

Creating an On-Line Interactive Earth Science Environmental Simulator



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January 4, 2014

1. Introduction

Instruction and student performance in math, science, engineering and technology (STEM) areas suffer from a lack of realistic applications that motivate students to learn and apply key interdisciplinary concepts. The innovation of this research is the development of a tool that uses four educational methodologies or pedagogies: 1) case studies, 2) inquiry-based virtual laboratories, 3) gamification, and 4) effective use of social interactions. This work also integrates advanced earth system modeling technology with advanced system application models and interactive analysis and visualization capabilities in a framework that allows for positive social interaction.

The project objective was to determine the technical feasibility and commercial potential of addressing the educational shortfall of a lack realistic applications in teaching STEM-related subjects with the development of an interactive tool called the Earth Science Environmental Simulator (ESES). This objective was met by developing a proof-of-concept prototype and testing it with both students and educators who will ultimately be the customers of this product.

This multifaceted tool will allow students to conduct realistic case studies and inquiry-based interactive experiments concerning engineering, atmospheric, hydrological, and geological processes. Case studies are used to put students in realistic occupational simulations to learn skills and concepts and can leverage the technologies to create training tools in numerous areas. Inquiry-based technologies and strategies that have been used for many years by graduate students and researchers in the earth sciences are used in the ESES to create virtual laboratories that allow realistic virtual experimentation of the earth-ocean-atmospheric system for grade 6 through the undergraduate level. The inquiry-based teaching and learning strategies used in the virtual labs are based on the investigation of questions, scenarios or problems. The key to making both the interactive case study and virtual laboratories usable for education is building the proper interfaces and analysis tools. In addition to utilizing the technology there is a need to leverage the basic elements of games and social interaction that make games fun and engaging.

The ESES consists of two main branches, the Virtual Earth Lab (VEL) branch and the Interactive Case Study (ICS) branch, as depicted in Fig. 1.

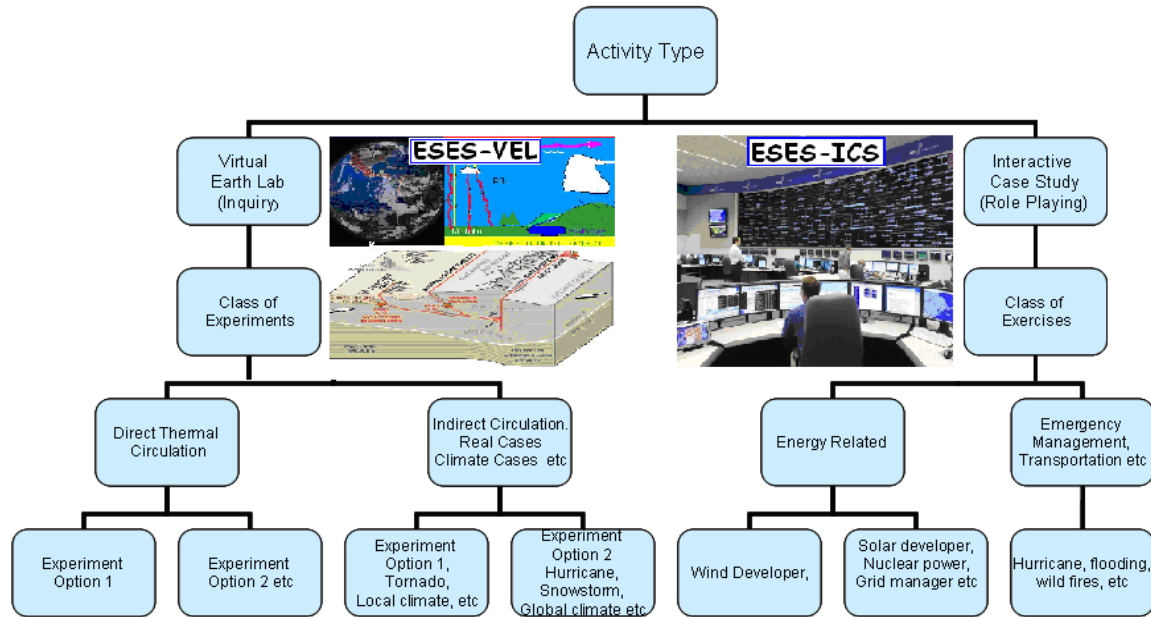


Figure 1. Hierarchy of the initial experiments and exercises. The left side depicts the Virtual Earth Lab (VEL) branch, which allows students to conduct realistic interactive experiments. The right side depicts the Interactive Case Study (ICS) branch, which allows students to learn in a realistic work or research setting.

2. Phase I Goals and Objectives

2.1 Description of Research, Goals and Objectives

The overall goals of the ESES project were to create and test a set of ESES proof-of-concept interactive tools that allow students and teachers to realistically explore concepts and applications related to the earth sciences. The proof-of-concept tools have been designed to allow the student to address the underlying scientific principles and concepts as well as mathematical concepts that control earth science processes and interactively use technology to understand how these concepts are applied in activities such as science research, designing efficient communities, energy engineering and other industries. In the testing, the prototype tools allowed students to address and work through problems and make decisions in real-world situations, with a focus on integrating concepts and knowledge from a variety of STEM disciplines.

The approach taken in developing the ESES is one of rapid software prototyping. Rapid prototyping uses an iterative software development methodology that uses feedback from user testing and analysis to rapidly improve the design and hasten the development of the proposed system. In this process, the two branches, ICS and VEL, were tested and revised based upon user feedback.

The three key questions addressed in Phase I in order to achieve the project goals were:

- (1) Can the ESES, with *all* its functionality, be made available in an online environment?
- (2) Can the ESES operation be made intuitive enough so that pre-college and college students and educators can perform meaningful experiments?
- (3) Is the proposed ESES an improvement over currently available literature, media, or technological resources for furthering science content knowledge through inquiry?

The primary objectives of the Phase I research to achieve the project goals were to:

- (1) Create a prototype interactive modeling system that addresses the STEM subject educational shortfalls.
- (2) Create a commercially viable ESES that is accessible using standard browsers.

- (3) Create intuitive interfaces and visualization tools for controlling the input data and analyzing the output data.
- (4) Do an initial educational evaluation with carefully selected pre-college and college-level science educators.
- (5) Develop an online and DVD-based video demonstration and presentation of the ESES for the purpose reaching out to educators and possible marketing partners.

2.2 Summary of Goals and Objectives Met

A prototype ESES was successfully created in order to allow student and teacher testing of the ESES. It was determined that the ESES, with all its functionality, can be made available in an online environment. However, it will take more development in Phase II to improve the intuitive aspect of the interface and analysis to meet the needs of the students. Also more development is needed to make the virtual labs a completely seamless and efficient process. It was determined that to reach potential customers and strategic partners a video demonstration is more effective online than a DVD, so the DVD alternative was not pursued.

The educational testing in Phase I determined that ESES operation (designing experiments, entering data, and selecting types of output for data analysis) can be made intuitive enough for pre-college, college students and educators. The initial testing found that even at the middle school level many students appear to have the computer skills and abstract thinking ability to operate ESES in a meaningful way. The Phase I testing with students illustrated three areas that need to be addressed in Phase II: (1) there is a need to improve the intuitiveness of the interface and analysis in order to maximize the effectiveness of ESES for a broad range of teaching environments and levels, (2) there is a greater need for detailed instructions in the online teaching environment than is needed in the face-to-face environment, and (3) the interfaces need to be structured differently at the middle and high school levels compared to the undergraduate level. It was found that with development the ESES interface can be made customizable to meet all three areas that need to be addressed.

There are many STEM-related online services and teaching tools, but it was found during the in-class testing of the ESES that even the proof-of-concept ESES addresses meaningful activities that go beyond anything that can be done with currently available literature, media, or technological resources.

3. Research Activities and Results

3.1 Technical Development

The following describes the results of the Phase I tasks that were designed to answer the three key questions and meet the objectives.

A proof-of-concept prototype ESES was created that is comprised of two branches. As depicted in Fig. 1, the two branches are: (1) the ICS branch that is application-based; and (2) the VEL branch that is inquiry-based. Early in the project, MESO learned of the GEOpod, a visualization learning tool developed by the Computer Science and Earth Science departments at Millersville University through a National Science Foundation grant NSF-IIS 0835411 (Yalda, 2012). The GEOpod is a useful visualization package for exploring meteorological and other scientific gridded datasets and will be leveraged in Phase II as part of the visualization capabilities in the ESES labs.

3.1.1 Technical Development: ICS Branch

The development of the ICS branch was accomplished first. ICS exercises provide students the opportunity to conduct interactive case studies in a realistic research or work setting involving the earth sciences and other STEM-related disciplines. The prototype ESES-ICS branch exercise was constructed under the Drupal content management system. Drupal was sufficient but there may be more optimal programming packages that will likely be more effective for further work. The prototype is an electrical grid management exercise and is a good example of how earth science information is used to make energy/engineering decisions in managing the grid. It is important to keep in mind that this is just one example of an ICS exercise; the same approach could be applied to any number of real world settings, such as transportation management, emergency management and environmental sensor design.

The student begins the grid operator exercise by constructing a simulated city to manage. The energy characteristics of the city can be specified in various methods, as shown by a portion of the user interface

in Fig. 2. In addition to the electrical load (demand) of the student's simulated city, the available electrical generation is chosen as a mix of conventional and/or other sources. The key is that some components of the electrical generation (wind, solar, and hydro) are sensitive to the weather, so the student must make a weather forecast. The actual weather will affect not only the use of energy but also the ability to generate it. To make the required 24 hour weather forecast, the student is given actual weather data for start of that day, just as if they were producing real-time forecasts. The student makes a forecast and receives immediate feedback on the potential impact of the forecast on both the load and power generation. The student then makes a decision on how much conventional power (coal, petroleum, and/or natural gas-fired) to dispatch, given the estimated wind, solar power, etc. that will be available if the weather forecast is correct. The student has to grapple with the real-world uncertainty of the weather forecast, the electrical load and the electrical generation from a mix of sources. Once the student makes a decision and submits the dispatch of conventional power, the student receives immediate feedback (Fig. 3) on whether or not the power needs of the city were met and data on any amount of unnecessary power (along with costs) that was requested.

Figure 2. A part of the graphical user interface for the grid operator case study.

Final Generation Analysis

Uh-oh! You have caused a blackout -- try again!

Weather Forecast Impact Analysis

Student total power forecast:
 Non-conventional power + conventional power called up: **2047 MWh**
 Actual generation needed based upon observed: **1975 MWh**
 Net total power forecast over or under actual power needed: **72 MWh**
 (want this to be as small as possible)

Conventional Generation Analysis

Conventional generation called up by student: **625 MWh**
 Conventional generation needed: **753.4 MWh**
 Conventional power over or underproduced: **-128.4 MWh**
 (want this to be the lowest positive value)

Final Generation Analysis

Yay! You have successfully met the needs of your city, and everybody has electricity!
 But keep in mind that for every megawatt hour that you go over the needed amount, the electric bill goes up.
 To see if you can get closer to zero, try again.

Weather Forecast Impact Analysis

Student total power forecast:
 Non-conventional power + conventional power called up: **2192 MWh**
 Actual generation needed based upon observed: **1975 MWh**
 Net total power forecast over or under actual power needed: **217 MWh**
 (want this to be as small as possible)

Conventional Generation Analysis

Conventional generation called up by student: **770 MWh**
 Conventional generation needed: **753.4 MWh**
 Conventional power over or underproduced: **16.6 MWh**
 (want this to be the lowest positive value)

Figure 3. The generation analysis feedback provided to the student tells student if weather forecast and conventional power generation dispatch were (a, top) unsuccessful, or (b, bottom) successful.

The educational evaluation of our first ICS prototype indicated that the ICS was adequate with face-to-face instruction when an instructor could offer guidance. The comments from both students and teachers, although generally quite positive in terms of the value of the ICS approach, indicated that considerable work will need to be done to refine the interfaces and delivery of the case study data to make the exercise acceptable at a commercial level. This was particularly true for classes that were done strictly in an on-line environment.

3.1.2 Technical Development: Virtual Earth Lab (VEL) Branch

The development of the VEL branch involved creating a prototype physics-based virtual laboratory that can address the needs of current earth science education. This initial proof-of-concept module is an atmospheric science virtual lab intended to help students understand the sea breeze circulation, a very common and important weather feature along coastlines in much of the world. The module begins with a series of slides describing the physical basis of the sea breeze circulation, which is driven by a surface temperature contrast between the land and water (land temperature is warmer). The module web pages are written using the advanced HTML5 markup language, which allows the module to be viewed easily on multiple platforms including desktop browsers, tablets, and smart phones. Fig. 4 shows a sample page that uses an HTML5 Canvas animation of the sea breeze circulation. The arrows seen in Fig. 4 move to show the circulation and the sea breeze front as the animation steps through a typical day.

The key VEL innovation is to permit the user to interact with powerful physical models, such as the atmospheric model used in the sea breeze module. The concept is that the user can quickly execute a set of "what if" simulation experiments designed to answer a particular question and explore the results with advanced visualization tools. While it is difficult to actually run live full-physics simulations in an online environment, it is possible to allow the students to choose a combination of several important input data and physics options and then see and explore the output of corresponding stored simulations.

For the sea breeze module, the student can vary the shape of the coastline, the initial land and water temperatures, the initial soil moisture, and then see videos of output from idealized simulations with the chosen characteristics to help in understanding the factors that are expected to make the sea breeze stronger or weaker.

In addition to the above options for the sea breeze module, our full access to the atmospheric model easily allows a wide range of other factors to be manipulated by the students in other "what if" experiments, for example: (1) changing the horizontal and vertical geographic distribution of all surface properties and atmospheric conditions; (2) controlling the schemes that model the physical processes of the atmosphere; and (3) modifying selected physical constants such as gravity, the rotation rate of the earth, or the latent heat of vaporization.

This kind of inquiry-based learning requires active participation and has been shown to engage students more than typical traditional methods (Geier et al. 2008, NRC 2012). In addition to idealized modeling, the same approach can be used on actual historical cases of interest, and eventually with real-time simulations of the current weather. A historical snowstorm case was partially developed as a second module to highlight this additional capacity.

The exploration and analysis tools developed for the VEL included 2-D and 3-D animation, time series and vertical profile visualization and analysis capabilities. An exciting component of the VEL exploration and analysis toolkit is the Millersville University GEOpod visualization package that was used to create 3-D "fly-through" videos; a frame of one of the videos is shown in Fig. 5. Other analytical tools were also developed, including the ability to create time series for a particular location and vertical profiles (soundings) of the atmosphere.

Preliminary investigations were performed to determine how to incorporate several earth science models within the VEL environment in order to broaden the approach to perform experiments that involve all parts of the earth-atmospheric-ocean system. The atmospheric models used were the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008), and the Mesoscale Atmospheric Simulation System (MASS) model (Manobianco et al. 1996, Kaplan et al. 1982). For complex earth surface and subsurface hydrological processes, the Distributed Hydrology Soil Vegetation Model (DHSVM, Wigmosta et al. 2002) was investigated. The National Center for Atmospheric Research's Community Earth System Model (CESM) contains several components, including climate, ocean, land ice and sea ice models, that could be included as part of VEL. A model based on the USGS Geologic Modeling Methodology Geological

process was also investigated for use in modeling geological processes (<http://pubs.usgs.gov/sir/2010/5246/section5.html>).

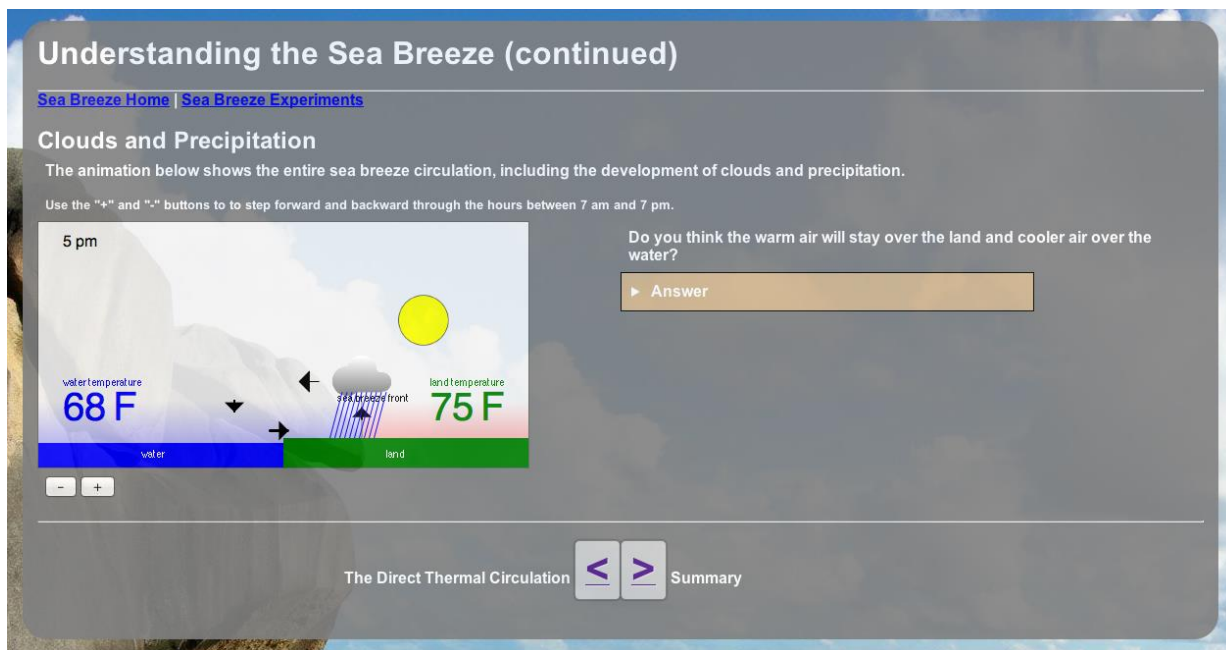


Figure 4. Sample page from the prototype ESES-VEL sea breeze module.

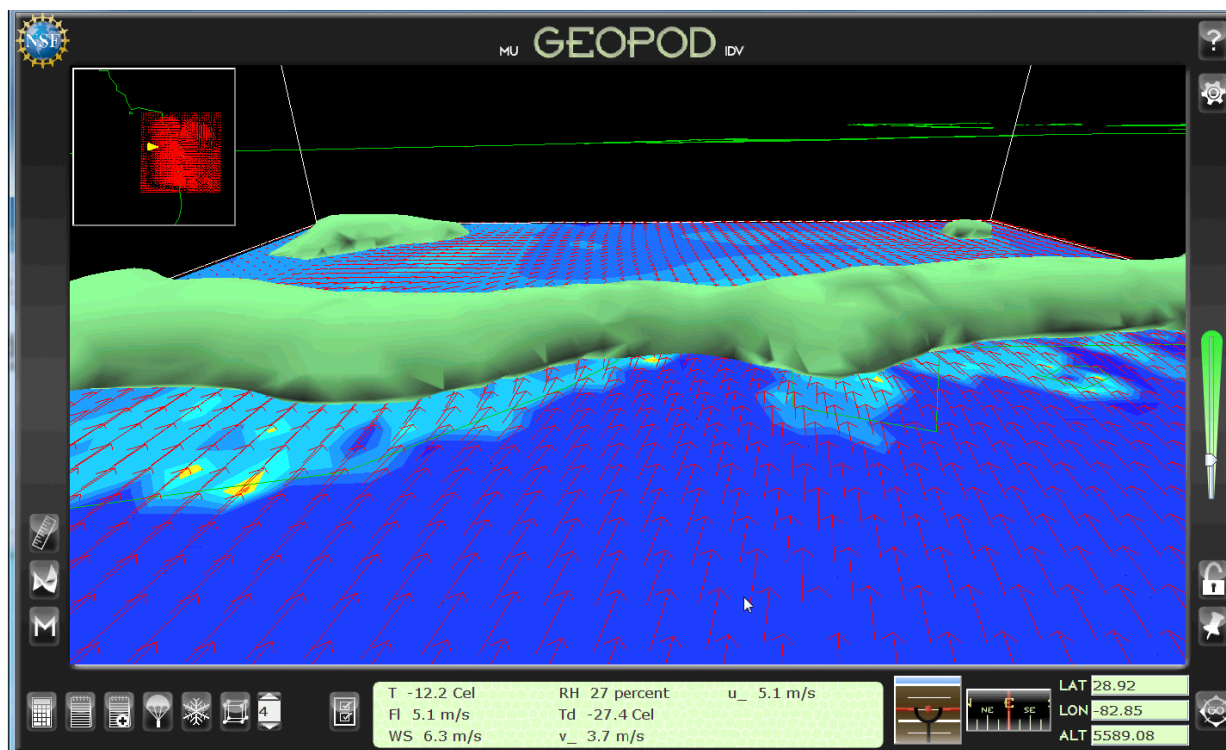


Figure 5. An example of a 3-D fly-through capability using the GEOpod. The view is from the water toward the land. The green tube is the 3-D surface of high vertical velocities (rising motion) parallel to the coastline caused by horizontal convergence in the sea breeze front.

Several challenges will need to be addressed to fully include the full range of models. They are: (1) integrating atmospheric model output that is needed to initialize the earth science models, such as hydrological, ocean and surge; (2) expanding the functionality of the GUI to be able to configure and analyze the output of the various earth science models as consistently and seamlessly as possible; and (3) putting the output from the earth science models in a format that can be read by the VEL visualization and analysis tools currently being developed.

3.2 Development of Supporting Instructional Material

Development of the ESES ICS and VEL Instructional Modules included the construction of an instructional module for the prototype exercises and experiments with three on-line components: (1) a tutorial and user's guide; (2) an electronic exercise lab manual; and (3) an information almanac and glossary.

The first step in developing a tutorial and user's guide involved developing a set of pre-run case studies and experiments that were created by MESO and tested by student assistants at the State University of New York Institute of Technology (SUNYIT) and Millersville University. Feedback from student assistants helped confirm that the tutorial and user's guide helped both instructors as well as students in understanding how to use and run the ESES sample cases and experiments.

MESO then created an initial version of the on-line electronic lab manual using hypertext and graphics to help organize the case studies, data exploration and model experiments. As part of the online help, MESO also created a prototype instructional database and almanac with term definitions, background mathematical information, and weather and climate information such as climatological means and extremes. The prototype almanac and glossary are accessible in both the data exploration and experimentation modules. MESO also created a separate instruction-generator utility that will permit a user to interactively create a specific instruction database.

3.3 Educational Research and Assessment

For the prototype, both a case study exercise (ICS branch) and a lab exercise (VEL branch) were developed in order to demonstrate and test the capabilities of the two branches of the ESES.

3.3.1 ESES ICS Exercise Examples

The sample case study exercise used for the evaluation revolved around a series of connected modules involving the planning and managing of the electrical grid. Fig. 6 illustrates the four areas covered in the modules: load planning, power generation, transmission, and grid management. It must be emphasized that this is just an example of how the ICS role playing exercises can be used in order to provide case exercises that could be evaluated in a classroom setting. Any industry or research area that is impacted by the environment could be addressed through similar role playing activities, such as emergency management, transportation management, sensor design, water management, and forensic meteorology, to name a few.

There are several exercises within each of the grid planning modules. For example, the load planning module has short exercises on energy efficiency that cover energy efficiency topics ranging from something as small as a home to those involving a whole city. There is also a separate module that covers how the weather and environment impact the performance of the grid. Exercises in this module cover multiple topics, from how each weather element and condition impacts the operation of the grid to load, to power generation, and transmission. In addition, historical and real-time exercises are provided on how to make a basic weather forecast for intermittent renewable energy generation.

The final module involves the management of the grid. The grid operator exercise can be used as a stand-alone set of exercises or as a set of capstone exercises based upon completing the planning and weather impact modules.

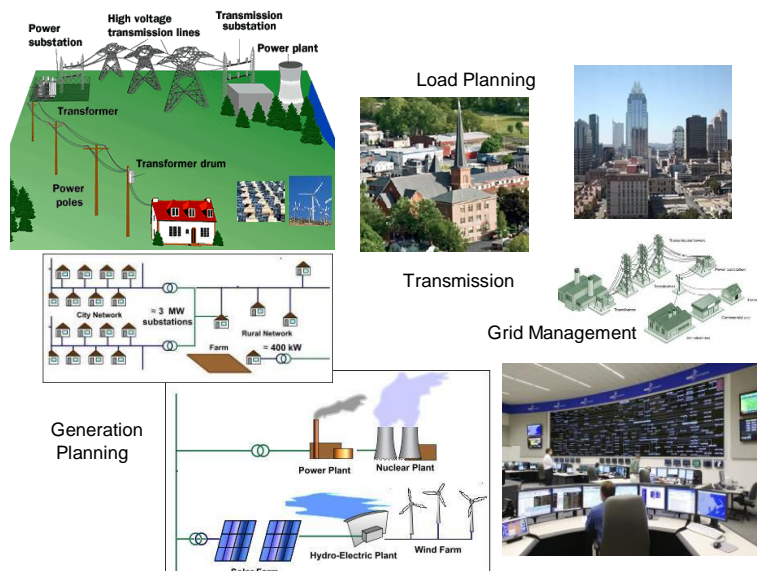


Figure 6. The four areas covered in the sample case study exercise are load planning, power generation, transmission and grid management.

3.3.2 ESES ICS Educational Evaluation

The ESES-ICS sample exercise was tested educationally during Phase I in several settings. The first testing was done by a small set of carefully selected students. Initial modifications were then made according to the preliminary student feedback. The sample exercise was then tested further in informal educational settings, such as science clubs, which provided more feedback for additional revisions to the prototype exercises. Finally, the sample ICS exercise was used in formal face-to-face and online courses at the undergraduate, high school and middle school levels. Additionally, the ICS was presented to several State University of New York instructors in a workshop setting in order to obtain their feedback on the exercises and gather their insights about the potential of this system for classroom instruction in the sciences. Table 1 provides a summary of the institutions, courses, and number of participants who were involved in the testing of the ICS.

Table 1. A Summary of Institutions and Participants in the ICS Educational Evaluation

Institution	Course	Participants
State University of New York (SUNY)	Workshop	10 professors
SUNY Information Technology	IEEE Student Association Meeting	3 students, 3 professors
SUNY Information Technology	ETC 299 Special Topics in Engineering	26 students, 1 professor
University at Albany SUNY	ATM 480: Weather, Climate, and Society	12 students, 3 professors
University at Albany SUNY	ENV 250: Energy and Resources	33 students, 1 professor
Millersville University, Millersville PA	ESCI 245 - Environmental Science	21 students, 1 professor
Saint Louis University, St. Louis MO	EAS-107- Understanding the Weather	24 students, 1 Instructor
NY LEAH, Home School group, Rome NY	General Science Grade 7-8	6 students, 4 parents
NY LEAH, Home School group, Rome NY	Physics Grade 11-12	2 students, 1 parent
Tech Valley High School (TVHS), Rensselaer, NY	TVHS Presentation	4 students, 4 teachers

Survey questions to evaluate the ease of use and educational merit of the sample exercises were prepared and administered in all the Table 1 evaluation sessions. For classes where there was an opportunity for both a pre- and post-exercise evaluation to test content knowledge assessment, a set of questions were provided to the participants. Comparisons of participant's pre- and post-test responses provided a metric for measuring the student's content knowledge gains as a result of completing the exercises.

Tables 2 and 3 summarize the result of the Likert-based scale surveys and the pre/post assessments from 99 undergraduate students. The comments from students, teachers, professors, and parents, thus

far have been very positive. However, because of the limited sample of students and the fact the ESES-ICS is still under development, it is too early to draw definitive conclusions about the educational value of using the ICS. Our findings suggest, however, that the use of ICS clearly changes the dynamics of the classroom with the students being the focus and the teacher becoming a facilitator. The general observations made by the students and instructors at all levels were that: (1) this approach added value educationally in terms of gaining more knowledge and deeper insight into why a certain scientific concept is important; (2) by bringing realism and application into the classroom, it increases student interest and better prepares them to use the knowledge gained in the world outside of the classroom; (3) because they can perform the same basic exercise for a new 'day' it becomes a whole new challenge; and (4) it allows students to develop and practice basic skills, such as math and computer science, by performing the exercises. Despite these very positive outcomes, participants also suggested that the ICS still needs much refinement to be user friendly enough for routine in-class use.

Table 2. Summary of survey results for face-to-face undergraduates (results are from 99 students)

Evaluation Element	Avg. Rating*	Summary of comments from Likert scale items, opened ended questions and in class discussion.
Instructions	3.3	Students felt the instructions were adequate but need some improvement.
Interface design	1.3	Students felt the interface needed to be more intuitive and interactive.
Keep their interest	4.1	Even though the students found that the interfaces needed to be better, they found them easy enough to work with in the context of the exercise, and that the exercises were very interesting.
Felt they learned something new	4.5	They felt that the exercises allowed them to delve into the material to understand it at a deeper level and learn information that they would not have otherwise understood.

Table 3. Summary of survey results for online undergraduates (results are from 21 students)

Evaluation Element	Avg. Rating*	Summary of Comments from Likert scale items, opened ended questions and in class discussion.
Instructions	2.4	Students felt the instructions were adequate but need some improvement.
Interface design	1.4	Students felt the interface needed to more intuitive and interactive.
Keep their interest	4.2	Even though the students found the interfaces needed to be better, they found them easy enough to work with in the context of the exercise, which they found very interesting.
Felt they learned something new	3.3	Students felt that the exercise allowed them to learn information that they would not have otherwise understood.

*Avg. Rating: 1=needs considerable work, 5=needs no work

There was a difference in the evaluation of the face-to-face classes as compared to the online class. It is apparent that the instructions and software still need considerable work to be as effective in the totally online environment as in the face-to-face classroom environment. However, the general consensus for both the face-to-face and online classes was that the approach was one that enhanced interest and learning. For those classes that answered pre- and post-conceptual questions, the improvement in understanding was noteworthy. For the conceptual question approximately 30% of the students selected the correct answers in the pre-test as compared to approximately 60% of the student selecting the correct answers in the post test after the exercises.

3.3.3 ESES VEL Exercise and Evaluation

Because the prototype VEL was still under development when the 2012-2013 school year ended, only informal evaluation of the VEL was possible. The informal evaluation consisted of three high school teachers, two college professors and three students in grades 8-10. Even though the evaluation was informal it was conducted in a simulated classroom setting and did give insights into the value of the inquiry tool.

The initial virtual lab experiments created for the prototype were based on the investigation of the direct thermal circulation associated with a sea breeze. The sea breeze experiments demonstrate how unequal heating generates a direct thermal circulation, the most basic of circulations. In order to achieve the Phase I goal of demonstrating feasibility, it was deemed best to first run a simulation experiment which was driven by local surface forcing, such as a sea breeze, instead of one driven by transient atmospheric

features. The main reason for selecting local surface forcing was the greater simplicity in generating initial conditions and the interpretation of the results by the students. It was decided to implement and test the sea breeze experiment first because it is a very basic, well-defined, and physically understood atmospheric circulation system, which exemplifies the concept of a direct thermal circulation. More importantly, there are easily definable parameters that the student can adjust to test the effect they have on the development of the sea breeze.

Another important aspect of the sea breeze experiment is that it is easy to document with sensible weather elements, such as temperature, dew point, wind direction and speed, clouds and precipitation. Also, it is straightforward to depict with satellite imagery and links to a well-established theoretical foundation found in the literature and textbooks.

In the sea breeze experiment, a series of model simulations were set up and run at a 1-km model resolution by the student to correlate the initial atmospheric conditions and land characteristics to the strength of the sea breeze, vertical motion and resulting sensible weather. Atmospheric conditions, such as temperature, humidity, stability and wind, as well as land characteristics, such as the shape of the coastline and type of land use, (Fig. 7) were defined by the student and teachers using the GUI (Fig. 8) for the control and subsequent experimental simulations. A series of experiments were then run by the students by modifying the initial atmospheric and land characteristics conditions of the simulations using the GUI as shown in Fig. 8.

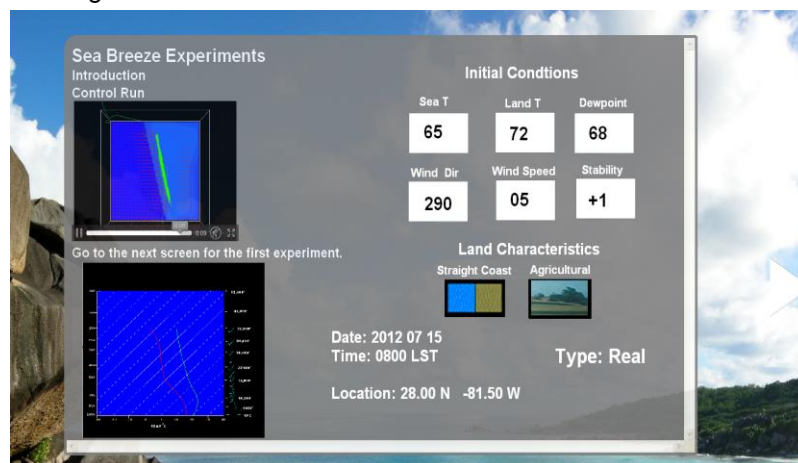


Figure 7. An example of a control run simulation set up page. The progression of the simulation can be viewed as an animation in the upper left screen.

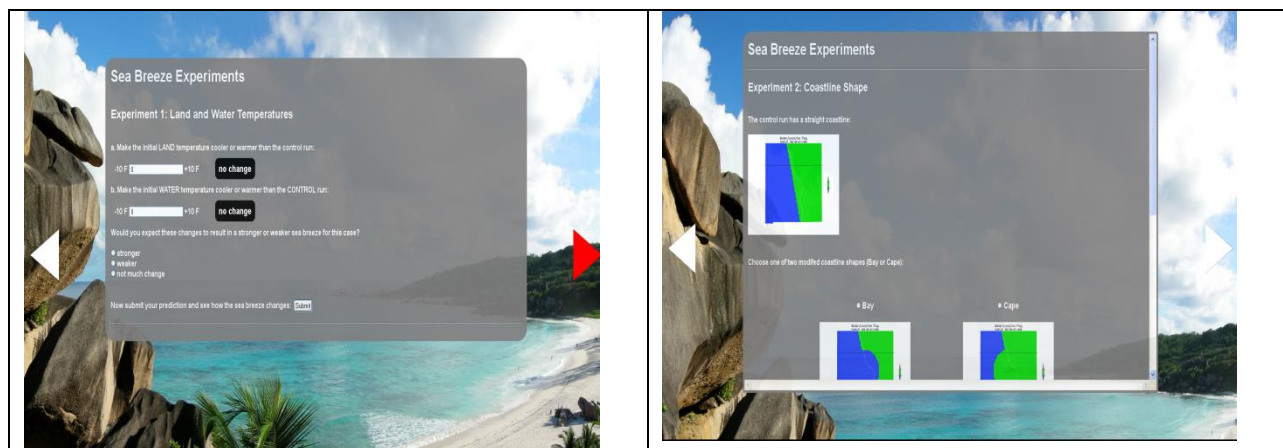


Figure 8. Example of GUI that allows student to modify initial atmospheric and land use characteristics.

The 2-D, 3-D, animation, time series and vertical profile visualization and analysis capabilities provided by the exploration and analysis tools described in 3.1.2 were then applied to the output data by the students and teachers.

Several teachers who evaluated ESES commented that it would seem more appropriate to investigate a "basic" weather concept such as a cold front that is more widely taught and understood than the sea breeze phenomenon. This misconception highlights the value of the ESES-VEL branch. Many of the concepts in meteorology, such as the cold front, are based on necessarily oversimplified conceptual models of very complex phenomena that are really the product of many interactions at numerous scales. The ESES can incrementally examine such complex phenomena.

The ESES-VEL can certainly be used to experimentally investigate and reveal the true nature of complex phenomena such as a front. It was felt, however, that it is essential to begin with a system that operates at one meteorological scale in order to be able to understand how to use the ESES-VEL and learn how to interpret the experimental data analysis. More complex topics could then be investigated. For example, after conducting the sea breeze experiments, the teachers and students understood how important it would be to start with simple concepts, such as the sea breeze induced direct thermal circulation, which has some of the characteristics of a cold front, and then build upon the knowledge they obtain to investigate more complex phenomena, such as fronts.

Another consistent comment made by the teachers who evaluated ESES was that the ability of ESES to create analytical cross sections was very important in allowing students to visualize and understand the dynamic processes of the atmosphere or ocean circulations. The 3-D fly-throughs were also helpful, but a time series of cross sections is needed to reveal the internal processes the sea breeze.

Another set of experiments (designed but not tested due to time limitations) was performed independently by the researchers developing the ESES. The experiments were performed to see how they could demonstrate certain aspects of the ESES-VEL utility as a teaching tool. Experiments involving the following concepts were performed but not tested by students:

(1) Understanding the geostrophic adjustment processes that take place in the vicinity of an upper-level jet streak (ULJ) and the resulting indirect thermal circulation. This is an important atmospheric process that is a cause of upward vertical motion and precipitation. However, it is conceptually a difficult concept to teach because cold air is forced to ascend and warm air descends in this process. The VEL could be a great asset in teaching this type of concept.

(2) The role of water vapor in the atmosphere on vertical motion and precipitation. Another key process not easily grasped by students.

(3) The impact of land surface characteristics, such as snow cover on storm development.

3.3.4. Next Generation Science Standards

The Next Generation Science Standards (Achieve, Inc., 2013) were in the process of being published during the period of this project. Upon review of the new science standards, many of them recommend the use of physical science models in order to effectively teach the earth sciences. The ESES has been designed to meet these new science standards, with the use of modeling, cross-disciplinary content and skill development.

4. Lesson Learned

The technical development and evaluation feedback from students and teachers involved in the classroom exercises support the case that both the interactive case studies and the virtual earth labs can help improve learning of STEM subjects that involve the earth sciences and related sciences.

We found that it is critically important that both the VEL and ICS be made available online as the cost in dollars and time to maintain an onsite system is prohibitive for most educational markets. The fact that the ESES is available online and accessible using standard browsers is a major marketing point.

4.1. Technical

This project successfully created a prototype interactive modeling system that provided a basic capability for performing role-playing case studies and virtual earth lab experiments, using real data and authoritative modeling systems. Both the prototype VEL and ICS are accessible online using standard browsers. The prototype virtual earth lab introduces interactive web animations to explain physical concepts, and images and video animations of atmospheric model output to explore real-data simulations and test hypotheses.

The ability to create intuitive interfaces and visualization tools for controlling the input data and analyzing the output data has been very challenging. Significant progress was made in the project, but much additional work is still needed, such as adapting the GEOpod software to run online.

4.2 Education

The evaluation of the technological innovation of the ESES demonstrated that it has a clear potential to help address the shortfalls of a lack realistic applications in STEM education, especially in the earth sciences and to assist teachers and students alike in engaging with difficult concepts and phenomena in the earth sciences. However, to become commercially viable, work is still needed to improve the functionality, visualization and analysis tools of the two branches the ESES.

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Work on this project was performed for the National Science Foundation Phase I Small Business Innovation Research grant IIP-1248765