitative research on the concepts of velocity and acceleration and several misconceptions discovered in this research. A correct understanding of fundamental topics such as velocity and acceleration allow a student to utilize an established foundation and transfer their knowledge to more complex applied concepts. When misconceptions are present, as illustrated by the dashed line in Figure 1, students may not correctly or completely arrive at the intended applied concepts. Students can have these fundamental misconceptions about important concepts that continue through other crucial courses as well as their future careers and ultimately cause negative societal consequences.

The research studies summarized in Figure 1 provide much more detail on student reasoning and thinking than work on CI development, and, as a consequence, have made it possible to develop theories of conceptual change (Chi and Roscoe, 2002) and develop curriculum (McDermott and Physics Education Group at the University of Washington, 1996a; McDermott and Shaffer, 2001) to guide students in repairing their misconceptions and developing more complete and correct understandings of physics principles. It is for this reason, among others, that the National Research Council has recommended determining misconceptions in science and engineering fields (National Research Council, 1999). Research is necessary in ozone formation and atmospheric chemistry to determine student's understanding, reasoning, and logic about these concepts, as well as to use this information to develop content-independent theories of knowledge of conceptual change, and to develop materials and methods to

(INSERT FIGURE 1)

Previous work on Conceptual Understanding in Ozone and Global Warming

The majority of the learning studies in the atmospheric sciences have focused on students below the collegiate level. Children's beliefs about global warming and energy sources were investigated to evaluate their environmental concern, personal awareness, and perceived responsibility (Devine-Wright et al., 2004). Several studies have illustrated that students ranging from elementary to the university level confuse or interchange ozone layer depletion and the greenhouse effect (Andersson and Wallin, 2000; Boyes and Stanisstreet, 1998; Dove, 1996; Groves and Pugh, 2002; Meadows and Wiesenmayer, 1999; Rye et al., 1997). Anderson and Wallin (2000) studied students' conceptions in grades 5, 9, and 12 of the greenhouse effect and ozone layer depletion. They found that students linked the model of an ozone barrier stopping harmful UV radiation to the greenhouse phenomena. The students believed that when ozone depletion occurs (barrier thins), more radiation gets through and it gets warmer as a result, i.e., the greenhouse effect. While students appear to understand that the ozone layer is protective against harmful UV radiation, there is a common existing misconception that the ozone layer depletion leads to the greenhouse effect. Although students indicate familiarity with the term greenhouse effect, there is low conceptual understanding of the surrounding topics, including heat radiation, pollution/emissions and the ozone layer (Andersson and Wallin, 2000; Dove, 1996). It was determined through Boyes and Stanisstreet's research (1998) if high school students' perception of environmental effects that cause skin cancer that students also confuse heat waves (infrared radiation) with ultraviolet radiation. An example extracted from Rye et al.'s results (1997) suggested that 75% of students believed that global warming was caused in some sort due to ozone depletion and/or increased UV radiation.

Similar conceptual difficulties were found in studies focusing on pre-service elementary teachers. Khalid (2001) studied collegiate students' misconceptions regarding three environmental issues: the greenhouse effect, ozone depletion and acid rain. The main misconceptions extracted from this study are that an increased greenhouse effect may cause skin cancer, that pollutants evaporate with water and later come down as acid rain and that there is a causal relationship between ozone depletion and global warming. Groves and Pugh (2002) investigated comparable subject matter with similar results, finding that students believed that UV radiation was both a cause and effect of ozone depletion. They similarly confused global warming and ozone depletion reasoning that the cause of the ozone problem was both too much sunlight as well as its inability to escape from the earth's surface.

A common thread in the previous atmospheric science literature is students' tendencies to interconnect and incorrectly relate atmospheric topics, especially the greenhouse effect and the ozone layer. These incorrect conceptions are robust and consistent; they are present in students ranging from grade school to the university level.

Research Justification and Goals

There has been little research conducted at the university level regarding student conceptual understanding of air pollution formation. Previous research has focused on larger scale phenomena in atmospheric chemistry- ozone depletion or the greenhouse effect. However, the majority of these investigations focused on students' understanding of the long-term environmental consciousness and societal consequences of these phenomena, and not on the technical aspects of ozone formation and atmospheric chemistry.

This study utilizes previously validated methodologies to address gaps in our knowledge of how students learn local scale atmospheric phenomena by examining students' understanding of the chemical processes by which ozone forms in the atmosphere. The goal of this research is to synthesize students' conceptions of ozone formation and its role in the atmosphere with emphasis in the following objectives:

1. Characterize conceptual understanding of fundamental ozone concepts including ozone and chemistry terminology; and
2. Identify student misconceptions associated with ozone formation.

The ozone formation processes investigated included advanced chemical concepts and were aimed at a higher academic level than previous studies. The above objectives will aid in revealing what concepts give students most difficulty when studying ozone in the atmosphere. Exposing these areas of concern will allow future progress toward more correct conceptual understanding in atmospheric chemistry by addressing student misconceptions. Methodologies used in this study can then be used as a foundation for future research in collegiate student misconceptions in advanced environmental engineering subjects.

III. METHODS

The goal of this study is to investigate students' conceptual understanding and not to evaluate instruction. This goal is in alignment with previous research on conceptual understanding (e.g., Andersson and Wallin, 2000; Trowbridge and McDermott, 1981a; Trowbridge and McDermott, 1980a). Additionally, previous research has shown that students seldom alter their existing conceptual understanding due to instruction (Brown, 2011; Chi and Roscoe, 2002; Dove, 1996; Meadows and Wiesenmayer, 1999). A brief overview of the course content is described below to provide some context for the students' course experience.

Most topics related to this research were present in course material multiple times throughout the semester. Initial lectures pertaining to ozone included information regarding atmospheric layers and the relationship between wavelengths and light. A two-week module immediately preceding the student interviews presented material on the formation of ozone and its effects in the stratosphere and troposphere through assigned reading, lecture, or exam material. The module included one homework assignment in the form of a small design project wherein students created a hypothesis for reducing tropospheric ozone levels in an urban setting and then tested their hypothesis using a web-based model designed as a teaching aid for the non-linear nature of ozone formation. All pertinent ozone exam questions were qualitative, requiring no calculations or derivations. The lectures discussed the interaction of stratospheric and tropospheric ozone with ultraviolet light through photolytic chemical reactions. This module placed a strong emphasis on the formation of tropospheric ozone, which encompassed the cyclic process and the importance of hydroxyl radicals.

Participant Selection

The research participants were selected from the pool of students enrolled in Introduction to Environmental Engineering, a junior level engineering course in the Department of Civil and Environmental Engineering at Washington State University, during the 2010 spring semester. Each student was recruited on a voluntary basis for a forty-minute interview; as incentives for their cooperation participating students were given ten dollars and extra credit in the course. For students who were not comfortable participating in a one-on-one interview, an alternate assignment was created with similar material to that found in the interview protocol. Forty-five out of fifty-five students enrolled in the course volunteered to be research participants, providing a representative data set. The data set of participating students, ranked according to their course grade, exhibited an even distribution of academic achievement with 17 students in the top, 14 students in the middle, and 13 students in the bottom third of the class. A high percentage of participating students combined with a representative sample across course grades ensures that the results are generalizable to the population from which the sample was drawn and transferable to other comparable populations. The transferability of the results, or the ability to apply qualitative results to an outside context (Trochim, 2006), is supported by the detailed description of the interview participant class and accompanied lecture material.

Interview Methodology

Investigating conceptual understanding requires obtaining students' knowledge of the concepts and ideas surrounding a content area, and is more than rote or procedural knowledge. The motive during interviews was not to evaluate the students based on their answers alone, but rather to gain insight into the thought processes and reasoning behind those answers. Physics (e.g., Trowbridge and McDermott, 1981a; Trowbridge and McDermott, 1980a) and engineering (e.g., Andrews et al., 2010; Brown et al., 2007; Montfort et al., 2009) education researchers have used the clinical demonstration interview technique to investigate student conceptual understanding. The clinical (Ginsburg, 1997) aspect of the interview refers to the goal of obtaining rich descriptions of student thinking and reasoning using flexible lines of questioning that are adaptable to individuals and their unique ways of knowing. This method includes developing real time hypotheses about student reasoning and investigating these hypotheses through probing questions. The interview protocol described below is semi-structured (Patton, 2002), with a set of questions that every student was asked, and related set of probing questions for each primary question that were asked depending on need. The demonstration aspect refers to the use of either a physical demonstration or a paper-based representation like a figure, graph or problem, and using this demonstration as a point of questioning in the interviews.

Interview Protocol

The material in the interview protocol was based upon content in the environmental engineering course, to which all research participants were exposed. Prior to the research interviews, pilot interviews were conducted by the lead author accompanied by two WSU faculty with air quality expertise, using students who had previously completed the same environmental engineering class. These pilot interviews helped ensure that the interview technique was appropriate and that a thorough interview protocol was developed. Results indicated that the original interview protocol was too technical for students to articulate answers in detail; students became overwhelmed, disengaged and mentally defeated during the pilot interviews. Accordingly, the final interview protocol included more graphical and conceptual questions, providing the opportunity for students to discuss and relate to the topic more broadly while still including technical content relating to basic chemical reactions, terminology, and fundamental ozone concepts.

Students' understanding of concepts can be dependent on the context in which it is presented (Brown, 2011). Learners conceptions seem to be organized into domains of knowledge (Vosniadou et al., 2008; White, 2002). The boundaries of these domains are difficult to define, however, and many researchers argue that the specific context of a problem statement or interview question can affect which domain students' are thinking in (DiSessa, 2007; Ivarsson et al., 2002). The practical and research implication of this are that student knowledge and reasoning remain correct until it's applied to an unfamiliar situation which requires them to incorporate and discuss a topic in different or multiple contexts (Brown, 2011; Stephanou, 1999), in which case their application of knowledge can be incorrect.

In order to obtain a complete view of students' mental representations of the content area and provide multiple and diverse opportunities for students to share their knowledge and discuss the same content, the interview protocol, summarized in Table 2, included interview questions within multiple contexts. Spatial, visual and vernacular segments were included in the protocol and it integrated a framework that first considered a broad understanding of ozone and transitioned into more detailed content regarding its chemical formation. Additionally, the order of the interview protocol was specifically designed to help extract such information and lower students' anxiety about the subject matter.

TABLE 2. SUMMARY OF INTERVIEW PROBLEMS AND QUESTIONS

			Category	
Problem	**Schemas**	**Interview Questions**	**CBC**	**OBC**
1	Figure representing the main cyclic tropospheric ozone formation components	Can you explain what is happening in the Figure?		X
		Can you describe what NO, NO_2, and $HO^{\bullet}$ are and their significance to our atmosphere?	X	X
2	A list of tropospheric ozone formation reactions	Can you define a chemical reaction as if explaining to someone with no chemistry background?	X	
		Discuss the difference between a stable and unstable atom using the provided list of reactions as a reference.	X	
		Discuss electrons and protons in terms of their location and role during a chemical reaction.	X	
		Describe some of the reactions from the provided list and any correlation they have to previous ozone figure.	X	X
		What does the arrow represent in a chemical reaction?	X	
		Can you describe in detail what a radical is and its purpose?	X	
		What is photolysis and a photon and do any of the provided reactions represent either of them?	X	
3		Can you describe what a hydrocarbon, VOC and NO_x are including how they are formed?		X
4		Explain what smog, photochemical smog and ozone are as well as any differences between them, if they exist.		X
5	Environmentally based hypothetical scenario	Describe the different molecular interactions and ozone concentrations inside a hypothetical box at various locations and altitudes.		X
6	Isopleth diagram relating NO_x, hydrocarbons and O_3 production	Explain the process of predicting ozone concentrations via the provided reactions and the NO_x-hydrocarbon isopleth diagram.		X
End of interview		Total coverage	8	7

Notes:
[1]CBC represents general chemistry concepts;
[2]OBC represents concepts specific to ozone processes.

The first interview problem, accompanied by a figure representing the main cyclic tropospheric ozone formation components (Masters and Ela, 2008), contained questions which required students to explain what they believed the diagram represented and to discuss any major themes or points of significance. Problem 2, accompanied by a pertinent list of ozone formation reactions from course materials (Masters and Ela, 2008), included general chemistry questions such as electrons, protons, photolysis and chemical stability. The list of reactions was meant to remain available for reference throughout the rest of the interview as a means of providing a way for students to connect to potentially unfamiliar material in a recognizable context. Next, problem 3 incorporated questions about students' understanding of ozone terminology including hydrocarbons, VOCs and NO_x. Problem 4 then contained questions requiring students to define smog, photochemical smog and ozone and provide any differences or similarities between them.

Problem 5 incorporated the concepts the questions in problems 1-4 investigated into an environmentally-based hypothetical scenario. This scenario would allow students to take an abstract concept that may be challenging to visualize and transform it into a situation where students could incorporate their spatial perception of the world to better relate and discuss the subject material. Problem 5 first instructed students to imagine a small box open to the atmosphere on two sides and then directing them to move their box to different locations (e.g., urban or rural areas), or to change its altitude. As part of the scenario, students would be asked to discuss altitudes in arbitrary units where altitudes of interest were whenever something crucial happened or changed in their box, generally occurring at a transitional atmospheric boundary layer. Problem five would progressively include probing questions on the status of their box, how components were interacting with one another and whether anything had changed in their box and why. This scenario would provide the same broad guidelines to each interviewee but allow each individual to incorporate their own assumptions and vision. Finally, problem 6 included questions about individual components of a provided diagram, such as how to interpret it as well as who would utilize the graph and for what purposes. The accompanied graph was an isopleth diagram representing the relationship between the amount of hydrocarbons and NOx in the atmosphere and the amount of ozone produced (Masters and Ela, 2008).

Data Analysis

Audio-recorded interviews were transcribed and the data was used for two parallel methods of analysis. The first was qualitative analysis using Atlas TI (ATLAS.ti, 1993-2011), a qualitative data analysis program, with the goal of determining patterns in student reasoning. Interview coding was an iterative process that involved grouping and refining codes after the three main stages of analysis, continually assessing the progression for consistency and comparison among the different levels of coding. The first stage involved coding pertinent information only considering student wording. It is crucial that coding initially focuses on direct phrases from the interviewee to avoid excessive interpretation early in the analysis (Miles and Huberman, 1994; Patton, 2002). The second stage linked themed phrases and topics (involving the majority of researcher interpretation), and the final stage of coding required a deeper analysis which searched for contradicting evidence for the findings (Lindlof and Taylor, 2002). Two main themes ultimately surfaced from the coding process, including students' responses regarding general ozone concepts and students' discussion about the relevance of sunlight in ozone formation.

The goal of the second parallel analysis was to roughly quantify student understanding and investigate relations of performance between content areas. A rubric was developed to score each interview based on topic area, and three faculty scored student interviews as discussed below. For the purpose of this analysis, the ideal student understanding was taken to be one that was in full agreement with an expert's view of the material. Expert views (experts in environmental engineering) were represented in this study by air quality engineering faculty at WSU. Although the numbers assigned do not hold any significant meaning on any absolute scale, they aid strictly as a counting system and help arbitrarily group the data into a visually appealing table. A five point (whole number) scale was chosen for this rubric. Low comprehension is represented by zero-one point, two to three points for a medium and four to five points for a high comprehension. Points were assigned according to Table 3.

TABLE 3. QUALITATIVE RUBRIC USED FOR CATEGORIZING BOTH STUDENTS' INDIVIDUAL UNDERSTANDING OF OZONE TOPICS AND OVERALL COMPREHENSION OF OZONE FORMATION

<table>
<tr><th rowspan="2">Interview Criterion</th><th colspan="3">Performance Indicators</th><th rowspan="2">Score</th></tr>
<tr><th>Low Comprehension (0-1pt)</th><th>Medium Comprehension (2-3pts)</th><th>High Comprehension (4-5pts)</th></tr>
<tr><td>General Ozone concepts</td><td>Demonstrates that ozone is either “good/bad” or only formed in one way</td><td>Can classify two different mechanisms for forming ozone; one blocks UV light and the other is a secondary pollutant</td><td>Identifies that:
1. Stratospheric Ozone
• protects from UV radiation
• formed through photolysis of O_2
2. Tropospheric Ozone
• harmful effects with too much
• formed through photolysis of NO_2</td><td></td></tr>
<tr><td>Photolysis Concepts</td><td>Acknowledges sunlight is crucial to the formation of ozone</td><td>Understands that molecules can absorb the electromagnetic radiation phenomena of photolysis</td><td>Understands that different molecules absorb at different wavelengths</td><td></td></tr>
<tr><td>HO Radicals</td><td>Knows what radicals are and how they are formed</td><td>Recognize HO radicals involved in chain mechanism</td><td>Understands HO radical is recycled in VOC-NOx reactions</td><td></td></tr>
<tr><td></td><td></td><td></td><td>Total</td><td></td></tr>
</table>

<u>General O3 Concepts:</u>

Students who fell into the low comprehension category for general ozone concepts were allotted zero points if they were unable to describe the basic formation of ozone and one point if they described ozone as either good/bad or only being formed in one way. In order to fall into the medium comprehension category, one must have acknowledged that ozone is formed in two different ways (no specifics required). A third point was awarded if they could also describe both of the different associated atmospheric roles that ozone plays in the atmospheric layers, blocking UV radiation and creating possible negative health effects. To fit into the high comprehension category students had to first identify the two atmospheric layers ozone is formed in (the stratosphere and troposphere) for four points. They gained a fifth point if they could correctly state that ozone is formed through the photolysis of O_2 and NO_2 (corresponding the correct atmospheric layer to each).

Photolysis Concepts:

In the lowest category of understanding, zero points were assigned to students who didn't ever mention the role of sunlight in ozone formation with one point designated for those who acknowledged in some form that sunlight is crucial to the formation of ozone. To score into the medium category and attain two points, students had to link the sunlight breaking or cleaving bonds to the formation of ozone. They were able to gain an extra point if they could also connect this concept to the process of photolysis. Four points were assigned in the high comprehension category for students who associated and explained the importance of wavelength energy and lengths (photon details) with the process of photolysis. Finally, students were awarded with five points if they were able to explain how wavelengths and photons affect photolysis during the different formations of ozone; the photolysis source of stratospheric ozone is ultraviolet radiation whereas the source for tropospheric ozone is visible light.

HO Radicals:

Under the low comprehension grouping, a student received one point for the ability to define a basic understanding of what a radical is (a highly reactive atom or molecule containing a free floating, unpaired electron) and zero points otherwise. The medium category allots two points for recognizing that the HO radical formation is a cyclic process and three points if the student also acknowledges that the HO radical is a crucial part of atmospheric oxidation (controlling the atmospheric lifetime of many molecules). Four points in the high comprehension category were awarded if students could explain the transition of the HO radical from a chemical reaction to the differential rate equation. Finally, five points were awarded if the differential rate equation was utilized as an explanation for how the HO radical contributes a crucial cyclic role in the oxidation of VOC's, NO_x and other atmospheric molecules.

The numerical data obtained from this rubric helped determine and categorize students' overall understanding of ozone formation as well as their comprehension of some of the key individual framework topics. The ability to visually cross reference conceptual categories individually as well as compare students' individual scores from the rubric analysis to one another helped piece together ozone conceptions students held. The overall rubric total score, out of fifteen possible points, was obtained by adding each of the individual categorical scores together. Students were then grouped into one of three categories based on their total score: Low Rubric Comprehension (LRC), Medium Rubric Comprehension (MRC), or High Rubric Comprehension (HRC). The score breakdown for each of these groupings was based on the total possible points allotted for the corresponding rubric category: (0-3) for LRC, (4-9) for MRC and (10-15) for HRC. The individual ozone topic scores were then classified into qualitative degrees of low, medium and high (which also correspond to the original rubric point breakdown). A separate grading criteria sheet was created to accompany the qualitative rubric, Table 3. It provided a more detailed explanation of the subject matter analyzed, which included unambiguously defined instructions on student score placement within each category to help with reproducing consistent results. Without the additional descriptions, the point distribution would be more interpretive, leaving the possibility to be strongly influenced by the grader's material knowledge.

IV. RESULTS

The number of students who were classified into each of the LRC, MRC and HRC categories is tabulated in Table 4. Also included in the table is a breakdown of how the students performed in each of the three conceptual categories. The conceptual category scores underneath the overall rubric breakdown illustrate that there is low overall conceptual understanding of ozone formation as well as low understanding of the individual ozone formation topics.

TABLE 4. STUDENT O_3 FORMATION COMPREHENSION GROUPINGS AND RESPONSES

O_3 FORMATION TOPICS	**Student O_3 Formation Comprehension Groupings**			
	LOW: 23	MEDIUM: 19	HIGH: 2	TOTALS
GENERAL O_3 CONCEPTS	L: 22 M: 1 H: 0	L: 10 M: 5 H: 4	L: 0 M: 0 H: 2	L: **32** M:6 H: 6
PHOTOLYSIS CONCEPTS	L: 15 M: 8 H: 0	L: 3 M: 12 H: 4	L: 0 M: 0 H: 2	L: 18 M: **20** H: 6
HO RADICALS	L: 23 M: 0 H: 0	L: 17 M: 2 H: 0	L: 1 M: 1 H: 0	L: **41** M: 3 H: 0

Interviewee #26: Low Understanding (General O_3 Concepts)
Interviewer: How about this kind of chemistry type stuff on the [tropospheric ozone formation figure], would any of that be in the box on the ground? Respondent: Um, you mean the reaction itself or just particles? Interviewer: Um, either one, would the particles be in there and then would the reactions be occurring? Respondent: There would definitely be oxygen at least hopefully. Um, probably some NO_2, um, I don't think that the reaction itself would be happening to produce ozone. Um, at least not very much. That takes place more in the ozone layer, at least as far as I know. Interviewer: Ok, and what about the ozone layer makes this stuff react that it wouldn't be reacting in the box down on the ground? Respondent: I could not tell you that.
Interview #33: Medium Understanding (Photolysis Concepts)
Respondent: The sun causes the NO_2 to split up and then it joins with the oxygen in the atmosphere, well that's later but it causes one of the oxygen to split. Interviewer: What's photolysis? Respondent: It's when the sun causes the molecules to split up.
Interviewee #5: Low Understanding (HO Radicals)
Interviewer: Do you know what a radical is? Respondent: Well, it's just like an unpaired electron, I still don't know what it is, like I know what it is like why it has a dot but I don't know what -- Interviewer: So why does it have a dot? Respondent: Because there is like - well the dot is like an unpaired electron, that's why it has a dot. And then since it has an unpaired electron, I guess it just makes it more active I am guessing and I didn't learn in class but it just makes it more active so that's why it can like react with a lot of stuff in the middle.

Notes:
[1]LOW, MEDIUM, HIGH represent overall rubric scores.
[2] L,M,H represent understanding breakdown of individual O_3 formation topic within each overall comprehension grouping.

Although both the overall student comprehension of ozone formation and individual ozone topic categories were low, there were students who scored into the medium and high categories. This distribution mainly occurred within the general ozone and photolysis concepts. The main trend observed through the rubric analysis is that students proved to have minimal to no understanding of the hydroxyl (HO) radical. The quotes included in Table 4 represent typical student responses from the average representation of each category. Interviewee #5's responses were typical of students exhibiting a low understanding of HO radicals. This student was one of only 15 of 44 students who were able to define a radical and describe its basic function (a low category requirement); 26 of 44 students were unable to do so. Furthermore, the HO radical topic was the only one that scored consistently low throughout all of the rubric comprehension categories: 23 of 32 for LRC, 17 of 19 for MRC and 1 of 2 students for the HRC category.

The rubric comprehension distribution for general ozone and photolysis concepts was not as straightforward. As might be expected students who were classified in the low and high rubric comprehension (LRC and HRC respectively) categories tended to have similarly weak or strong scores in the individual categories of understanding; however, the medium rubric comprehension (MRC) students did not show this same trend. Twenty-three students were placed into the low overall understanding category based on the sum of their individual ozone formation topic scores. Within this low-comprehension category, the following numbers of students scored low in the individual corresponding topics: 22 of 23 for general O_3 concepts and 15 of 23 for photolysis concepts. These data indicate a strong correlation between low individual topic and low overall ozone formation comprehension. Similarly, the two students who scored into the HRC category had high associated topic scores in both general ozone and photolysis concepts (though not the HO radical concepts).

Students falling in the MRC category did not demonstrate any such easily generalizable relationship between their understanding of individual topics and their overall comprehension. For students in the MRC category, 10 of 19 students demonstrated low understandings of general ozone concepts while 12 of 19 students showed medium understanding of photolysis concepts. Interviewee #26 (from Table 3) exhibited a low understanding of general ozone concepts. 32 of the 44 students demonstrated minimal knowledge and subject-familiarity in their explanations for ozone formation, and typically incorporated wrong or contradicting details. Interviewee #26 indicated that NO_2 would probably be present near the ground but that they didn't believe that the ozone formation reaction will occur, as that occurs up higher in the ozone layer. This quote illustrates that the student 1) does not understand the tropospheric ozone formation mechanism; and 2) does not grasp that ozone is formed both differently and separately in different atmospheric layers. Interviewee #33's responses were characteristic of a medium understanding of photolysis concepts. While 20 of the 44 students were able to define and describe the basic concept of photolysis, there were only six students who were able to incorporate more advanced concepts such as wavelength dependence into their explanations. Within each of these individual topics (general and photolysis concepts), there was a comparable distribution for the remaining subcategory values under the MRC category.

The rubric analysis of students' overall and individual topic understanding of ozone formation indicates two crucial discoveries: 1) The varying level of MRC results suggest that students retain different degrees of understanding for general ozone and photolysis concepts, and 2) there are 41 of 44 students with low understanding of hydroxyl radicals when those students with minimal understanding are combined with those who could not provide either a definition or description. The few students who were able to describe the role of HO radicals were not able to go into much further detail on the subject, failing to link it clearly to the formation of tropospheric ozone. These results indicate that student's comprehension level of ozone formation is a multifaceted problem, amidst high student difficulty with HO radicals, which requires that students link together pieces of information from different subject areas.

Each student's rubric topic scores in the three categories were plotted against each other to determine whether any clear correlations existed in their understanding of the different topics (Figure 2a,b,c).

(INSERT FIGURE 2)

Within our sample, the data suggests that students' understanding of either general ozone concepts or photolysis concepts had no predictive value for their understanding of HO radical concepts. In combination with the consistently low scores in the HO radical category, this suggests that the HO radical concepts are "missing conceptual links" with respect to the understanding of ozone formation. While neither an understanding of general ozone concepts nor of photolysis concepts correlated with an understanding of HO radical concepts in our sample, the former two categories did correlate positively with each other (Figure 2c). Students who exhibited strong understanding of general ozone concepts also tended to score well in the photolysis category. Still, even this tendency was not especially strong; there were students who demonstrated medium to high understanding of photolysis concepts while showing only low understanding for the general ozone concepts. The correlated rubric scoring trends between these two topics suggest that students' abilities to learn these concepts are somehow interlinked; understanding the nature of these linkages required the additional qualitative analysis methodologies described above.

Detailed analysis of the qualitative interview data resulted in four areas of conceptual difficulty. Each area of conceptual difficulty, located in Table 5, represents at least 25% of the sample population interviewed. Students have formed incorrect and or incomplete mental models from these four conceptual difficulties (CDs); three of them are due to missing links of knowledge, one is attributed to a misconception.

TABLE 5. FOUR STUDENT CONCEPTUAL DIFFICULTIES ASSOCIATED WITH OZONE FORMATION

Incorrect mental models due to misconceptions:	**#**
1. Pollutants and gases float up and react up high.	16
Incorrect mental models due to missing links of knowledge:	**#**
2. Students fail to differentiate *function* of ozone in ozone layer (stratosphere) with functions in tropospheric atmospheric layer.	15
3. Students fail to differentiate ozone's role as a greenhouse gas versus ozone's harmful role as a component of smog in the troposphere and its protective role in the stratospheric ozone layer.	20
4. Students fail to differentiate *effect* of UV radiation in stratosphere and troposphere.	12

The discussion sections provide examples for how students utilized these CDs to create mental models which were correct in some contexts and incorrect in others. Many students intertwined various conceptions of ozone in an attempt to form coherent mental models while including both new and previous knowledge. The student quotes in the following sections support and reiterate the importance of determining student misconceptions and conceptual difficulties in the process of conceptual change. The established CDs not only influenced students' understanding of a single ozone component but affected their entire mental model, greatly hindering their comprehension of the entire ozone formation process.

V. DISCUSSION

Incorporation of Conceptual Difficulties (CDs) into student mental models

The subject of atmospheric ozone formation incorporates numerous abstract, interacting scientific concepts. Figure 3 presents the concepts that are linked to the formation, interactions, and impacts of atmospheric ozone in the stratosphere and troposphere. The diagram illustrates an acceptable way to link the individual pieces of ozone knowledge together to form a correct mental representation. The three different dashed boxes on the figure represent areas of student conceptual difficulty and visually signify that the student confusion associated with ozone formation encompasses a majority of the concepts involved through the CDs relating to the ozone layer, the greenhouse gas effect and UV radiation.

(INSERT FIGURE 3)

An important feature of Figure 3 is that in several instances identical or very similar content can be found in different contexts on the diagram. For example, separate boxes labeled UV radiation (or a close variant) are shown to indicate 1) its role in driving the stratospheric photolysis of O_2 to form ozone; and 2) its role as a cause of skin cancer. Other examples of concepts appearing in different contexts are pollutants and the role of sunlight. These instances are important because interview data indicate that such content overlap may be one of the main obstacles that prevent students from achieving a strong overall conceptual understanding of ozone formation. Specifically, the material overlap within the students' conceptual difficulties inhibits many of the conceptual links necessary for correct material understanding to exist.

This potential outcome is illustrated in Figure 4, which demonstrates how a missing conceptual link can affect the overall understanding of the ozone formation process. The diagram illustrates an incomplete conception that was observed frequently in our model. 41 of 44 students in our sample were successful in linking photolysis concepts (sunlight) to tropospheric ozone formation, represented in Figure 4 by a solid bold line. This association is a true link, and an important concept supported by the positive correlation found in Figure 2c. However, the lack of correlated data found among HO radicals with photolysis and general ozone concepts in Figures 2a & b indicate a missing conceptual link (represented by the dashed lines in Figure 4). Most students failed to articulate the intermediate concepts that are necessary for a fuller understanding of the process; most notably the role of atmospheric radicals (especially the HO radical) in driving the cyclical reactions that allow ozone to accumulate in the troposphere.

(INSERT FIGURE 4)

The formation of tropospheric ozone includes several technical chemistry concepts. When students encountered concepts that were difficult for them or when there were strong existing CDs, alternative and incorrect links were formed in order to define a logic pathway that could merge their newly established knowledge with their existing incorrect conceptions. For example, we believe that because the strong foundation in chemistry necessary for understanding ozone formation is missing for many students, they often failed to grasp that HO radicals are involved in a cyclic process that constantly oxidizes NO_x and VOCs and reforms in the atmosphere. In order to account for this missing conceptual link or difficult conception, many students then misunderstood the role of pollutants in this process and created conceptual links accordingly, such as incorporating NO_x into the ozone formation process located in the stratosphere.

The conceptual difficulties discovered greatly affected the cohesion of students' mental representations. There was consistent difficulty in integrating all aspects of ozone formation in a clear and coherent manner. As illustrated in examples below, many of the student responses were correct to some degree, but were also either incomplete or incorrect in some aspect. As the students' foundations were weak in the concepts needed to understand ozone formation, they incorporated incorrect links to create alternate mental models. Both the quantitative and qualitative data suggest that many students relied heavily on the four established CDs described above in developing their mental representations of the ozone formation process, as indicated on the key areas of Figure 3.

<u>CD #1: Students fail to differentiate *function* of ozone in ozone layer (stratosphere) with functions in tropospheric atmospheric layer</u>

Over half of the students exhibited low comprehension of atmospheric ozone by only articulating one mechanism for ozone formation. Interestingly, many of these same students were still able to describe the multiple atmospheric roles of ozone in their responses-- they had learned that ozone could be found in two layers in the atmosphere, and serve two contrasting functions, but they had not retained that its formation was controlled by distinct mechanisms. Majority of students understood that ozone could be harmful if concentrations were too high but that ozone's presence in the atmosphere was necessary to protect humans and block UV radiation. Moreover, nearly every student understood that pollutants, specifically NO_x and VOCs, were involved in ozone formation. While these responses exhibit correct knowledge of some basic concepts related to the topic, much of the students' reasoning and logic surrounding these basic facts were incorrect and represented an effort to build connections in the absence of sufficiently strong conceptions.

Although most students were able to recall the two roles of ozone, there were many instances in which they intertwined these different atmospheric ozone functions into an incorrect mental model.

Interview #2:

Respondent: *[Looking at figure 1] They are more concerned with ozone being formed in the troposphere because it absorbs like the radiation a lot more than in the stratosphere where it blocks it, like incoming radiation.*

While student #2's explanation includes correct aspects of ozone absorbing radiation within the troposphere, it is not the critical reason tropospheric ozone is a concern. This line of reasoning appears to incorporate the concept of stratospheric ozone absorbing radiation and blocking UV rays into the importance and function of tropospheric ozone and, therefore, deranging their overall mental model. Regardless of their confusion with atmospheric ozone functions, this particular student portrays a weak understanding of how radiation absorption affects ozone molecules. For, student #2 contrasts the formation of ozone in the differing atmospheric layers indicating that ozone “blocks” radiation rather than absorbing it in the stratosphere, whereas ozone is actually absorbing radiation in both of these atmospheric layers in order to form.

Many of the missing links of knowledge in student’ mental models were revealed when students were probed to justify their reasoning. For example, many students incorporated the perception that ozone is mainly found high in the atmosphere, because that is where the ozone layer is located (a common observation). The following student interview is a good representation of students who attempted to incorporate the common conception of an ozone layer into their newly founded knowledge of how ozone is formed in the troposphere.

<u>*Interview #26:*</u>

Interviewer: *How about any kind of all this kind of chemistry type stuff on [figure 1] (from interview protocol). Would any of that be in the box on the ground?*

Respondent: *There would definitely be oxygen, at least hopefully. Um, probably some NO_2, um, I don’t think that the reaction itself would be happening to produce ozone. Um, at least not very much. That takes place more in the ozone layer, at least as far as I know.*

Interviewer: *Ok, and what about the ozone layer makes this stuff react that it wouldn’t be reacting in the box down on the ground?*

Respondent: *I could not tell you that.*

This quote was extracted from the hypothesis box scenario portion of the interview. Student #26 discussed that while some of the tropospheric ozone reactions (figure 1 from interview protocol), such as oxygen and NO_2, would be present on the ground, the reaction to produce ozone would not occur. Their justification was then that the reaction to produce ozone took place more in the ozone layer. This student response, like many, illustrates the students' tendencies to incorrectly overlap the importance and roll of NO_x and VOC pollutants and the ozone layer in the process of ozone formation. Although student #26 clearly understands that NO_2 is present down below and apart of ozone formation (stated previously in interview) and places an emphasis on the ozone layer, due to their low conceptions, they form an incorrect conceptual link between these two concepts.

Furthermore, when student #26 is probed to explain why reactions occur in the ozone layer and not on the ground, they are unable to answer. Students had difficulty in explaining why the pollutants could react and form ozone high in the atmosphere but not near the surface. At this point students frequently exhibited a breakdown in their mental model and attempted to articulate other reasons to explain their conceptions.

CD #2: Pollutants and gases float up and react up high *(misconception)*

A common response to the above dilemma was for students to assert that most pollutants and gases float upwards and react higher up in the atmosphere. Students incorporated this misconception into their argument as a way of rationalizing their flawed and incomplete logic, typically as a means of explaining why there was significant ozone aggregation in the stratosphere. The incorporation of this misconception is a good example of how students create their own mental representations for occurrences that they cannot otherwise explain.

The students who exhibited this misconception demonstrated a low conceptual understanding for the process of a chemical reaction, specifically in regard to where and how molecules interact with one another in order for a reaction to take place, although their responses indicated that there were pollutant and other gaseous molecules present lower down (towards the ground), the reactions that originate in the gaseous state (especially those involved with ozone formation) supposedly occurred higher in altitude. Part of the misconception argues that molecules float up to the altitude in which they react, but this claim doesn't acknowledge any reactions transpiring during this process.

Interview #14:

Interviewer: *Okay, can sunlight get in through the sides of the box?*

Respondent: *Oh yeah, but I don't think it reacts on like that close to ground, I don't know. The way like I was always explained to, like when they showed a picture of different like spheres, it's always like at the top of the, I think troposphere is the first and then like up above is where other things react. So nothing ever reacted like right on the ground level really.*

……………………………………………………………………………………

Interviewer: *Okay so how come all this middle stuff on the Figure 7.7(interview protocol problem 1 figure: main cyclic tropospheric ozone formation components) wasn't going on down below?*

Respondent: *I think there was some, but like not as much as compared to up there, I feel like when the cars emit the exhaust like all the different pollutants are around you, they tend to like go upwards and they don't really just sink to the ground you know, I mean like all the atoms and molecules if they flow upwards automatically then there is a denser population of* *each of the different molecules, atoms up high where there are like they are there too.*

Although students utilized this misconception to discuss general atmospheric chemical reactions not only for pollutants (including NOx and VOC's) but for gases, there is a strong possibility this misconception is associated to the large abundance of ozone found "high" in the stratosphere. For example, this quote illustrates that student #21 is connecting NOx and VOC's going up high and becoming "trapped."

<u>Interview #21:</u>

Respondent: I see the sun and I think about the gases going up and then how do they interact on the atmosphere.

…………………………………………………………………………………

Interviewer: Okay. So what's causing I guess these concentrations of NOx and VOCs to go straight up and get trapped in this layer rather than like reacting in our box lower (stated previously by respondent), does that make sense?

Respondent: Oh yeah, you mean like why they are going to up high.

Interviewer: Yeah like why don't they start reacting like down lower at all?

Respondent: Because the VOCs and NOx they are gases, like every time they have been made, they just go up to the atmosphere…

The majority of the students who modeled this misconception also had the lowest understanding of general ozone concepts in accordance to the qualitative rubric, Table 3. This further indicates that this misconception may strongly correlate to the significance of the ozone layer as students in this lowest category believed that ozone was only formed with one mechanism. While there were general chemistry concepts not pertaining to ozone that were discussed throughout the interview, students were given the precursor that the interest of the interview was to extract information regarding ozone formation. Therefore, students may have used this misconception for general gases, but ultimately it was within the context of ozone.

CD #3: Students fail to differentiate ozone's role as a greenhouse gas versus ozone's harmful role as a component of smog in the troposphere and its protective role in the stratospheric ozone layer

In many cases, students' inability to thoroughly explain the processes of ozone formation were likely due to the many pre-existing misconceptions that they bring with them to class regarding general ozone concepts. These misconceptions appear to stem from students' life experiences, and were frequently used in their explanations of ozone formation, i.e., CD#2. Therefore, as students attempt to explain a new concept, they rely heavily on these conceptions. For topics relating to atmospheric pollution, the foundation of many students' mental representations includes aspects of global warming and the greenhouse effect.

The ozone molecule in itself is a greenhouse gas. It absorbs some IR radiated from earth's surface and this absorption then heats the atmosphere and acts as a thermal blanket around the globe. However, the ozone molecule serves distinct atmospheric roles separate from its role as a greenhouse gas; a harmful role as a component of photochemical smog in the troposphere and a protective role in the stratospheric ozone layer. This was one of the most common set of concepts that students took out of context to aid in justifying their mental representation-- 20 of 44 students linked ozone formation to the greenhouse effect incorrectly in some way. Some of their statements exhibited a highly erroneous mental model, while in other cases the concepts articulated were true if they were considered and scrutinized separate from the interview context. In either case, when their conceptions of greenhouse gases were used to explain ozone formation, students' conceptions would become incorrect.

The example below illustrates how students have incorporated the greenhouse gas effect into their notion of both how ozone is formed and what effects it has in our atmosphere. Student #35 in particular utilizes the greenhouse effect as an explanation of how ozone is a negative proponent in our atmosphere.

Interview #35:

Respondent: It's [ozone] a bad thing because formation of ozone makes it harder. Ozone is a bad thing because it creates like a layer that makes it harder, it's with the warming of the earth like it makes it harder for the earth to reflect its heat back to space so it warms, it kind of like acts like a lid that's why on earth it's becoming warmer in certain places because there is like a high concentration of this ozone layer then it makes it harder for earth's surface to reflect its heat back to space.

Interviewer: Anything else about ozone that you would tell somebody who didn't know about any of this?

Respondent: There are ways to prevent it I think.

Interviewer: How is that?

Respondent: With this diagram like the NO_x *and VOC diagrams it helps pinpoint like what exactly you need to do to reduce ozone.*

Student #35 acknowledges key components of ozone's atmospheric roles within their response. First, they recognize that ozone can be bad (tropospheric layer role) in the first line and continue on to incorporate the concept of the ozone layer (a stratospheric layer component). While these are both accurate elements of ozone's role in each atmospheric layer, they incorrectly link aspects of the greenhouse effect to justify these atmospheric roles that ozone has. For example, when given the opportunity to justify their reasoning, student #35 incorporates the warming of the earth, a greenhouse gas effect concept, into their explanation of why ozone is bad. While this statement may contain some truth, it is not the correct reasoning to describe why ozone is negative in context of tropospheric air quality.

Moreover, toward the bottom of the quote, student #35 states that a way to prevent this warming from occurring is to utilize a NOx-VOC diagram which pinpoints exactly what needs to occur to reduce ozone. Once again, if taken out of context, it is correct to indicate the use of such a diagram to reduce O_3. However, this student's lack of strong conceptions caused them to incorrectly link this NOx-VOC diagram to preventing the warming of the earth rather than correctly connecting it to the control of high tropospheric ozone concentrations in order to prevent severe health implications.

In the quotation below, student #30 first intertwined the separate concepts of a large abundance of both ozone and greenhouse gases into one location: the stratosphere. Secondly, they confused the effect of ozone in the stratosphere with as a greenhouse gas. Although they correctly recognized ozone as a positive attribute for its function of "blocking" sunlight from getting to lower atmospheric layers, they incorrectly mistook the greenhouse gas effect's concept of increasing temperatures for the actual negative human and environmental implications of the ultraviolet radiation.

Interview #30:

Interviewer: Does ozone ever reach a max or is it like highest like--?

Respondent: Right in the stratosphere I think that's where it is at.

Interviewer: What do you mean by the stratosphere?

Respondent: That's like the point in the atmosphere where all the greenhouse gasses are and -

Interviewer: Why do they remain there?

Respondent: Because that's like a point where they are like at equilibrium or they can't escape and they can't release back to the earth.

Interviewer: How come they don't go down or move up?

Respondent: I am not sure.

Interviewer: Okay. So they are just like stuck there?

Respondent: Not stuck but for the most part they just can't join up there.

Interviewer: Okay. And is that a good place for them to be or?

Respondent: Yeah, because they block sunlight from getting to the earth which causes the earth to heat up.

Student #30 indicates that ozone reaches a max concentration in the stratosphere, which they then define as the point in the atmosphere where all the greenhouse gases are. This student incorrectly overlapped the separate functions of ozone as a greenhouse gas and stratospheric ozone into one key location. Student #30 creates further incorrect conceptual links between the greenhouse effect and the role of stratospheric ozone at the end of their response stating that the gases in the stratosphere "block sunlight from getting to the earth, which causes the earth to heat up."

Unlike the previous examples, student #27 does not only conflate the effects of ozone’s role as a greenhouse gas with its main role in the troposphere and stratosphere. Instead, this student relies entirely on the concept of the greenhouse gas effect as the foundation for the formation of ozone, incorrectly stating that ozone is formed by greenhouse gases.

Interview #27:

Respondent: Yeah like the ozone is like higher up in the atmosphere and it like reflects, but it’s like created because that absorbs things that come off the earth kind of.

Interviewer: The ozone does?

Respondent: Yeah or it’s like created by things that are absorbed out there, so I think that higher it would go, the more ozone would be there.

…………………………………………………………………………………

Interviewer: Okay. What is ozone? Like how would you explain ozone to somebody?

Respondent: I should say it’s probably like formed by greenhouse gases that are absorbed from the earth and then reflected back down on to it.

Student #27 incorporates the notion of more ozone higher up, a correct aspect of ozone’s stratospheric role, into their response of moving their hypothetical box into different altitudes. However, this student also indicates that higher in the atmosphere, ozone reflects and absorbs things that come off of earth. This is not one of ozone’s roles in the troposphere or stratosphere, but rather an incorrect conceptual link created by student #27. Furthermore, this student highly uses the idea of greenhouse gases as a crutch in their overall model of ozone as they believe ozone to be formed by greenhouse gases.

Because of their pre-existing conceptions, in the absence of adequate information students may find it easier to comprehend ideas by linking them to the greenhouse gas effect and global warming. The existence of overlapping concepts facilitates this; knowledge of the greenhouse effect requires the incorporation of key concepts like wavelength dependent radiation, temperature effects, and the role of ozone as one of the main contributing greenhouse gases. Many of the same topics appear within varying ozone formation conceptions, and students may then consequently not only conflate these environmental issues but also find the greenhouse gas framework provides more easily relatable content. Linking the greenhouse gas concept to other ozone subject matter allows students to identify with atmospheric content in a context they are familiar with. For example, the greenhouse gas effect is discussed in media and politics as a general environmental concern.

CD #4: Students fail to differentiate *effect* of UV radiation in stratosphere and troposphere.

Students were generally able to link sunlight to the formation of ozone, but their lack of understanding how sunlight drove that process appears to have played a major role in their overall low comprehension of the material. Rather than comprehending that through the absorption of O_2 and O_3 almost all of the solar UV light is attenuated in the stratosphere, students believed there to be a sufficient amount to photolyze molecules in the troposphere. The fundamental chemical role of photolysis was ignored by the majority of interviewees; they could not form a direct link between ultraviolet radiation as the source of stratospheric ozone and new knowledge gained.

Interview #37:

Respondent: (looking at reaction sheet and figure 1) Further down this chart, we have the equation NO2+HV, I forgot what HV actually stands but, basically it's sunlight or UV, goes to NO+O so it breaks NO2. And further down this chart, we have looks like NO2 that's being formed throughout some of these reactions. Sunlight, it represents HV coming in breaking NO2 apart to, result in O3.

Student #37, like majority of the students with this conceptual difficulty, believed NO2 to be photolyzed by ultraviolet radiation in order to form (tropospheric) ozone. Their response indicated that, when considering the tropospheric ozone figure and their associated reactions, UV broke apart NO_2 to eventually result in O_3. While this difficulty may appear minute in the big scheme of student understanding of ozone formation, this concept proved to pose more problematic the further embedded it was in their mental models, as illustrated with the following interview.

Interview #9:

Respondent: [Ozone is good] because it blocks UV-Cs which are really strong ultraviolet radiation which can actually break apart atoms or chemical structures…We do want that in the upper atmosphere. But in the lower part of the atmosphere, it's not good because O3 doesn't get broken down through the UV-C rays because they don't make it that far. So they actually get - so then you have O3 in the lower part of the atmosphere which isn't good to breathe because we learned in class that O3 is bad for your lungs really.

……………………………………………………………………

Respondent: If the box was in this room, there wouldn't be a whole lot of ozone formation because there is very little light and I believe light is one of the key ingredients to ozone formation because it's not formed through metabolic processes, or it's *actually formed through photo, light is I believe the primary ingredient for ozone creation.*

Interviewer: So when you say that we don't have light it's because --

Respondent: No, not light but UV-C radiation I guess from the sun.

Student #9 incorporated the essential role of UV radiation into their description of ozone, including the breaking apart of chemical structures and that UV rays do not reach the troposphere for the most part. This was indicative of the first three lines and lines five and six of their response. However, toward the end of student #9's quote, this student also articulated the erroneous concept that ozone in the troposphere requires UV radiation in order to form. These contradicting notions illustrate the difficulty many students have in incorporating new material (ozone formation in two atmospheric layers) to fundamental conceptions. For, many of the students in this conceptual difficulty category associate UV rays not only with ozone's atmospheric roles, but sunlight as well, which they strongly connect to the formation of ozone. Furthermore, Student #9's discussion of how UV rays interact with ozone molecules does not seem to reflect a true understanding of ultraviolet radiation's role in the process of photolysis, nor of how UV rays contribute to ozone formation. The mention of UV rays breaking down molecules is an accurate portrayal of how photolysis occurs, yet the student associates its significance with the destruction of tropospheric ozone rather than as a source of its formation.

Example of conceptual difficulties combined & modeled in one mental representation:

Many of the students who demonstrated one of the areas of conceptual difficulty described above exhibited more than one. Students' mental models typically became further complicated with the addition of more conceptual difficulties. With a low existing conceptual understanding of ozone formation, there was a declining progression of complete and correctness associated with students' mental models when multiple conceptual difficulties were incorporated. Those students who demonstrated multiple CD's were typically toward the lower spectrum for the conceptual understanding of ozone formation, as might be expected. The following interview is an example of how distorted a students' mental representation of ozone formation can become when incorporating multiple conceptual difficulties.

Interview #20:

Respondent: Since my box is on the ground I don't know if there would be any ozone concentrations in my box but if it was up higher, like hundreds of meters there might be reactions going on at that point.

Interviewer: How can there be no reactions in ozone on the ground?

Respondent: Because, well that's a difficult question. If we are up higher things are rising, and lighter things are rising because they are lighter and gravity pulls things down. So I am guessing emissions are something that floats up because they are a lighter molecule. And that's why there would be O_3 I mean O_3 is lighter than oxygen, it is lighter than oxygen because that makes up for atmosphere. So oxygen is kept in by our atmosphere and that's I mean that's why there wouldn't be O_3 in my box because there is because it's too light and it floats up.

Student #20 incorporated the misconception of pollutants floating up to a higher altitude into their mental model. They conceived that because emissions are a lighter molecule and therefore float upward, ozone molecules would follow the same line of reasoning. Although there is an implied association, this student never actually stated the relationship between emissions and ozone molecules. Further exploration in their mental representation of ozone formation indicated that they incorrectly justified that an ozone molecule was lighter than an oxygen molecule in order to rationalize why concentrations weren't present near ground level. Their inability to explain the leap from no ozone near the ground to a sudden presence of ozone higher in altitude caused them to incorporate not only notions of a "light" ozone molecule but aspects of the greenhouse effect as well, shown below.

………………………………..Interview #20 continued…………………………

Interviewer: *I was just wondering are there any key components that, you know, have to be there or something for ozone formation to take place because you said it's most abundant, or highest in the highest layer. So I didn't know if there was something that either disappeared out of the box or all of a sudden got added to the box like up in the highest layer that caused all of this O_3 production?*

Respondent: *Well our sun gives us, emits radiation or energy to the earth and the earth surface then reflects the energy and radiation back up and it's then, it's then captured in one of the atmospheres, the energy is captured in one of the atmospheres. Because it takes on a different form from the actual radiation from the sun, it's able to capture it when it bounces off the earth and there is where you are going to have oxygen, I mean O_3 forming I guess, in that layer where that's [ozone] getting the energy. So maybe that [ozone] takes the energy bouncing off the earth to keep it there and get it there.*

Interviewer: *Is that a good thing that energy is bouncing, a good thing that I guess the energy or rays are bouncing off?*

Respondent: In what respect.

Interviewer: Do we want that or is that a negative thing, or…?

Respondent: Well I think we want to keep, I mean we want it, we have to have it for earth to survive and so yeah we want it, but we also, I mean I don't know how to say this, but you know not too much but because we have emissions and other things floating around if we had too much sun sometimes it's a bad thing I guess. It's sometimes clouds are good to have and they block some of the sunlight and that allows us to not have so many emissions reacting with heat and stuff. So yeah, I mean but we need it but I don't know how much we need or how to say that.

Student #20 incorrectly adds the greenhouse effect to their already flawed "lighter molecule" logic as further explanation for the large ozone abundance found in the highest atmospheric layer. Details of their reasoning revealed they believe the energy created and captured during this process to be involved with the formation of ozone. They correlated the reflected energy with sunlight and deemed it negative for emissions to react with this heat. Their reasoning then follows that the less sunlight, and therefore energy, would allow for less emissions reacting. This student mentions that it's negative for too much heat (sunlight) to react with emissions, however, they don't state why this is a detrimental concern or in what atmospheric layer this occurs. The following excerpt provides additional details to this incomplete conception.

…………………….……Interview #20 continued…….................................

Interviewer: So is ozone a positive or a negative thing?

Respondent: It's a positive thing. It keeps oxygen in, and I mean it's not the layer that keeps oxygen in, but it's definitely keeping everything in that we need to survive.

Interviewer: So you said that the sun could speed up the process..?.

Respondent: Could speed up the process [of] emissions reacting with each other to make pollutants that then go into the ozone and deteriorate it. So the pollutants would be bad if they entered the ozone.

Interviewer: Because they are making the ozone go away?

Respondent: Yeah and they are filling it with things that aren't necessarily supposed to be there in the amounts that they are in.

Interviewer: Okay so what happens when the pollutants are there then?

Respondent: Chemically?

Interviewer: Yeah, either one.

Respondent: I don't know. I think it's creating holes in the ozone and that's allowing certain rays from the sun that are harmful into the earth, so I am guessing the ozone is also blocking some things or it's not allowing some certain sun rays, UV rays, I don't know what they are called, if they are ultraviolet rays or what, but it's keeping something out and the pollutants are a part of that I think.

Although this quote contributes a descriptive explanation for the negative implications of emissions reacting with heat, student #20 actually embedded and conflated two separate functions of emissions (within the realm of ozone) into their rationale for the process of ozone formation. They confused how ozone formed in the stratosphere with pollutants deteriorating the ozone layer and the importance of the ozone layer. Their logical justifications that incorporated emission and pollutant topics overlapped crucial aspects of ozone formation and ozone depletion. This affiliation of ozone depletion with ozone formation follows previous research trends which determined that students integrate aspects of ozone depletion into multiple atmospheric chemistry subject matter. These include UV radiation (Groves and Pugh, 2002), and the climate change topics of global warming (Rye et al., 1997) and the greenhouse effect

(Andersson and Wallin, 2000; Boyes and Stanisstreet, 1998; Dove, 1996; Groves and Pugh, 1999; Meadows and Wiesenmayer, 1999).

There is a lack of conceptual understanding found in the above quotes, not only for the individual components but how all of these elements interact with each other. Student #20 incorporated many aspects into their mental model that are a part of ozone formation, including sunlight heat energy, an area of large ozone accumulation higher in the atmosphere and the importance of pollutants and emissions involved in this process. However, this student was unable to correctly associate these atmospheric concepts, which leaves an incomplete model of ozone formation. Therefore, because of the failure to distinguish between key components within the overall context of ozone, they incorporated contradicting beliefs and their model lacked appropriate and logical justifications, multiple conceptual difficulties were intertwined into their model, including: the greenhouse effect, emissions floating up high and distinguishing between ozone's function in the ozone layer (stratospheric layer) with its function in the tropospheric layer.

Originally, student #20 associated ozone with emissions, implying a vague causal relationship. However, their model slowly evolved this relationship into pollutants negatively affecting ozone by creating holes in the ozone which allow UV rays through, indicating that ozone was no longer reliant upon these emissions in order to form. Out of context, aspects of these relationships remain, yet because the model revolved around overlapping locations; it was unclear where the boundaries of these relationships occurred. Furthermore, a common theme found throughout their model was the importance and implications of sunlight and the energy that it created and caused; this was a recurring trend amongst the students interviewed.

In an attempt to make sense of knowledge they have already attained with new knowledge gained, individuals incorporate fragments of correct and incorrect information into their mental models. However, ozone formation appears to be an overly difficult concept to grasp. No student interviewed in this research study was able to correctly explain the process of ozone formation (whether due to one of the four prominent conceptual difficulties or due to other issues with the material). Therefore, the majority of the mental models regarding this topic were not only incorrect but incoherent and ambiguous.

VI. CONCLUSION

Many students did not understand the process of ozone formation; their low understanding and attributing misconceptions may be complicated by the abstract nature of atmospheric studies. The confusion associated with such a complex topic can lead to conceptual difficulties which then hinder further comprehension of the subject matter. The four ozone formation conceptual difficulties identified in this study are: students fail to differentiate the function of ozone in the ozone layer (stratosphere) with functions in the tropospheric atmospheric layer, students fail to differentiate ozone's role as a greenhouse gas versus ozone's harmful role as a component of smog in the troposphere and its protective role in the stratospheric ozone layer, students fail to differentiate the effect of UV radiation in the stratosphere and troposphere, and the misconception that pollutants and gases float up and react up high. As a result of these conceptual difficulties, students are unable to form correct and coherent models regarding ozone formation. They instead form alternate or incorrect links in order to connect missing pieces of knowledge that doesn't otherwise logically fit into their mental models. These four conceptual difficulties are likely connected and/or can be used to explain other atmospheric chemistry topic difficulties as well.

Although a low level of collegiate student conceptual understanding for ozone formation was determined, more research is necessary in order to obtain the substantial information required for conceptual change to occur. The data found in this paper can be used as a baseline for other research on collegiate understanding of ozone formation. Future research may incorporate additional procedures and approaches as a means of measuring the conceptual understanding of this topic, including a larger sample size and integrating the opportunity for students to visually map out their personal ozone formation mental models in the interview process. Incorporating the non-linearity of ozone topics into the investigation can provide vital insight and allude to additional ozone conceptual difficulties, which can be extended to other atmospheric chemistry-related misconceptions. Using pre- and post-instruction interviews may help gauge students' conceptual improvement. Finally, it would be of interest to consider and assess atmospheric chemistry teaching approaches, specifically active collaborative strategies that are non-lecture based and interactive techniques. Using a traditional lecture-based learning atmosphere as a control, the effectiveness of multiple learning environments and strategies in atmospheric chemistry can then be considered and compared.

(CHAPTER 2 FIGURES):

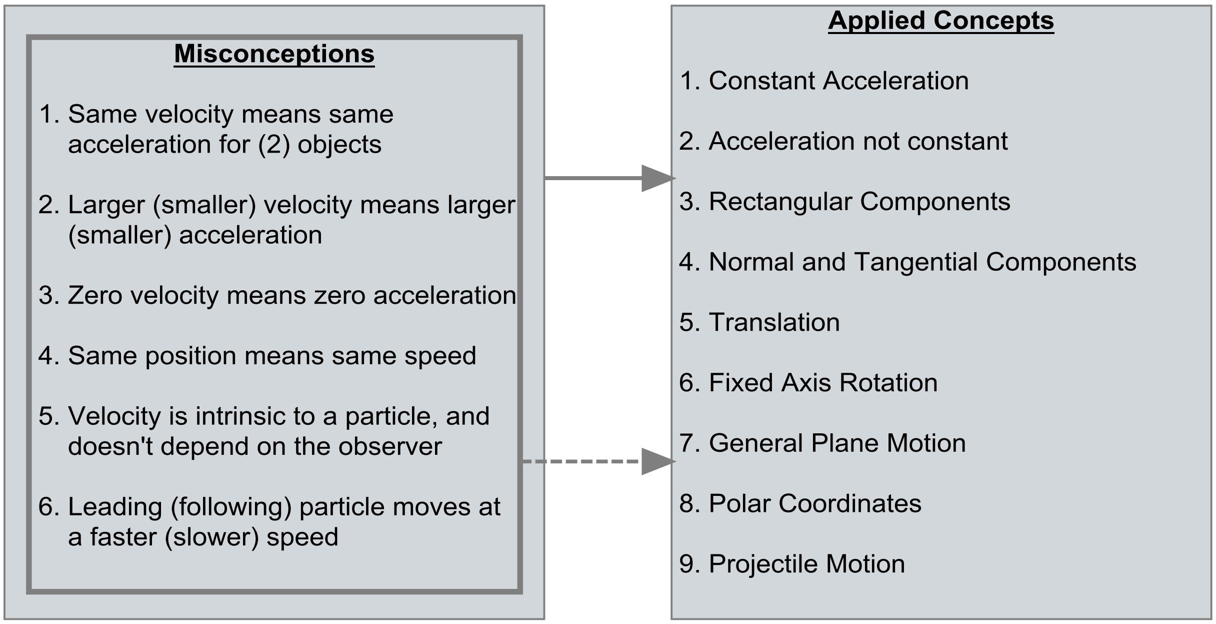

FIGURE 1. CONCEPTUAL CHANGE DIAGRAM REPRESENTING STUDENTS' INTERACTIONS WITH KINEMATIC PHYSICS SUBJECT MATTER (Aguirre, 1988; Trowbridge and McDermott, 1980b, 1981b)

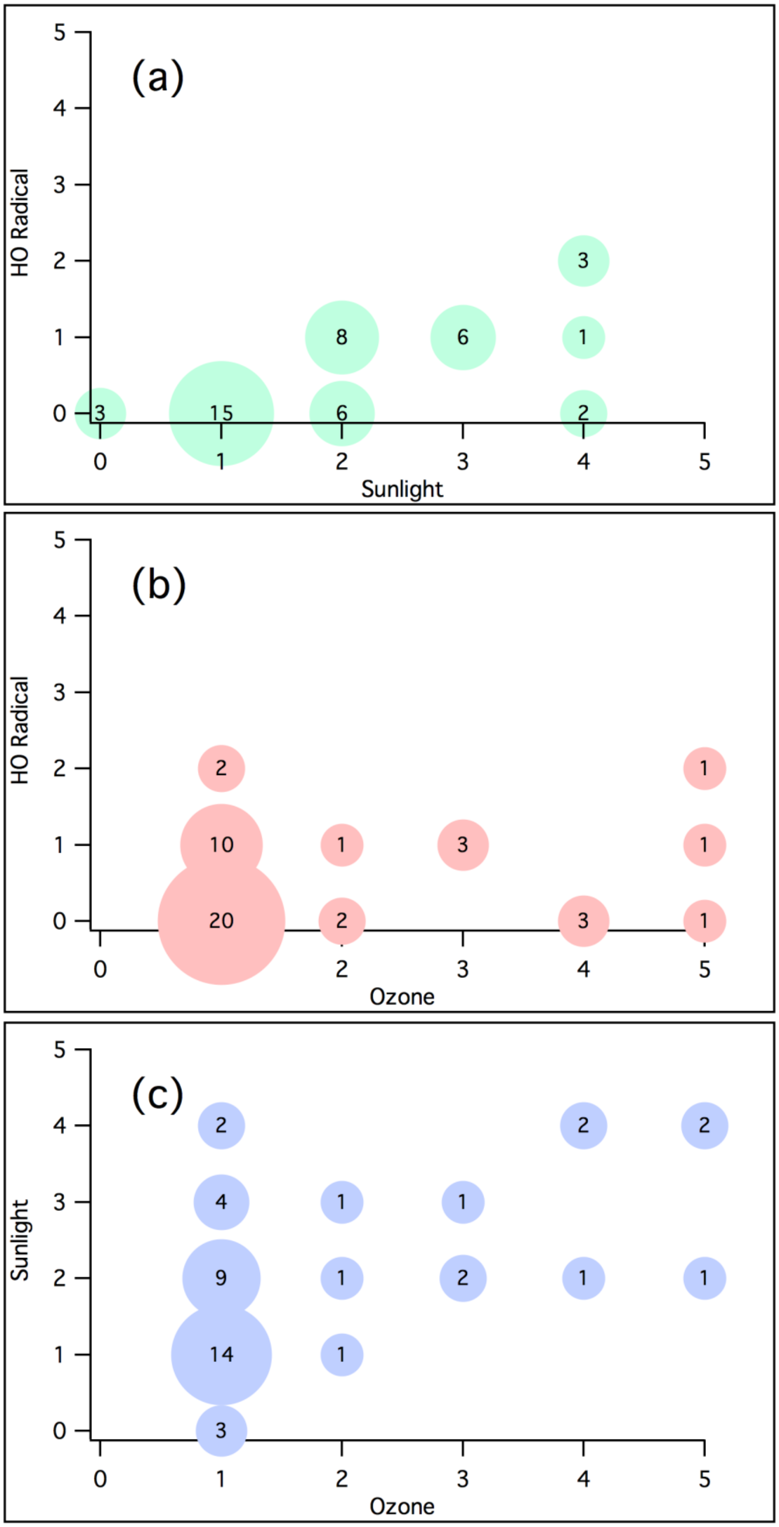

FIGURE 2. (a) SUNLIGHT-HO RADICAL RUBRIC TOPIC POINT COMPARISON, (b) GENERAL OZONE CONCEPTS VERSUS HO RADICAL RUBRIC CATEGORY POINT COMPARISON, (c) GENERAL OZONE CONCEPTS AND SUNLIGHT RELATIONSHIP IN REGARDS TO THE RUBRIC POINT DISTRIBUTION

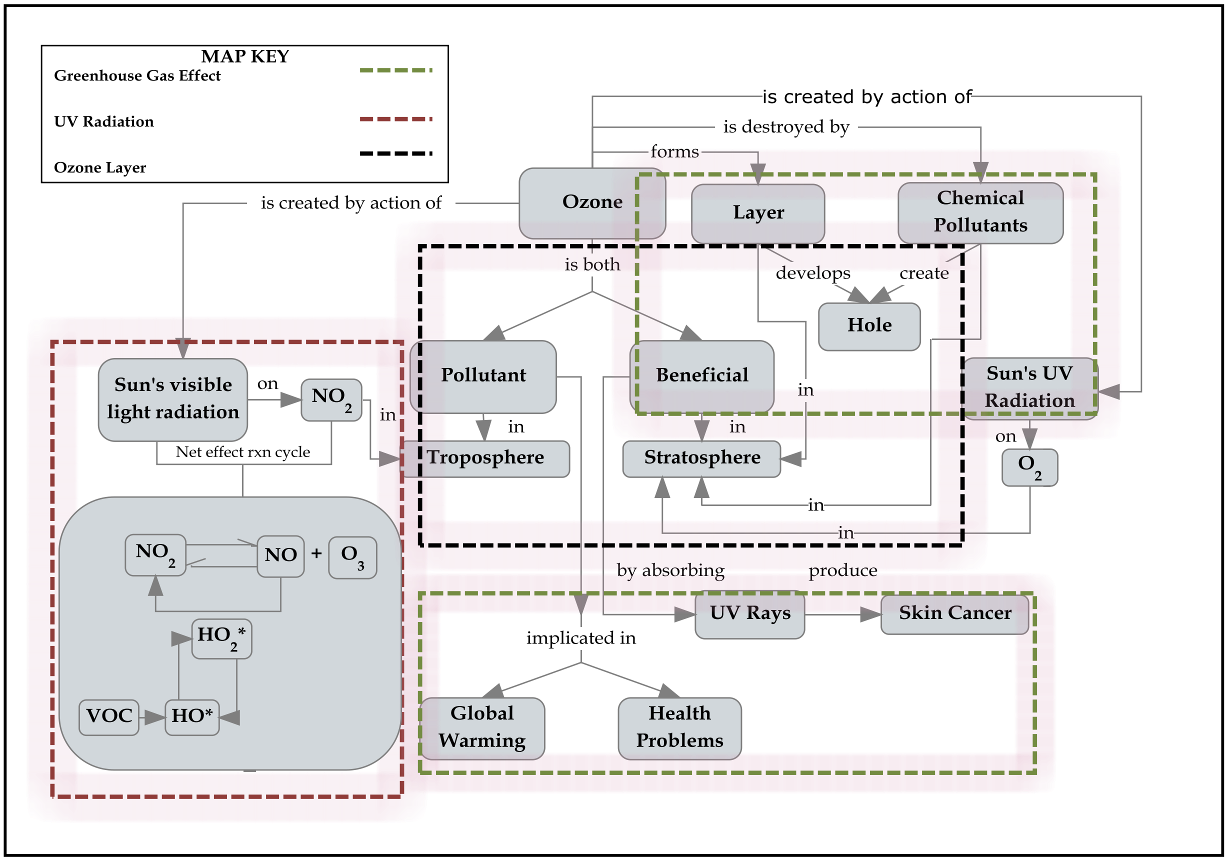

FIGURE 3. REPRESENTATIONS OF OZONE FORMATION

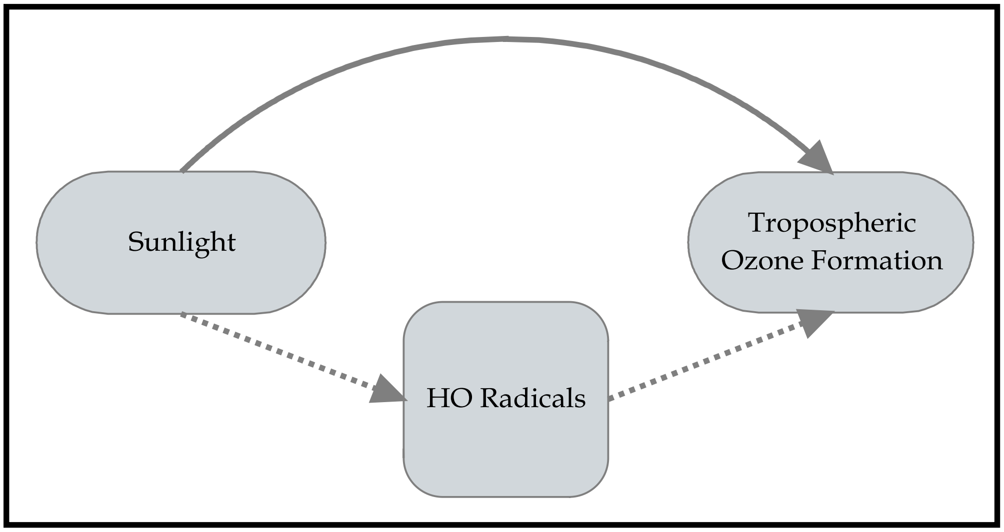

FIGURE 4. SIMPLISTIC MENTAL REPRESENTATION WHICH ILLUSTRATES THE ONLY DIRECT PATHWAY THAT STUDENTS WERE ABLE TO CORRECTLY LINK.

CHAPTER 3: Additional Results

The main results that were acquired throughout this study are presented in chapter 2; this chapter presents in tabular form some additional results from the interview protocol. These extra results are presented with minimal analysis; they were not critical to this investigation but may prove useful for future researchers. There were various student answers to the interview protocol questions. The following tables detail which responses were most recurrent throughout the interviews and quantify the number of students who responded with the correlating statement.

Table 6 presents the student responses to atmospheric vocabulary topic questions and demonstrates the overall result of students' difficulties with simple, fundamental environmental terminology. Students were asked to define NO_x and explain the components that characterize it. Approximately a quarter of the students interviewed believed NO_x to be a combination of NO and NO_2. Around half of the students associated the subscript 'x' with NO and/or NO2, however, a quarter of the interviewees described 'x' as a place holder for any arbitrary number, not necessarily connected with NO or NO_2. There were various responses to the chemical nomenclature of NO and NO_2 as well as their roles in our atmosphere. Many students went back and forth on these terms, confusing and intertwining them, such as the overlap of the term nitric acid. There was one typical straight-forward, non-elaborated response associated with each of the student descriptions of hydrocarbons, VOC's and smog. These examples include: several students noted that a hydrocarbon has hydrogen and a carbon, students recited the acronym VOC as a volatile organic compound, and a the common definition for smog was smoke and fog.

TABLE 6. STUDENT RESPONSES TO ATMOSPHERIC VOCABULARY TOPIC QUESTIONS

Topic Questions	Student Responses	#
What is NOx?	Combination of NO and NO_2	14
	It is a pollutant	5
Where does it come from or how is it formed?	Formed from emissions	9
Does the subscript 'x' hold any significance?	X is a variable (place holder for any number)	16
	Doesn't know what significance is	9
	X means <u>*both*</u> NO and NO_2	5
	X can mean NO <u>*or*</u> NO_2	17
What is NO?	Nitric Oxide	3
	Nitrous Oxide	10
	Nitrogen Oxygen	2
	Nitrogen Oxide	4
	It is required to produce O_3	4
Does it have any positive/negative significance in our atmosphere?	It is bad because it is a greenhouse gas	2
	It is a pollutant	12
Where does it come from?	From car emissions	8
What is NO_2?	Nitric Oxide	1
	Nitrogen Dioxide	2
	Nitrous Oxide	3
	Does not know what NO_2 is	6
Does it have any positive/negative significance in our atmosphere?	It is a pollutant	7
	It is bad because it is a greenhouse gas	3
Where does it come from?	From emissions	5
What is a hydrocarbon?	It has a hydrogen and carbon	16
	Doesn't know what it is	13
	It is an organic thing	3
What is the purpose of a hydrocarbon?	Can use it for energy	4
What is a VOC?	Volatile Organic Compound	19
	It is very dangerous, reactive and bad	6
	Doesn't know what it is	7
	It is a pollutant	5
Where does it come from or how is it formed?	From trees	18
	From cars/industry	18
	From paints	6
	From organic things	6
Can VOC's be controlled?	They can be controlled with cars	2
	Not all can be controlled (trees)	3
What is smog?	Smoke and Fog	10
	Layer of air (cloud)	6
	Smog and O_3 are interrelated	12
	Comes from emissions	7
	A group of pollutants	9

Table 7 presents the frequent student responses and descriptions students gave to describe electrons and protons and their roles during chemical reactions. Most students were upfront with their anxiety and feeling of being overwhelmed at the prospect of having to answer chemistry questions. A main verbalized concern was that the chemistry course was taken so long ago and they didn't feel comfortable with the information. Over half of the students interviewed believed electrons to be negatively charged particles and protons to be positively charged particles. While approximately half of the students thought that electrons float around the outside of the atom/nucleus, only sixteen students considered protons to be located in the nucleus. Student responses varied less answers were given when inquired about the roles of these elementary particles. For example, although some students acknowledged that electrons help bond molecules together they were not clear on the role of a proton or the relationship between a proton and electron. There were a handful of students that used a magnet analogy to describe their interaction.

TABLE 7. ELECTRON AND PROTON STUDENT RESPONSE COMPARISON

QUESTIONS	ELECTRONS	#	PROTONS	#
What are they?	Negatively charged particles They have shells	23 7	Positively charged particles # protons never change	28 4
Where are they located?	Float around outside of atom/nucleus Inside of the atom Are in a cloud	23 4 5	In the middle, in the nucleus	16
Do they have a particular job?	Help hold/combine molecules	4	Keep electrons around Determine the specific weight of atom Balance out atom	2 2 4
Do they play any role during a chemical reaction?	They lose energy Molecules share electrons Help bond atoms together	4 7 11		
electron-proton relationship described using magnet analogy				8

Table 8 summarizes the mechanisms that students utilized to describe and explain what a chemical reaction was to a person with no chemistry background. There were four main categories that students fell into when describing this process. There were some students who used cooking analogies to explain the interaction between molecules, including one student who described the interaction of atoms like stirring or mixing a cake together. Although students were particularly asked to imagine a person with no chemistry background, there were still a handful of students who included chemistry terminology into their response. For example, various students used the term atoms and molecules with some students explaining the process as compounds reacting together to form new compounds or involving reactants that convert into products. Other students incorporated the concept of bonding into their explanations (another chemistry term) to include the notion of one reactant having to be stronger in order to break a bond of something. Lastly, there were students who used collision analogies to explain the process of a chemical reaction. This included using physics concepts or ideas of things flying around and hitting each other. Perhaps the most interesting was a student who reflected on a game they had growing up with a velcro mitt on their hand that caught and stuck to a velcro tennis ball when thrown at it.

TABLE 8. MECHANISMS STUDENTS UTILIZED TO DESCRIBE AND EXPLAIN WHAT A CHEMICAL REACTION WAS TO A PERSON WITH NO CHEMISTRY BACKGROUND

Mechanism Used to Explain What a Chemical Reaction Is	#
Cooking Analogies	6
Chemical Terminology	23
Chemical Bonding	5
Collision Analogies	8

Many students incorporated the concept of energy being required for different chemical processes to occur into their responses to general chemistry questions (regarding the relationships of ozone formation reactions), highlighted in Table 9. There were twenty-three various student responses that used the term “energy” including: needing energy for reactions to occur, energy is either used or created during a reaction, and energy cannot be created or destroyed. Some of those students went on to further incorporate and associate “energy” into their chemical process explanations. One example many students associated energy with was chemical bonding. There were several students who stated energy was required to break a chemical bond. Stability was the other example students used energy to explain, including the notion that it takes more energy to break apart a stable molecule versus an unstable one.

TABLE 9. TOPICS STUDENTS ASSOCIATED ENERGY WITH

Energy (23)	#
Chemical Bonding	18
Chemical Stability	11

Finally, Table 10 represents the student confusion that is associated with earth's atmospheric layers. Students had both a hard time recalling the correct number of atmospheric layers and frequently mixed up atmospheric layer names and/or their location. Describing the different aspects of ozone and its roles in the atmosphere was especially difficult for those students who exhibited this tendency. Students would switch the atmospheric layer terminology they were using throughout the interview and it would be unclear if they just confused words or they didn't understand the concept of the atmospheric layers in general. One common example is the students who switched the stratosphere and troposphere locations.

TABLE 10. STUDENT CONFUSION ASSOCIATED WITH EARTH'S ATMOSPHERIC LAYERS

Topic of Atmospheric Layer Confusion	#
Students confused the number of layers	6
Students confused the atmospheric layer names and/or location	12

CHAPTER FOUR: Teaching Implications

There are several implications for teaching based on the findings in this study. Although students can appear to sufficiently learn material based on their exam scores, they can still maintain a flawed mental model of the overall conceptualization of ozone formation. They may utilize rote memory to correctly answer simplified questions relating to individual topics, like those found on exams. However, as our results indicated, if they are probed to explain or connect varied content relating to ozone, they link pieces of knowledge together in their mental models incorrectly. Therefore, it is necessary for instructors to be aware of the conceptual difficulties students enter classroom environments with in order to help students rectify them and initiate the process of conceptual change.

Many students with incorrect mental models are unaware that they exist and those who are aware are frequently unable to pinpoint their model's defects without assistance. Students may become overwhelmed, disengaged or mentally defeated (indicative from student interviews) if new information is too technical or complicated to fit into their existing mental models. They may be less likely to investigate material they don't understand from their peers or instructors for fear of incompetency, ultimately hindering their progress of learning. It may then prove helpful for instructors to be upfront about the difficulty of material relating to ozone formation and to more directly address the conceptual difficulties associated with it. For example, Koulaidis and Christidou's (1999) research suggested that students have difficulties understanding the conceptual distinction between ultraviolet and other forms of solar radiation. They proposed teaching this material by introducing crucial aspects of this conceptual difficulty that would emphasize these differences, to include:

1. "The conceptualization of the 'sunlight' as a spectrum comprising different bands of radiation of different 'character'" (pg 571) and
2. "The notion that different atmospheric gases absorb electromagnetic radiation at different wavelengths," (pg 571).

Although there may be some success in addressing large conceptual concerns early on, the material content found within ozone formation is exceptionally technical and abstract. Therefore, the intent of the following suggestions is to help students overcome learning barriers related to ozone.

Novak "found concept maps to be powerful tools to represent knowledge structures in all subject matter fields and for learners of any age," since 1975 (pg. 2, as cited in Novak and Gowin, 1984). Concept maps can both help assess students' basic understanding of ozone formation and also serve as an ongoing teaching tool throughout the learning process. Students can utilize them to organize information in a spatial way that makes sense to them and incorporate difficult material into their mental model slowly by building upon a simple foundation. If students are able to build new information around concepts they are already familiar with, it could help them reduce confusion; when there is less missing information in the model, students may create fewer incorrect links. Additionally, if students do create incorrect links in their mental models, professors can catch it early on and help realign them.

Another teaching suggestion to help students overcome their learning barriers is to create a conceptual framework that teaches the ozone formation topics in context of each other (stratospheric versus tropospheric ozone) so students are able to correctly overlap the appropriate material, while at the same time stressing the distinct roles of each concept involved with ozone formation. The students in this study frequently had difficulties correctly connecting aspects of ozone formation while demonstrating when and how concepts were supposed to overlap. Overlapping material content could help reduce gaps of confusion that students might otherwise fill with their own mental representations. One possibility which may aid in this notion of contextual learning and help students correctly overlap material content is to use visual aids that incorporate the various key locations and different functions of ozone onto one representation. For example, this might include a plot indicating the altitudes of the stratosphere and troposphere which also include the key atmospheric roles of ozone and their associated simplified chemical formation processes.

Instructors helping students to distinguish between similar (but distinct) ozone content may further facilitate students' abilities to correctly connect components of their ozone formation mental models. Some main concepts associated with ozone that could be formed into a conceptual framework to support these material differences may include:

1. <u>Stratospheric Ozone</u> is one of two mechanisms that form ozone. Located in the stratosphere and produced through the photolysis of oxygen molecules driven by UV light, it primarily plays a beneficial role by absorbing harmful UV radiation before it reaches earth's surface.

2. The Ozone Layer is the accumulation of stratospheric ozone, located in the stratosphere: it contains approximately 90% of atmospheric ozone.
3. Tropospheric Ozone forms with different mechanisms than in the stratosphere. Located in the troposphere, it contains approximately 10% of the atmospheric ozone, forming through the photolysis of an NO_2 molecule driven by photons in the visible & near-UV portions of the electromagnetic spectrum. It relies heavily on the regeneration of NO_2 through hydrocarbons and the highly reactive hydroxyl radical and functions as a secondary pollutant, where elevated concentrations cause severely negative impacts to humans and agricultural systems.
4. Ozone Depletion occurs when chemical compounds including chlorofluorocarbons (CFC's) reduce the ozone layer forming an O_3 "hole" and negative human and environmental impacts such as skin cancer can occur.
5. The Greenhouse Gas Effect refers to the ability of certain gases to absorb radiant energy. These greenhouse gases absorb long wavelength IR radiation from earth's surface that act as a thermal blanket by heating up the atmosphere and raising earth's surface temperature.

While the level of conceptual detail is considerably simple compared to its actual technical intricacy, the statements above represent the main points that students continuously intertwined.

The student mental representations that utilized the CD's (conceptual difficulties) for their foundation, especially those based on the greenhouse gas effect, suggest strongly that the media, current political issues, or other outside sources can greatly influence student thought and understanding about ozone subject matter. This is unsurprising, as these are frequently discussed topics in the popular media. It seems in many instances students incorporate information from these sources, as the abstract concepts in atmospheric chemistry appear to cause students to search for alternate methods of explaining complex phenomena. The majority of the subject material in engineering is tangible and typically accompanied with governing equations with solutions that are usually easier for students to visualize. Therefore, it is suggested that instructors relate the ozone formation topics they are teaching to a current environmental or political topic that students would be familiar with in their everyday life. Doing so may help students associate difficult, technical information they learn in a classroom setting and correctly apply it to and link information they already have from their everyday experiences.

Finally, creating an atmospheric chemistry model-interface easily utilized by collegiate students falls under the NSF grant #110822-001. A simple box modeling interface was created for use by the undergraduate environmental engineering course who was interviewed for the research in this paper. This interface was designed to be used in conjunction with an inquiry-based assignment in which students generated an individual hypothesis (without technical support) for reducing tropospheric ozone levels in an urban setting. They were then able to interact with the computer model by changing the initial NOx concentrations in order to test their hypothesis. The model would then calculate ozone as a function of time for ten initial VOC concentrations with the purpose of teaching the non-linear nature of ozone formation. General observations as well as the results tabulated in chapter 3 strongly suggest not only that the learning approaches discussed in chapter 1 can be applied to atmospheric chemistry but that a combination of such strategies may prove an effective proponent for conceptual change.

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APPENDIX A: INTERVIEW PROTOCOL AND MATERIALS

INTERVIEW PROTOCOL:

1. Can you explain what is happening in FIGURE 7.7?
   a. What do you see going on overall in the figure?
   b. Is there anything that stands out as crucial or important?
2. What is NO?
   a. Is there any positive or negative significance to NO in our atmosphere?
   b. Where does it come from?
3. What is NO_2?
   a. Is there any positive or negative significance to NO2 in our atmosphere?
   b. Where does it come from?
4. What is OH dot?
   a. Does the dot have any significance?
      i. What contribution does it have to the diagram or the rest of the reactions?

(Show complete list of all reactions):

5. Define a chemical reaction as if explaining to a friend who has no chemistry background.
   a. Do you picture anything in your head?
6. Looking at reaction (2) do the subscript two's and coefficient two represent the same thing?
   a. Why or why not?
   b. What is happening with this reaction?
   c. Can two subscripts replace the two coefficients on the right hand side?
7. Discuss the difference between a stable atom and an unstable atom.
8. Are the N_2 or O_2 stable?
   a. Are these easy or hard to break apart?
9. What are electrons?
   a. Where are they located?
   b. Do they have a particular job?
   c. Do they play any role during a chemical reaction?
10. What are protons?
    a. Where are they located?
    b. Do they have a particular job?
    c. Do they play any role during a chemical reaction?
11. Is there any correlation or relationship between reaction (4) and FIG. 7.7?
    a. If so, how?
    b. What does the hv mean?
    c. Why does reaction (4) include something outside the periodic table an reaction (2) doesn't?

12. Looking at reaction (5) it looks like an O_2 and an O combine to form an O_3 but what is the M?
    a. It doesn't look like to me it even reacted, is this true?
    b. Can we just take the M out of both sides of the reaction?
13. What does the arrow represent in a chemical reaction?
    a. Does the direction of the arrow carry any significance?
    b. Can there be more than one arrow present in a single reaction?
14. Can you explain in detail what a radical is and its purpose?
15. What is photolysis?
    a. How, if any, does photolysis affect ozone formation?
    b. Do any of the equations on the equation list represent photolysis?
    c. What is a photon?
16. What is a hydrocarbon?
    a. What is the purpose of a hydrocarbon?
17. What is a VOC?
    a. Where does it come from or how is it formed?
    b. Can VOC's be controlled?
18. What is NO_x?
    a. Where does it come from or how is it formed?
    b. Does the subscript 'x' hold any significance?
19. What is smog?
20. Is there a difference between smog and photochemical smog?
    a. If so, what is it?
21. Is there a difference between smog and ozone?
    a. What are they?

You might have to be a little imaginative for this next part…Imagine that you have an open box and you can put it wherever you want (inside, outside, on the ground, up high). At some point in time we take a sample from inside the box and we have a camera that can see at microscopic levels. What would be inside the box and what would we see going on?

22. So first, where do you want to put your box?
    a. What kind of things are in the box?
        i. Are they moving around?
        ii. Do they run into each other?
        iii. Are there reactions occurring?
        iv. Are there ozone concentrations inside the box?
23. What happens to the ozone concentrations if we move the box?
    a. Outside/inside?

    b. On the ground?
    c. In a city?
    d. Up high?

24. How would you explain ozone?
    a. Is ozone a good thing or a bad thing?
        i. If so, how do these differ and can you explain them?
25. Given the amounts of reactants, can the ozone concentration be predicted from reaction (1)?
    a. Why or why not?
        i. Can you walk through how the ozone concentration would be predicted?
        ii. Are there any circumstances that would change or affect this prediction?
26. Can ozone concentrations be predicted using FIGURE 12-4?
    a. Why or Why not?
    b. Should FIGURE 12-4 and reaction (1) give the same ozone concentration?
        i. Why or Why not?
    c. Who do you think would use FIGURE 12-4 and why?
        i. How would it help them?
    d. What does the bold line mean?
        i. Do we want to be on this line?

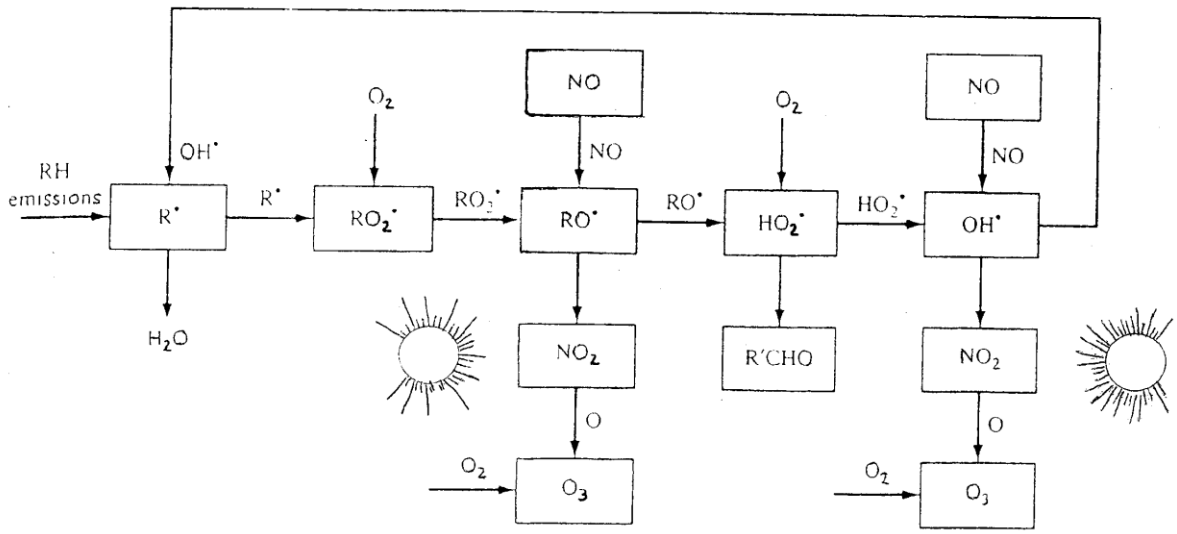

FIGURE 5. THIS FIGURE 7.7, EXCERPTED FROM THE INTRODUCTION TO ENVIRONMENTAL ENGINEERING AND SCIENCE TEXTBOOK (Masters and Ela, 2008, pg. 387), WAS PRESENTED TO STUDENTS DURING PROBLEM ONE OF THE INTERVIEW PROTOCOL REPRESENTING THE MAIN CYCLIC TROPOSPHERIC OZONE FORMATION COMPONENTS, BUT EXCLUDED THE ORIGINAL CAPTION.

LIST OF TROPOSPHERIC OZONE FORMATION REACTIONS PRESENTED TO STUDENTS DURING PROBLEM TWO OF INTERVIEW PROTOCOL:

$$\text{VOC's} + NO_x + \text{Sunlight} \longrightarrow \text{Photochemical smog} \quad (1)$$

$$N_2 + O_2 \longrightarrow 2\ NO \quad (2)$$

$$2\ NO + O_2 \longrightarrow 2\ NO_2 \quad (3)$$

$$NO_2 + h\nu \longrightarrow NO + O \quad (4)$$

$$O + O_2 + M \longrightarrow O_3 + M \quad (5)$$

$$O_3 + NO \longrightarrow NO_2 + O_2 \quad (6)$$

$$RH + OH^{\bullet} \longrightarrow R^{\bullet} + H_2O \quad (7)$$

$$R^{\bullet} + O_2 \longrightarrow RO^{\bullet}_2 \quad (8)$$

$$RO^{\bullet}_2 + NO \longrightarrow RO^{\bullet} + NO_2 \quad (9)$$

$$RO^{\bullet} + O_2 \longrightarrow HO^{\bullet}_2 + R'CHO \quad (10)$$

$$HO^{\bullet}_2 + NO \longrightarrow NO_2 + OH^{\bullet} \quad (11)$$

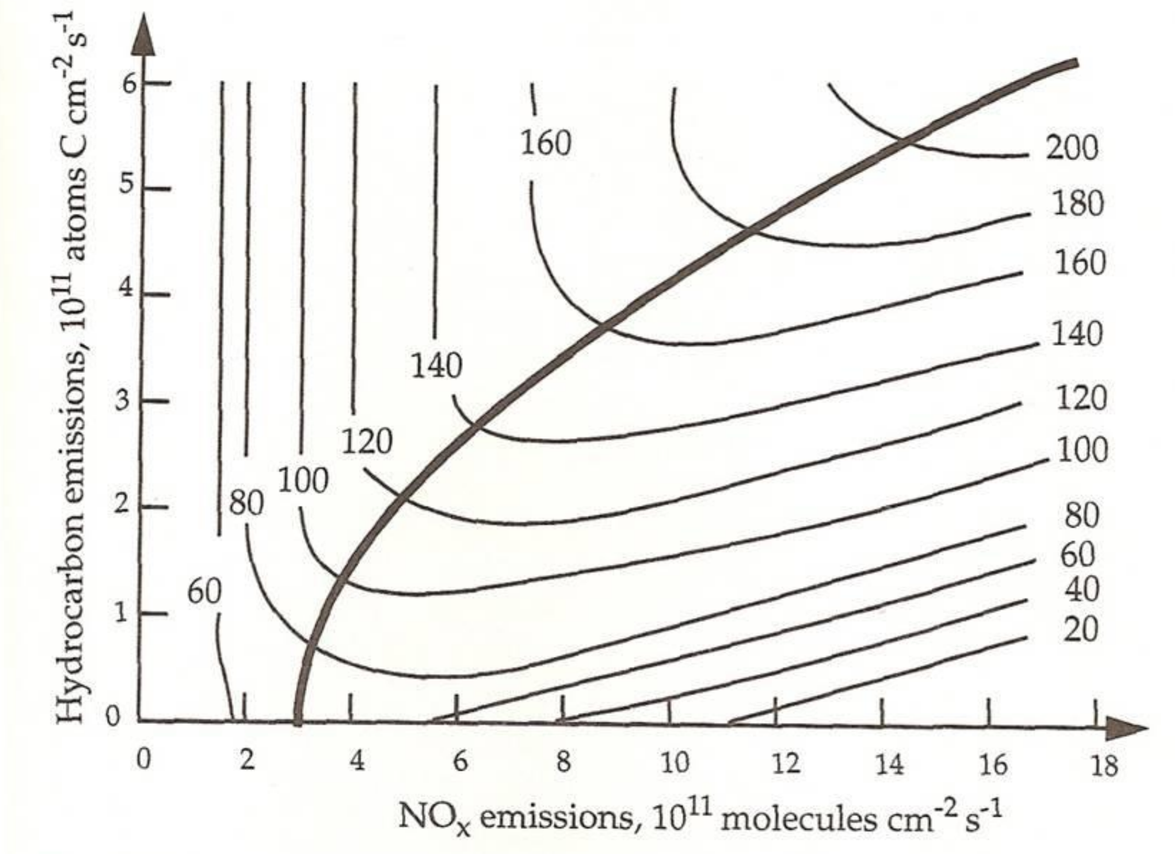

FIGURE 6. THIS FIGURE 12-4, EXCERPTED FROM THE SENSITIVITY OF OZONE TO NITROGEN OXIDES AND HYDROCARBONS IN REGIONAL OZONE EPISODES (Sillman et al., 1990), WAS PRESENTED TO STUDENTS DURING PROBLEM SIX OF THE INTERVIEW PROTOCOL REPRESENTS AN ISOPLETH DIAGRAM RELATING NOx, HYDROCARBONS AND O_3 PRODUCTION, BUT EXCLUDED THE ORIGINAL CAPTION.

APPENDIX B: QUALITATIVE RUBRIC AND ACCOMPANIED GRADING SHEET

TABLE 11. QUALITATIVE RUBRIC USED FOR CATEGORIZING BOTH STUDENTS' INDIVIDUAL UNDERSTANDING OF OZONE TOPICS AND OVERALL COMPREHENSION OF OZONE FORMATION

<table>
<tr><th rowspan="2">Interview Criterion</th><th colspan="3">Performance Indicators</th><th rowspan="2">Score</th></tr>
<tr><th>Low Comprehension (0-1pt)</th><th>Medium Comprehension (2-3pts)</th><th>High Comprehension (4-5pts)</th></tr>
<tr><td>General Ozone concepts</td><td>Demonstrates that ozone is either "good/bad" or only formed in one way</td><td>Can classify two different mechanisms for forming ozone; one blocks UV light and the other is a secondary pollutant</td><td>Identifies that:
3. Stratospheric Ozone
• protects from UV radiation
• formed through photolysis of O_2
4. Tropospheric Ozone
• harmful effects with too much
• formed through photolysis of NO_2</td><td></td></tr>
<tr><td>Photolysis Concepts</td><td>Acknowledges sunlight is crucial to the formation of ozone</td><td>Understands that molecules can absorb the electromagnetic radiation phenomena of photolysis</td><td>Understands that different molecules absorb at different wavelengths</td><td></td></tr>
<tr><td>OH Radicals</td><td>Knows what radicals are and how they are formed</td><td>Recognize OH radicals involved in chain mechanism</td><td>Understands OH radical is recycled in VOC-NOx reactions</td><td></td></tr>
<tr><td></td><td></td><td></td><td>Total</td><td></td></tr>
</table>

TABLE 12. GRADING CRITERIA THAT ACCOMPANIES THE QUALITATIVE RUBRIC, TABLE 11. THIS TABLE PROVIDES A MORE DETAILED DESCRIPTION AND POINT BREAKDKDOWN FOR EACH CATEGORY, AND INCORPORATES A SUCCESSIVE GRADING SYSTEM IN WHICH EACH STUDENT MUST SUCCESSFULLY CHECK OFF EVERY SECTION OF THE PREVIOUS SCORING BOX IN ORDER TO PROGRESS TO A HIGHER SCORED CATEGORY. EACH CATEGORY IS SCORED OUT OF A TOTAL OF FIVE POINTS, IN WHOLE POINT INCREMENTS.

Grading Criteria

Interview Criterion	**Performance Indicators**			**Score**
	Low Comprehension (1pt)	**Medium Comprehension (3pts)**	**High Comprehension (5pts)**	
General Ozone concepts	(0pt)-Can't describe basic formation of ozone (1pt)-Ozone formation is described as either good/bad or only being formed one way	(2pts)-In order to fall into category, MUST acknowledge that ozone is formed in two different ways (not specifics) (3pts)-Gain extra point if they can ALSO describe BOTH of the different associated atmospheric roles ozone plays in atmospheric layers (blocks UV radiation AND possible negative health effects)	(4pts)-In order to fall into category, MUST identify the two atmospheric layers ozone is formed in (Stratosphere AND Troposphere) (5pts)-Gain extra point if they can also state type of photolysis that occurs at EACH layer (of O2 AND of NO2) for ozone formation	
Photolysis Concepts	(0pt)-Doesn't ever mention the role of sunlight in ozone formation (1pt)-Acknowledges in some form that sunlight is crucial to the formation of ozone	(2pts)-In order to fall into category, MUST correlate the sun breaking/cleaving bonds to the formation of ozone (3pts)-Gain extra point if they can ALSO connect the concept of sunlight cleaving or breaking bonds to the process of photolysis	(4pts)-Associates and explains the importance of wavelength energy and lengths (photon details) with the process of photolysis (5pts)-Explains how wavelengths and photons affect photolysis during different formations of ozone (photolysis source: Stratosphere-UV radiation; Troposphere-Visible light)	
HO Radicals	(0pt)-Has no understanding of what a radical is (1pt)-Can define basic understanding of what a radical is (free floating, unpaired electron, very reactive)	(2pts)-Recognizes that the HO radical formation is a cyclic process (3pts)-ALSO acknowledges that the HO radical is a crucial part of atmospheric oxidation (controls atmospheric lifetime of many molecules)	(4pts)-Can explain the transition of the HO radical from a chemical reaction to the differential rate equation (5pts)- Utilizes the differential rate equation as an explanation for how the HO radical contributes a crucial cyclic role in the oxidation of VOCs, NOx and other atmospheric molecules	
			Total	0