Inquiry Based Learning Modules for Atmospheric Science Using Student-Accessible Modeling Tools

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Project Summary

Title
Inquiry Based Learning Modules for Atmospheric Science Using Student-Accessible Modeling Tools

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Intellectual Merit: Research has shown that undergraduate students frequently do not have a clear understanding of what it means to do science. We aim to address this knowledge gap by introducing inquiry-based learning modules that include metacognitive aspects into several courses in our program. This investigative approach works by approximating the scientific method in guided student activities. We will build on previous results that have shown that the inquiry-based approach not only improves student understanding of the scientific method, but also of the underlying fundamental concepts. We will focus specifically on our atmospheric chemistry program, where learning is currently inhibited by a lack of accessible computer-based model systems; however, our approach would be readily adaptable to other fields of study. Our specific objectives are fourfold: 1) to develop student-accessible modeling tools for atmospheric chemistry; 2) to create and implement inquiry-based learning modules for using the new modeling tools throughout the atmospheric science program at WSU; 3) to assess the impact of this approach on student conceptual understanding of non-linear system dynamics in science and engineering; and 4) to disseminate these new learning tools to the broader community.

Objectives 1 and 2 will result in new course materials to enhance student learning. High quality research models for atmospheric chemistry and aerosol processes are already available, but their interfaces require more expertise than can be expected of undergraduates. We will build new web-based interfaces for these models to make them more useful as teaching tools. We will then create inquiry-based learning modules using these tools and incorporating metacognitive aspects for seven courses spanning the range of student experience. Students in our program will be exposed to the inquiry-based approach several times as they advance, thereby reinforcing their understanding of the scientific method while continuing to build on their fundamental knowledge base.

Objective 3 of the project is to assess the effectiveness of our approach on student learning. We will use a combination of approaches, including clinical demonstration interviews, in-class observations of students, analyses of student work, and pre- and post-testing. This process will achieve two things: first, it will allow us to iteratively improve the models and learning modules to make them more effective classroom tools; and second, it will yield useful data for increasing the STEM education knowledge base.

Broader Impacts: We anticipate that our framework for introducing inquiry-based learning modules will be adapted by other programs within and outside of WSU. The final objective of the project is to disseminate our modeling tools and research results as widely as possible. To accomplish this on campus we will take advantage of our strong connections with WSU's Center for Environmental Research, Education, and Outreach, and its Center for Teaching, Learning, and Technology. To extend our impact outside of the university, we will present our work at national conferences and in peer-reviewed journals, and we will make our modeling tools and learning modules freely available over the internet.

This effort to improve our undergraduate curriculum is one component of a strategic effort to improve all aspects of atmospheric research and air quality engineering program at WSU. These efforts include: 1) the conversion of our undergraduate research program into an NSF-sponsored REU site; 2) the acquisition of a mobile atmospheric chemistry laboratory to significantly upgrade our research capabilities; and 3) the creation of an enhanced graduate program focusing on atmospheric research with a public policy context. The success of this project will have a positive impact on those efforts as well.

The proposed work will also support the student training goals of NSF by involving a Masters student to conduct the educational research and learning outcomes assessment, and two undergraduate summer researchers to assist with the development and testing of the student-accessible modeling tools.

1. Motivation

Students lack fundamental understandings of the scientific method, including the meaning of the scientific method, the type of data necessary to test hypotheses, and necessary analyses to draw causal conclusions. The book How Students Learn: Science in the Classroom, published by the National Research Council (2005), makes this point and suggests three principle areas of learning as fundamental to science preparation: preconceptions, what it means to do science, and metacognition. Preconceptions are students' preexisting models of scientific phenomenon, many of which (termed misconceptions) are incorrect and interfere with developing correct conceptual understandings. Existing curriculum on the scientific method largely ignores student preconceptions and focuses on step-by-step experimentation with given predictable results. This approach to education has little impact on students' developing conceptual understanding and their productive and robust views of science. Additionally, this approach leaves no opportunities for metacognition, or guided and meaningful student reflection on their thinking. Extensive curricular reform in the K-12 setting has occurred to address this lack of understanding, yet less has been done in higher education. This project intends to develop, implement, and assess curricular materials that can be used from the freshmen to graduate level aimed at what it means to do science and the scientific method.

A proven technique for conveying to students what it means to do science is to adapt an inquiry-based approach for in-class exercises and homework assignments. In this approach, learning modules focus on whatever scientific concepts are appropriate for the curriculum, but assignments are organized in a manner that will lead the students through a process replicating the scientific method in the course of completing the tasks. The general structure of an inquiry-based assignment would be as follows: 1) Students develop a hypothesis, based on previously learned concepts, that can be tested using a model system; 2) Students design an experiment that can be implemented to test the hypothesis; 3) Students conduct the experiment by probing the model system; and 4) Students analyze the data form conclusions that reinforce the underlying concepts (White & Frederiksen, 1998). Including a metacognitive aspect in each of these steps has been shown to improve student learning (White & Frederiksen, 1998).

A critical requirement for this approach is that there must be a model system that students can explore in sufficient detail to make the inquiry-based approach authentic. Interactive resources that follow a linear narrative or offer only limited choices are inadequate for this purposes- there must be sufficient flexibility for the model system to fluidly respond to reasonable inquiries from the student. For many problems in many fields, the best model system will be a physical example of the system itself. For example, very successful inquiry-based learning modules can be developed using the circuit prototyping equipment commonly found in electronics laboratories. However, it is frequently the case that isolating a physical manifestation of the actual system is impractical- this is true of most environmental systems and especially of atmospheric systems. In these latter cases, a computer model can be used successfully to represent the system in an inquiry-based approach, but care must be taken to ensure that the complexity of the model meets the students' educational needs. If the model is too complex, there is great risk that the students will become lost in the process and the desired learning outcomes will not be achieved. If the model is too simple, there are two possible negative outcomes: the model may not accurately represent the actual system, or there may not be sufficient interactivity to support an authentic inquiry-based approach. Obviously the "right" level of complexity will depend on the students' experience; ideally the model system would have sufficient flexibility so as to be adaptable for a range of experience levels.

The inquiry-based approach can potentially be adapted to any field within science and engineering education. Our particular interests lie in the chemistry and dynamics of atmospheric trace gases and particulates, subjects where inquiry-based learning modules using flexible computer-based model systems could greatly aid students' learning of key concepts. Atmospheric chemical processes are characterized by numerous independent variables with complex nonlinear interdependencies. Both transient and steady state behavior can be important, depending on environmental circumstances that are rarely obvious. Understanding such a system at any level of realism is nearly impossible without computational assistance. Current approaches for teaching these complex systems are typically two-tiered. Students are first taught the underlying fundamental concepts using a simplified model system that includes many assumptions that do not reflect reality. Then they are shown results from a more realistic model which they are not able to probe directly, and effectively told to accept the results on faith. This approach is obviously less than ideal, but there is currently no good alternative- the more complex, more realistic models were developed for research purposes and are not accessible to undergraduate students without extensive training. Our chief goal in this project is to make these research-grade atmospheric models accessible for less experienced users and then incorporate these new learning tools into our undergraduate curriculum and research program.

2. Objectives

We have observed that in many cases students' abilities to learn key concepts in atmospheric chemistry are inhibited because there are no feasible means for them to investigate system response to varying inputs. The atmosphere is too complex for a simple model to replicate observed behavior- there are too many independent variables and nonlinearities involved for either a scaled down physical model or for a simple numerical model to be appropriate. Effective models do exist, but they are intended for use as research tools and they presently require computer literacy beyond what can be expected of undergraduate students. Our goal in this proposed project is to adapt these existing research models for use in the classroom to provide students with a means of exploring the behavior of pollutants in the atmosphere.

Our specific objectives for the project are the following:

1. <u>To develop student-accessible modeling tools for atmospheric chemistry</u>. As noted above, research models already exist that are capable of simulating the chemical processes occurring in an air parcel. We will adapt two such models for use in the classroom- one for gas-phase chemistry and one for aerosol physical and chemical processing. The key to this adaptation will be the creation of new input and output interfaces for the models. The input interfaces will be web-based forms that will allow the student to either choose a preset scenario or manually select a set of independent variables for a simulation; these input choices will then be used to run the underlying model and generate an output file. The output interface will allow the students to either create basic data visualizations directly or to download data for more detailed analysis.
2. <u>To create and implement inquiry-based learning modules for using the new modeling tools throughout the atmospheric science program at WSU</u>. The Laboratory for Atmospheric Research (LAR) oversees an extensive research, education, and outreach program in atmospheric science at Washington State University. We have identified seven different courses (including our undergraduate research program) in which student learning could be improved by the addition of inquiry-based learning modules using the new student-accessible modeling tools. These courses span the range of expected student backgrounds, from freshman with minimal Science, Technology, Engineering, and Mathematics (STEM) background to graduate students in atmospheric science. Regardless of the targeted level, the effectiveness of the new modeling tools in improving learning outcomes will be critically dependent on having lesson plans and assignments that encourage students to probe the model system in a thoughtful, inquiry-driven manner. After introducing the fundamental concepts in class, students will be presented with a problem scenario and asked to formulate a hypothesis and develop an experiment plan to test the hypothesis using the modeling tools. Then, after completing the model simulations, students will be asked to analyze their results and explain how their hypothesis is or is not supported. Most importantly, each step will include metacognitive aspects that require students to reflect on their thinking and reasoning.

3. To assess the impact of this approach on student conceptual understanding of non-linear system dynamics in science and engineering. Because the ultimate goal of the project is to improve student learning, its success can only be gauged by formally assessing the impact of the new modeling tools and learning modules on student performance. A combination of approaches will be employed. We will conduct clinical demonstration interviews (Sommers-Flanagan & Sommers-Flanagan, 1999) with engineering students to characterize and understand student preconceptions, including misconceptions, of equilibrium points, temporal evolution, and non-linear behavior within atmospheric systems. Assessments of student learning will be accomplished using a combination of quantitative and qualitative methods, including analyses of student work, observations of students engaged in developed activities, student surveys, and student interviews.

4. To disseminate the tools to the community. To maximize the potential impact of the new student-accessible modeling tools, we will make the tools available to the community and will publicize our research results at scientific meetings and in the peer-reviewed literature.

3. Previous Work

The foundation of the this work is based on extensive work on developing correct and robust understandings of what it means to do science (*National Science Education Standards*, 1996; *Classroom Assessment and the National Science Education Standard*, 2001; *How Students Learn: Science in the Classroom*, 2005). The process of scientific inquiry is usually defined to include the development of a research question, the generation of a set of possible results, the design and completion of a set of experiments, the analysis of results to more broadly describe other physical phenomena, and finally a return to the development new research questions (White & Frederiksen, 1998). This process differs greatly from the way that experimental tasks are commonly presented in educational settings, wherein students are given an experimental design and required to conduct the experiment and summarize their results; this latter process results in a form of reasoning that is not considered to be authentic (Chinn & Malhotra, 2002). When learning to navigate the inquiry process, students require direction in the form of prompts and definitions of each step. Previous efforts to implement curriculum designed to foster an understanding of the scientific method have included guided instruction on conducting scientific inquiry with metacognitive components (metacognition refers to student reflection on their thinking and reasoning as part of the learning process). For example, Lin and Lehman (1999) found that reason justification was the most effective form of metacognition for increasing college biology students' ability to transfer knowledge to problems in different contexts.

Within the environmental sciences, computer-aided approaches have long been recognized as an effective way to expose students to large complex systems in the classroom. There are many examples in which student assignments are designed around a student-accessible model (e.g., Boyd & Romig, 1997; Mohtar & Engel, 2000). The effort described in the latter paper is of particular interest due to the similar strategy between that effort and the one proposed here. Mohtar & Engel (2000) adapted for classroom use two models specialized for agricultural environments- the GLEAM pasture management model (Mohtar et al., 2000) and the NAPRA pesticide runoff model (Manguerra & Engel, 1997). Both models were developed to be accessible via the world-wide web. At the models' websites, students enter the appropriate parameters for their problem and run the model; upon completion, results can either be displayed graphically on the website, or students can download data to a text file for additional analysis.

The flexibility and ease of use of the model interfaces described by Mohtar & Engel (2000) would make it an excellent tool for pursuing inquiry-based learning strategies in the classroom. However, this was not among the authors' goals. Instead, they followed a more traditional engineering-oriented approach. Sample assignments provided in the article and in a follow up study (Mohtar et al. 2007) ask students to obtain a concrete answer to a well-posed problem, having been given most or all of the parameters needed to run the model. For these goals the modeling tools and associated assignments have improved learning outcomes- Mohtar et al. (2007) found that use of the modeling tools resulted in significant improvements to both quantitative and qualitative learning categories, and that students had a favorable response to the models' inclusion in the curriculum.

Another major effort with goals and strategies similar to the proposed project, this one specific to atmospheric science education, is the Educational Global Climate Modeling (EdGCM) Cooperative Project at Columbia University (http://edgcm.columbia.edu). Like the work proposed here, the EdGCM project was motivated by the need for students to have a working knowledge of a large environmental system, and the recognition that the best path for them to obtain that knowledge was by providing a means for them to probe the system as part of their instruction. Similar to our strategy, the EdGCM framework depends on an underlying, pre-existing research-grade model- in this case the GCM developed and maintained by NASA's Goddard Institute for Space Studies (GISS). Instructors and students throughout the world (as well as the general public) can use the model by installing the model onto their computer via an internet connection. Several preloaded scenarios are available, or users may create their own inputs files. Once complete the output can be exported as a text file for analysis, or can be visualized using tools included in the EdGCM framework. (EdGCM, 2008).

The EdGCM framework provides a powerful tool for improving students' understanding of the Earth climate system. Coupling the model with an inquiry-based learning module would give students a clear conceptualization of how climate research proceeds. However, only a limited number of lesson plans are available from the project site, and these do not follow an inquiry-based approach. Moreover, the decentralized usage pattern makes it difficult to evaluate what impact the availability of EdGCM is having on student learning. To date no evaluation of the educational impact of the project is available in the peer-reviewed literature.

4. Preliminary Work

While planning the proposed project we wanted to confirm that students of atmospheric chemistry would respond as favorably to the use of modeling tools as had students in other fields. To that end we used MatLab to write a box model for simulating stratospheric chemistry and developed a learning module incorporating the model for our graduate level atmospheric chemistry course (CE 589). The goal of the exercise was for students to understand how changing levels of water vapor and nitrogen oxides (NO_x) would impact stratospheric ozone concentrations and why the effects of water vapor and NO_x are not additive. These are usually difficult concepts for students because the observed system behavior is in conflict with the most common intuitive conceptualizations. In the atmosphere, NO_x and HO_x radical species act as radical chain catalysts in photochemical reactions to either create or destroy ozone. The catalytic destruction cycles involving HO_x and NO_x species are not additive because chemical reactions between these chemical families create "reservoir" species that lower catalyst concentrations. Our expectation was that a hands-on approach investigating system behavior would facilitate learning for these difficult but fundamental concepts.

This demonstration model helped us understand how a modeling tool could be used to teach important concepts in atmospheric chemistry to engineering students. Students were provided with an in-class demonstration of the model and then given an assignment to determine how the steady state ozone concentration depended on the initial system concentrations of H_2O and NO_x. Assignment questions were designed to test students' understanding of the underlying chemistry. Based on results from the course's oral final exam, students exhibited better understanding of these concepts than had previous years' students.

A written survey was conducted to assess whether students thought the exercise had helped them understand catalytic destruction cycles in the stratosphere. Four responses were received from a class of seven students; results are shown in Table 1. The general response confirmed that the model helped students understand the underlying concepts. Written comments also suggested that the exercise could be improved by requiring more detailed thought by students early in the assignment. Specifically, students indicated that requiring them to input the chemical reactions as differential equations with corresponding rate coefficients would improve their understanding of the equations and of the differences between slow and fast reactions in the model system.

Table 1. Results of Box Model Survey for CE 589 Class

Question	Responses				
	Completely agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Completely disagree
A. The stratospheric model helped me understand chain reactions	1	3			
B. I wish that we did more box modeling exercises	2	1	1		
C. The model did not add value to this course				1	3
D. Tropospheric box modeling would help me understand HO_x / NO_x chemistry	2	2			
E. My understanding of atmospheric chemistry would be improved by using box models	2	2			

5. Research Plan

Our preliminary work has demonstrated that student-accessible modeling tools facilitate understanding for difficult concepts important to atmospheric chemistry. Our goal for this project is to implement the use of these modeling tools throughout our curriculum. These tools will improve understanding of the core concepts for our courses and will emphasize throughout our program the importance of an inquiry-based approach to science and engineering. We will achieve this goal by first developing the necessary student-accessible modeling tools and then designing course learning modules that take advantage of these new capabilities. To determine whether our course modifications are having the desired effect, we will assess the learning outcomes associated with the curriculum changes. Finally, to ensure maximal impact of our work within the academic community, we will present our work at national conferences and in peer-reviewed publications targeted at both the STEM education and atmospheric science communities.

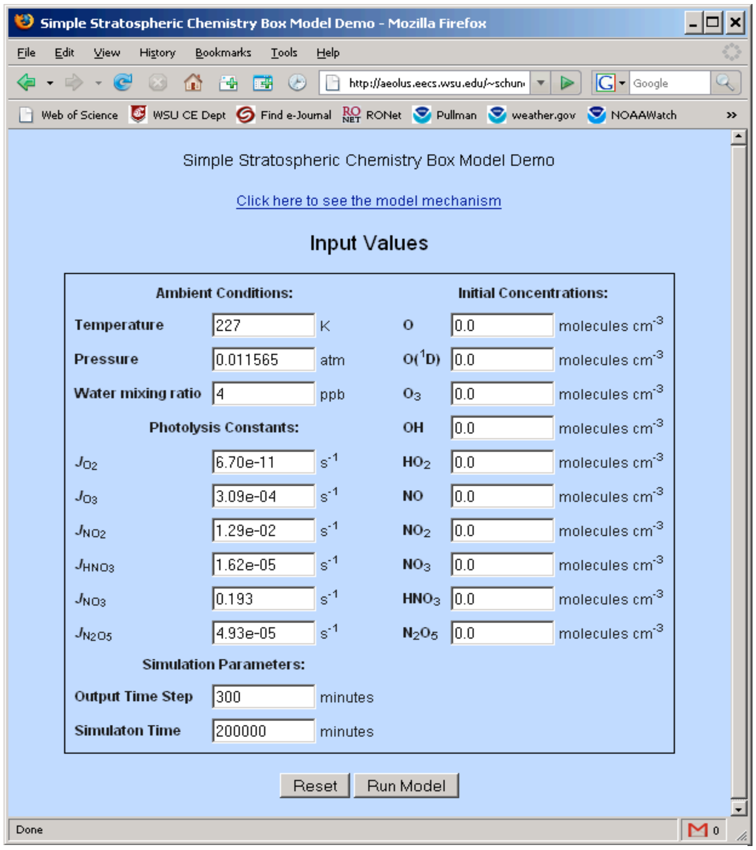
5.1. Objective 1: Developing Student-Accessible Modeling Tools

The first key to introducing investigation-based learning modules into our curriculum is to provide our students with a system model with which to pursue their investigations. Fortunately, integrating student-appropriate modeling tools into the classroom does not require developing new atmospheric models. Models for atmospheric chemistry and aerosol processes already exist and are already used within LAR for research purposes. The critical step for this work is to develop interfaces that will make it possible for undergraduate students to interact with these models at levels appropriate for their experience. For each model the interface will facilitate the selection of physically realistic inputs, thereby allowing the students to focus on developing experiments to probe the underlying behavior of the model system. We will also create an output interface to allow for easy data visualization or export after the model has run. The underlying models are powerful and flexible enough to allow a wide range of modeling experiments to be developed once the student interface is in place. The details of the underlying research models and of the how the student interface will be developed are described below.

The gas-phase chemistry modeling tool will be built to interface with the publicly available NCAR Master Mechanism (Madronich and Calvert, 1989). The Master Mechanism contains explicit and detailed chemical mechanisms for atmospheric gas-phase oxidation of hydrocarbons and includes photolysis rate calculations. The model includes over 1800 chemical species and 5000 reactions; users can choose a subset of species and reactions to use depending on the purpose of the simulations. We will take advantage of this last model capability by designing the interface to limit student options to those relevant to the concepts introduced in class.

For the aerosol dynamics and chemistry modeling tool, we will use a state-of-the-science aerosol dynamics model previously developed by Co-Investigator Chung. The aerosol model explicitly simulates both aerosol number and mass distributions using an approach previously employed in cloud growth models (Tzivion, 1987; Tzivion et al, 1989). The continuous tracking of both aerosol number and mass allows the examination of strongly non-linear aerosol physical processes such as the competing effects of coagulation and condensation. The same modeling approach to modeling aerosol dynamics has been applied to global climate models (Adams and Seinfeld, 2002). Aerosol condensational growth is driven by the chemical equilibrium between the condensed phase and the surrounding gas. This is a complex thermodynamic problem, in part due to the number of chemical species involved. The aerosol dynamics model is integrated with the thermodynamics model ISORROPIA (Nenes et al, 1998) to calculate the driving force for condensation/evaporation. ISORROPIA has been used in large scale air quality models (Binkowski and Roselle, 2003) and in global climate models (Adams et al, 1999). It includes several inorganic aerosol species, including sulfate, ammonium, and nitrate.

Again, the models mentioned above already exist and being used currently for research within LAR and elsewhere. The critical task for this objective is to build a platform-independent, user-friendly interface so that students can use the models without having to be familiar with the underlying code. To achieve this, we will build a web-based interface using a combination of the Common Gateway Interface (CGI) and Hypertext Preprocessor (PHP) scripting languages. CGI and PHP are server-side scripting languages for creating dynamic and interactive websites. From the web interface, the users will be able enter input parameters (e.g., temperatures, initial concentrations of species, initial aerosol size distributions) for the model. The actual models themselves will be unchanged except for rewriting the input and output portion of the FORTRAN codes. The webpage will be hosted on the server connected to our 28-processor Linux cluster where the models reside. The users will be able to submit the input values and the models will be run on our Linux cluster. After the model simulation is completed, graphs of selected model output will be displayed on a new webpage. The users will also have the option to output model results in ASCII files so that they can be imported to other programs for further data analysis and visualization. A mockup of the atmospheric chemistry model input interface is shown in Figure 1. The use of the web interfaces require only that the user have access to the world-wide web,



Simple Stratospheric Chemistry Box Model Demo

Input Values

Ambient Conditions:			**Initial Concentrations:**		
Temperature	227	K	**O**	0.0	molecules cm^{-3}
Pressure	0.011565	atm	**O(^{1}D)**	0.0	molecules cm^{-3}
Water mixing ratio	4	ppb	**O_3**	0.0	molecules cm^{-3}
Photolysis Constants:			**OH**	0.0	molecules cm^{-3}
J_{O2}	6.70e-11	s^{-1}	**HO_2**	0.0	molecules cm^{-3}
J_{O3}	3.09e-04	s^{-1}	**NO**	0.0	molecules cm^{-3}
J_{NO2}	1.29e-02	s^{-1}	**NO_2**	0.0	molecules cm^{-3}
J_{HNO3}	1.62e-05	s^{-1}	**NO_3**	0.0	molecules cm^{-3}
J_{NO3}	0.193	s^{-1}	**HNO_3**	0.0	molecules cm^{-3}
J_{N2O5}	4.93e-05	s^{-1}	**N_2O_5**	0.0	molecules cm^{-3}
Simulation Parameters:					
Output Time Step	300	minutes			
Simulaton Time	200000	minutes			

Figure 1: Mock-up of input interface for atmospheric chemistry modeling tool.

from any computer platform. There is no requirement to download and compile the models. Most importantly, no knowledge of the programming details of the models is required for the users to take advantage of the models' capabilities.

5.2. *<u>Objective 2:</u> Creating and Integrating New Learning Modules*

For the new student-accessible modeling tools to have the greatest impact, we must develop learning modules that take advantage of the new capabilities in a manner consistent with course objectives and student experience level. To achieve the additional goal of improving students' understanding of the scientific method, our new learning modules will be structured according to the inquiry-base approach described in Section 1. After discussing the fundamental concepts in class as well as how to use the modeling tools, students will be given an assignment based on real-world problems related to the underlying material. The assignment will lead them through the scientific method as it relates to the problem, first asking them to develop a hypothesis, then to design an experiment to test the hypothesis using the model, and so on. At each step, students will be asked to explain why they make the choices they do. This will encourage the metacognitive process which is known to improve students' ability to learn. A example learning module using the inquiry-based approach can be found in Box 1 below. The module is intended for junior environmental engineering students studying tropospheric ozone formation.

<u>Box 1: Sample Inquiry-Based Assignment</u>

<u>Problem Statement:</u> In an effort to reduce dependence on foreign oil, government officials in your region have proposed mixing corn-derived ethanol into the gasoline supply. Your manager at the regional air quality agency has asked you what impact this change will have on ambient ozone concentrations. He has provided you with a table indicating the NO_x and hydrocarbon emissions for different fuel mixtures.

<u>Task 1:</u> Before running the model, write a clear statement explaining how you think the local atmospheric system will respond to vehicle fleet emissions changes arising from a changed fuel mixture. Why do you think the system will respond as you describe?

<u>Task 2:</u> Design an experiment to test the hypothesis you developed in Task 1. What parameters do you need to vary, and over what range should they be varied? What values should you choose for any unspecified parameters? Explain how you arrived at your answers.

<u>Task 3</u>: Conduct the experiment according to your plan and summarize the results using figures and text for your manager. Was your hypothesis supported? Why or why not? What would you tell him about the advisability of mixing ethanol into gasoline for the automobile fleet? Is this a causes and effect relationship? Why or why not? What data and analysis characteristics are necessary to infer cause and effect?

<u>Task 4:</u> Reflect some more on your results. Which of the assumptions in your experiment plan are most likely to significantly affect your results? Why are they the most likely to affect your results? If you had more time, what additional questions about the behavior of the system do you think you should explore? Develop a preliminary plan to investigate these questions using what you have learned in this exercise.

Learning modules incorporating the new student accessible modeling tools will be incorporated into courses throughout the air quality component of WSU's Environmental Engineering program. These include courses for students just entering the university (ENGR 120, CE 174), courses targeted for juniors and seniors (CE 341, CE 415), and those targeted for seniors and graduate students (CE 589, CE 591). The modeling tools will also be incorporated into the educational component of the NSF Research Experience for Undergraduates (REU) program hosted by WSU's Civil & Environmental Engineering

Program and Laboratory for Atmospheric Research (LAR). Our strategies for incorporating appropriate learning modules for each of these courses are summarized below.

ENGR 120: Innovation in Design. ENGR 120 is a freshmen level engineering course required by all engineering students with an annual enrollment of approximately 400 students. The focus of this course is to introduce students to the engineering discipline and concepts and ideas fundamental to the discipline; the course is currently being modified to focus on the environment, energy, and sustainability. The learning modules that will be implemented in ENGR 120 will focus on the relationship between human activities and air quality. Students will investigate these relationships by developing and testing hypotheses using the model interface. For the lower division courses (ENGR 120 and CE 174) the learning modules will be developed as scenario alternatives in which students do not directly control most model parameters. Rather they will qualitatively compare the air quality outcomes when varying the initial pollutant levels representative of different degrees of human influence. The parallel focus on the environment and fundamental engineering ideas (designing and conducting experiments) of ENGR 120 will be specifically addressed with the implementation of these modules.

CE 174: Introduction to Meteorology and the Atmospheric Environment. CE 174 is an elective course intended for freshman and non-engineering majors; annual enrollment is 10-20 students. The bulk of the course consists of an overview of weather phenomena, but the last quarter includes topics related to air quality and anthropogenic climate change. Topics in air quality include the sources and health impacts of criteria pollutants, plume dispersion, and secondary pollutant formation (i.e., ozone and aerosols).

The learning module to be incorporated into CE 174 would explore how meteorological parameters (e.g., temperature, solar intensity, winds, and atmospheric stability) influence the severity of air pollution episodes. As with the ENGR 120 course, the learning modules for CE 174 will be developed as scenario alternatives wherein students do not directly control most model parameters (e.g., “clear summer day” vs. “overcast winter day”). Given the nature of the course and of the students enrolled, the learning module will likely consist entirely of an in-class exercise.

CE 341: Introduction to Environmental Engineering. CE 341 is a required course for civil and environmental engineering majors. It is taught each semester with an enrollment of 130-140 students per year. The objectives of the course are to provide students with basic introduction to air and water pollution problems and engineering solutions that are used to restore the environment and reduce pollution. Topics include indoor air quality, urban and regional photochemical smog, and the radiative forcing of climate.

The atmospheric chemistry model will be incorporated into a learning module designed to aid students in understanding photochemical smog formation. Students will be asked to investigate the impact of alternative fuels, such as ethanol, on urban air quality. The chemistry behind smog formation is will be modeled using a simplified set of reactions that simulate urban air chemistry. Students will manipulate a hypothetical vehicle fleet with varying NO_x and/or hydrocarbon emission rates to determine the impact on the maximum ozone concentration (see Box 1). The modeling tools will help students understand reaction rate laws and the non-linear dependence of ozone formation on NO_x and hydrocarbon concentrations.

CE 415: Environmental Measurements. The CE 415 class is an elective laboratory course designed to instruct students in common techniques used in air and water quality monitoring. The course is offered each fall with a typical annual enrollment of 15 undergraduates, with ~5 additional students enrolled each year for graduate credit (CE 515). The chief goal of the air portion of the course is for students to understand how pollutants are monitored and what causes pollutant levels to vary on a daily basis. Each week students working in pairs first learn how to operate an instrument used for measuring one of the criteria pollutants (CO, NO_2, SO_2, O_3, and particulate matter) and then collect ambient data for the rest of the week.

Currently students are evaluated based on lab reports incorporating their measurements and those of the other teams. They are expected to demonstrate their understanding of atmospheric processing and pollutant sources by relating trace gas and aerosol concentrations to one another and investigating the impact of meteorology on pollutant concentrations. The incorporation of the student-accessible models into the course will provide powerful additional tools to aid students in their analyses. Here, they will allow students to explore the differences between transient and equilibrium system behavior. For each assignment, students will first be required to predict and explain whether their measurements should match model predictions, based on their preexisting understanding of the underlying concepts. They can then compare their measurements to the model predictions and discuss the level of agreement given the model and experimental uncertainties. The comparison will require that students consider practical monitoring issues – would surface-based measurements near a roadway be in steady state? How long would the system take to reach equilibrium?

CE 589: Atmospheric Chemical and Physical Processes. CE 589 is an introductory graduate class offered each spring; annual enrollment is typically 5-10 students. The class is also open to senior undergraduates. The objectives of the class are to give students an understanding the major chemical and physical process that determine trace gas abundance in the atmosphere. One of the major topics covered in the course is the catalytic destruction and production cycles that impact ozone concentrations in the stratosphere and troposphere. Such catalytic cycles are of central importance to atmospheric chemistry, but it is nearly impossible to conceptualize how the chemistry of HO_x radicals and NO_x interact to influence ozone concentrations without a box model to investigate this behavior.

Learning modules for this course will build on the successful preliminary work described in Section 4 above. The atmospheric chemistry model will be used for assignments based on ozone chemistry in the stratosphere and in the troposphere; the framework for the former module is described here. For the stratospheric learning module the students will be asked to investigate the impact on steady state ozone concentrations when initial conditions of key constituents are changed (e.g., NO_x and water vapor), or when key reactions that couple chemical families (such as HO_x, NO_x, ClO_x) to create reservoir species are removed. Students will choose the appropriate reactions to be included in the simulation as well as the relevant reaction rate coefficients, photolysis rates, and initial conditions. We expect that letting students directly control model parameters will lead to an improved understanding of the fundamental importance of radical cycling reactions in atmospheric chemistry.

CE 591: Aerosol Dynamics and Chemistry. CE 591 is a newly created graduate level course (also open to senior undergraduates) focusing on the physical and chemical processes affecting atmospheric particles. Annual enrollment is currently 4-5 students, though this number is expected to increase as the university community becomes more aware of the course and as the number of students affiliated with LAR grows. The course focuses on of the processes that affect atmospheric particles at the microphysical scale, including condensational growth, coagulation, cloud droplet activation, depositional loss, and new particle formation. Presently these processes are studied primarily from the perspective of a single particle. This approach is effective enough when aerosol processes are occurring in isolation and when only one particle size and composition is being considered at a time. However, understanding aerosol processes in the atmosphere requires to a population-based approach, wherein the inherent aerosol size and compositional variability must be addressed.

It is at this point that the student-accessible aerosol model interface would greatly improve the students' understanding of aerosol dynamics. For the first time it will be possible for students to probe aerosol processes in groups as well as individually, and thereby gain an understanding of how the various processes interact as the population evolves under realistic atmospheric conditions.

Learning modules will be developed that will allow students to explore how initial simplifying assumptions (e.g., aerosol size distribution and composition, and trace gas concentrations) can affect the overall behavior of the system.

LAR Research Experience for Undergraduates (REU) Program. LAR has recently received NSF funding to convert its preexisting undergraduate research program into an REU site. The first cohort of REU students will arrive in 2009; each year there will be 12-15 sophomore- and junior-level students. For the program we will be specifically targeting science and engineering students from underrepresented groups at schools where only limited research opportunities exist for undergraduates. The REU students will work on projects spanning the breadth of LAR's research activities, though there will be particular emphasis on the measurements and data interpretation associated with field observation capabilities. At the beginning of each summer we will hold a series of workshops to provide a fundamental understanding of the basic concepts of air quality and climate change science, and to teach what it means to do scientific research. Each student's project advisor will then build on this framework by explaining how their specific research problem fits within the larger context and by training the student the specialized techniques required for their project. There will also be an education research component to the REU project. Co-PI Brown of this project is also the co-PI for the REU project and will conduct research on student learning and attitudes towards science. Each year one of the REU students will focus on engineering education and will assist the co-PI in conducting this research.

The new student-accessible modeling tools will enhance the educational components of the REU program in two major ways. First, they will be used during the training workshops to explore the interconnectivity of meteorology, gas-phase chemistry, and aerosol processes within the atmospheric system and to demonstrate how changes to the initial state of the system can lead to complex non-linear responses. Secondly, we expect that the student-accessible modeling tools will also be useful as the REU participants learn more about their individual projects. To successfully complete their work students will have to understand the details of their research problem more fully than will be achievable in the group workshops; project mentors will be able to use the modeling tools in their discussions with students for this purpose. Additionally, the students will have direct access to the modeling tools throughout the program so that they can individually probe the implications of their research and can collaboratively investigate how the different projects are interconnected.

5.3. Objective 3: Assessing Learning Outcomes

The learning outcomes of this project are focused on conceptual understanding and the scientific inquiry. An assessment of these learning outcomes will be conducted by Co-PI Brown and a graduate student. The graduate student will have an undergraduate degree in engineering and will focus their masters research on the assessment of these learning outcomes. Assessment efforts will utilize summative assessment and mixed quantitative and qualitative methods. The results of the assessment will also be used for formative assessment (i.e., providing feedback to students on their learning), but the primary goal will be to determine how well students meet the learning outcomes. The learning outcomes, assessment methods, and timing of assessment are described in Table 2 below. Assessment methods will consist of pre- and post-testing, analyzing student assignments, observing students as they conduct in-class assignments, and pre- and post-assignment student interviews. Pre- and post-tests will be conducted for a representative sample in all courses implementing the new learning modules; assessing each of these groups will allow us to compare results for students with significantly differing educational experience and backgrounds. Analysis of homework and exam questions, interviews, and class observations will focus on students in CE 341. This course has the second largest enrollment of those included in the implementation plan and is focused on environmental processes, making it most suitable for a more in-depth investigation of student learning.

Table 2: Learning Outcomes Assessment Methods and Timing

Learning Outcome and Associated Questions	Assessment Method
Understanding of what it means to do science: o Are students able to develop hypotheses? o Are students able to test hypotheses? o Do students appropriately determine causal relationships?	Pre- and post-test. Student interviews. Analysis of student homework and exam questions. Observations of students during in-class assignments.
Do students have correct conceptual understandings of equilibrium points, temporal evolution, and non-linear behavior within atmospheric systems?	Student interviews. Analysis of student homework and exam questions. Observations of students during in-class assignments.

Pre- and post-tests will be developed to assess students understanding of the development and testing of hypotheses and causal relationships. The tests will utilize a scenario that is comparable to those analyzed using the model interface. Students will be asked to establish a testable hypothesis and to develop a plan to test it. Additionally, students will be asked open-ended questions to determine the necessary characteristics of data to determine cause and effect (statistical significance, non-correlation, etc.). Students will have some experience with the scientific method through high school or college science courses, and should be able to develop some responses to pre-test questions. A valid and reliable rubric will be developed to assess results of these tests. The results of the pre- and post-tests will be compared for each student to determine average gains in student understanding. Qualitative results will inform modifications to the model and associated assignments.

Student homework and exam questions will be analyzed to determine students understanding of key concepts. This analysis will be guided using a rubric comparable to the one used to analyze pre- and post-test results.

A group of students will be interviewed after the course to identify preconceptions and misconceptions about the material covered in the learning modules. The interview methodology will be clinical interviews (Ginsburg, 1997; Sommers-Flanagan & Sommers-Flanagan, 1999) similar to those used by the Physics Education Research Group at the University of Washington (PEG). The PEG group has more than twenty years of experience investigating student preconceptions and misconceptions. The goal of clinical interviews is to investigate students thinking and knowledge of a concept without interfering with their thought patterns. Students will be provided with a scenario that is comparable in focus to assignments and asked to describe how they would approach the scenario. Student thought patterns will be investigated using clinical questioning.

Students will be observed during class time when they are conducting exercises using the model interface. Gathering valid and reliable observation data will be enhanced with the use of an observation protocol. The protocol will be designed to focus on the nature of student comments and how they relate to their understanding of scientific inquiry and their conceptual understanding.

Data from CE 341 students will be analyzed in-depth to determine student pre and misconceptions, student understanding of scientific inquiry, and reasons for lack/presence of understanding. Triangulation of data from multiple sources will allow for a more rigorous analysis and more robust and generalizable results.

5.4. Objective 4: Disseminating Project Results

The successful completion of Objectives 1-3 of the proposed project will result in new student-accessible modeling tools and a set of investigation-based learning modules designed to improve student performance across all levels of post-secondary education. Maximal impact of the project will depend on making the modeling tools and learning modules freely available to the broader academic community and on publicizing the project results as much as possible.

To make the modeling tools and learning modules readily accessible to the general public, we will establish a website specifically dedicated to the project. The website will include documentation about the modeling tools and suggestions about how the tools can be effectively incorporated into different teaching environments. For tracking purposes, the model interfaces themselves and detailed teaching plans will only be available to site visitors who have registered and logged in to the website. The site will also include pointers to the download sites for the underlying research models, which are already available to the public by their developers. In accordance with the instructions laid out in the CCLI Program Solicitation, we will also make our web resources available in the National Science Data Library (NSDL).

We will publicize the project results along parallel tracks focusing on both the STEM education and atmospheric science research communities. There is unfortunately much less overlap between these communities than one would hope. For both communities we will raise awareness of the results through both conference presentations and peer-reviewed journal articles. For the STEM education community, we anticipate presenting our results at either the American Society for Engineering Education annual meeting or the Frontiers in Education National Conference and submitting an article to the Journal of Engineering Education. Within the atmospheric science community, we anticipate presenting our work and the annual meetings of the American Geophysical Union and the American Association for Aerosol Research, and would likely submit an article for publication in the journal *Atmospheric Environment*.

6. Project Evaluation and Reporting

Project evaluation will be conducted by the Center for Teaching, Learning, and Technology (CTLT) at WSU with the assistance of the research team and will incorporate formative (along the way) and summative (at the conclusion of project) evaluation. In Table 3 below are the project outcomes from each effort, the evaluation method(s) and the timing of evaluation.

Table 3: Project Evaluation Strategy

Project Objectives and Related Outcomes	**Evaluation Method**	**Participants and Timing of Evaluation**
Objective 1: To develop student-accessible modeling tools for atmospheric chemistry. *Objective 2: To create and implement inquiry-based learning modules for using the new modeling tools throughout the atmospheric science program at WSU.*		
Students are able to utilize modeling tools efficiently.	Survey of student attitudes towards the accessibility of tools. Focus groups with students.	Students in all courses listed after implementation. Students in ENGR 120 and CE 341 after implementation.
Objective 3: To assess the impact of this approach on student conceptual understanding of non-linear system dynamics in science and engineering.		
**Evaluation of this objective is described in Section 5.3.		
Objective 4: To disseminate the tools to the community.		
Sharing of tools and evaluation results with broader community. A new website with accessibility to modeling tools and modules.	Number of conference presentations and journal publications. Focus groups with students.	Conclusion of project.

A survey will be developed to assess student attitudes about the accessibility and usefulness of the modeling tools and learning modules in their learning. Additionally, a focus group will be conducted with students from ENGR 120 and CE 341 to access students' the same attitudes. It is expected that the focus group results may reveal issues that are not revealed through the surveys. Results of both surveys and focus groups will be utilized to make improvements to the tools and modules.

7. Synergy with Other Programs

The proposed project to improve our undergraduate curriculum is one component of a strategic effort to improve all aspects of atmospheric research and air quality engineering program at WSU. These efforts include: 1) the conversion of our undergraduate research program into an NSF-sponsored REU site; 2) the acquisition of a mobile atmospheric chemistry laboratory to significantly upgrade our research capabilities; and 3) the creation of an enhanced graduate program focusing on atmospheric research with a public policy context. These programs and their links to the proposed project are described briefly below:

1. REU Site: Regional Atmospheric Chemistry: State-of-the-Art Measurement and Modeling in the Pacific Northwest. This program has already been described in some detail in Section 5.2 above. The modeling tools and teaching modules developed in the proposed project will be directly integrated into the REU teaching workshops and will also be valuable to the students as an analysis tool in their individual research projects. Ideally, this will expand the impact of the project beyond WSU as the students bring what they learn back to their home institutions.
2. Integrated Mobile Atmospheric Chemistry Laboratory. In 2007 LAR was awarded an NSF Major Research Instrumentation grant to acquire a mobile trailer with a suite of instruments to simultaneously measure trace gas species, aerosol physical and chemical properties, and boundary layer dynamics. This integrated facility will provide critical infrastructure for field research projects investigating the impact of urban, biogenic, and agricultural emissions on regional atmospheric chemistry. A key component of the mobile laboratory is a communications system that will make field data available in real time via the internet for research purposes and for use in the classroom. This system is highly complementary to the student-accessible modeling tools and teaching modules proposed here. Modules will be developed centering on real-world case studies. After covering the fundamental concepts relevant to the case, we would present the students with a set of field observations from the mobile laboratory. Assignments would then be structured around explaining the real-world observations using the modeling tools.
3. Atmospheric Policy Trajectory. In 2007 LAR received substantial internal funding to develop an enhanced graduate program, named the Atmospheric Policy Trajectory (APT) (http://www.lar.wsu.edu/policy.html). The new program aims to merge LAR's existing research strengths with a new emphasis on the public policy implications of pollution control strategies. The program will have several components, including travel opportunities for the participants, a seminar series with nationally prominent experts in atmospheric policy and, as a capstone experience, policy-oriented internships with relevant public or private organizations. Students participating in APT will complete our normal graduate level courses as well as additional coursework in economics, political science, and environmental systems modeling. The inclusion of inquiry-based learning modules in our graduate level courses (CE 589 and CE 591) will ensure that our students have a firm grounding in the scientific method as they broaden their learning in these new fields.

8. Broader Impacts

We expect that the curriculum improvements that will result from the proposed work will have considerable impacts beyond the educational improvements we anticipate for our own students. Indeed, these broader impacts have been alluded to throughout this project description. Within LAR, the new modeling tools will enhance our research program by increasing the knowledge base for our graduate students and summer researchers, and by providing a convenient analysis tool to help explain field observations. Section 7 describes several other LAR programs that complement this work; the success of this project will have a positive impact on those efforts as well. We also anticipate that our framework for introducing inquiry based learning modules will be adapted by other programs at WSU. Our approach is easily adaptable to other fields, and we have strong connections throughout the university arising from our participation in WSU's Center for Environmental Research, Education, and Outreach, and its Center for Teaching, Learning, and Technology (a letter of support from CEREO Director Prof. G.H. Mount is included with the proposal). We also intend to make our modeling tools available to STEM education and atmospheric science communities to broaden our impact beyond WSU; the extent of these efforts is detailed in Section 5.4.

In addition to these impacts, the project will support three students during its duration. Funds are included in the budget to support an undergraduate student during each of the two summers to assist with the development of the model interfaces and learning modules. We have also requested funds to support a masters student during the project's second year; this student will conduct the education research and learning outcomes assessment described in Section 5.3.

9. Project Management & Personnel

The proposed work will be completed within the Laboratory for Atmospheric Research and the Department of Civil and Environmental Engineering (CEE) at Washington State University.

Dr. Timothy VanReken will serve as principal investigator and have overall responsibility for the project. He will also have immediate responsibility for integrating the new learning modules into the early level courses (ENGR 120 and CE 174), one senior/grad level course (CE 591), and into the REU program. Dr. VanReken is an assistant professor with LAR and CEE; his research consists of observational studies of aerosol physical and chemical processes.

Dr. Shane Brown is a clinical assistant professor in CEE specializing in engineering education. He will serve as co-PI on the project and will be primarily responsible for: 1) ensuring that the learning modules are consistent our educational objectives; and 2) conducting outcome evaluations to determine whether course changes result in improvements in learning.

Dr. Serena Chung is a research assistant professor in LAR and CEE and will be a co-investigator on the project. She developed the aerosol research model that we will be adapting for classroom, and is also experienced with the atmospheric chemistry model; she will be responsible for the development, testing, and maintenance of the student interfaces that will enable these models to be used effectively in the classroom.

Dr. B. Thomas Jobson is an associate professor in LAR and CEE specializing in atmospheric measurements of trace gases. He will be a co-investigator on the project and will be immediately responsible for integrating the new learning modules into the two junior/senior level courses (CE 341 and CE 415) and one senior/grad level course (CE 589).

10. Project Schedule

The project will require two years, beginning in January 2009. The model interface development will begin immediately upon the start of the project, with the goal of having the student-accessible interface for the atmospheric chemistry model ready for pilot implementation in time for the 2009 launch of LAR's NSF-sponsored REU program. As the atmospheric chemistry model will be used in more classes and by more students, our efforts will focus initially on this interface and then continue with the aerosol model in summer 2009.

Learning module development will begin in spring 2009 and will continue as the models are integrated into our educational activities. Classroom implementation will occur first during the summer 2009 REU program, and will be occur for all of the target classes during the 2009-2010 academic year.

Assessment of the educational outcomes resulting from the introduction of the new learning modules will occur in parallel with the integration process. By beginning implementation in the first year of the project, we will be able to fully evaluate the effectiveness of the new learning modules and make an initial round of improvements for the fall courses within the two-year project timeline. Any modifications suggested by our initial experience and/or the formal outcome analysis would take place in summer and fall 2010. Manuscript preparation and the dissemination of our results would also occur in these last few months.

A visualization of the project timeline is provided in Table 4 below.

Table 4: Project Timeline

	2009			2010		
	Spring	Summer	Fall	Spring	Summer	Fall
Model Interface Development – Atmospheric Chemistry	▨					
Model Interface Development – Aerosol Processes		▨				
Learning Module Development	▨	▨	▨	▨		
Pilot Implementation – REU		▨				
Implementation – Fall Courses			▨			
Implementation – Spring Courses				▨		
Outcome Data Collection		▨	▨	▨		
Outcome Evaluation and Curriculum Adjustments				▨	▨	▨
Dissemination of Results						▨

11. Results from Prior NSF Support

Capstone Engineering Design Assessment: Development, Testing, and Adoption Research,
NSF Award #0717561, 08/01/2007 – 0/31/2009 ($499,850), D. Davis and S. Brown.

The focus of this project is to develop, implement and test assessment instruments in capstone engineering design courses across the country and to research issues of widespread adoption of these instruments. Co-PI Brown is conducting the adoption research utilizing the theoretical frameworks of the Concerns Based Adoption Model (CBAM) and Diffusion of Innovation. Qualitative data collection methodologies, including in-depth semi-structured interviews and observations, are being utilized to develop a theory of adoption applicable to engineering design assessment in capstone senior design courses. Two publications are in preparation to be submitted to the Journal of Engineering Education.

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