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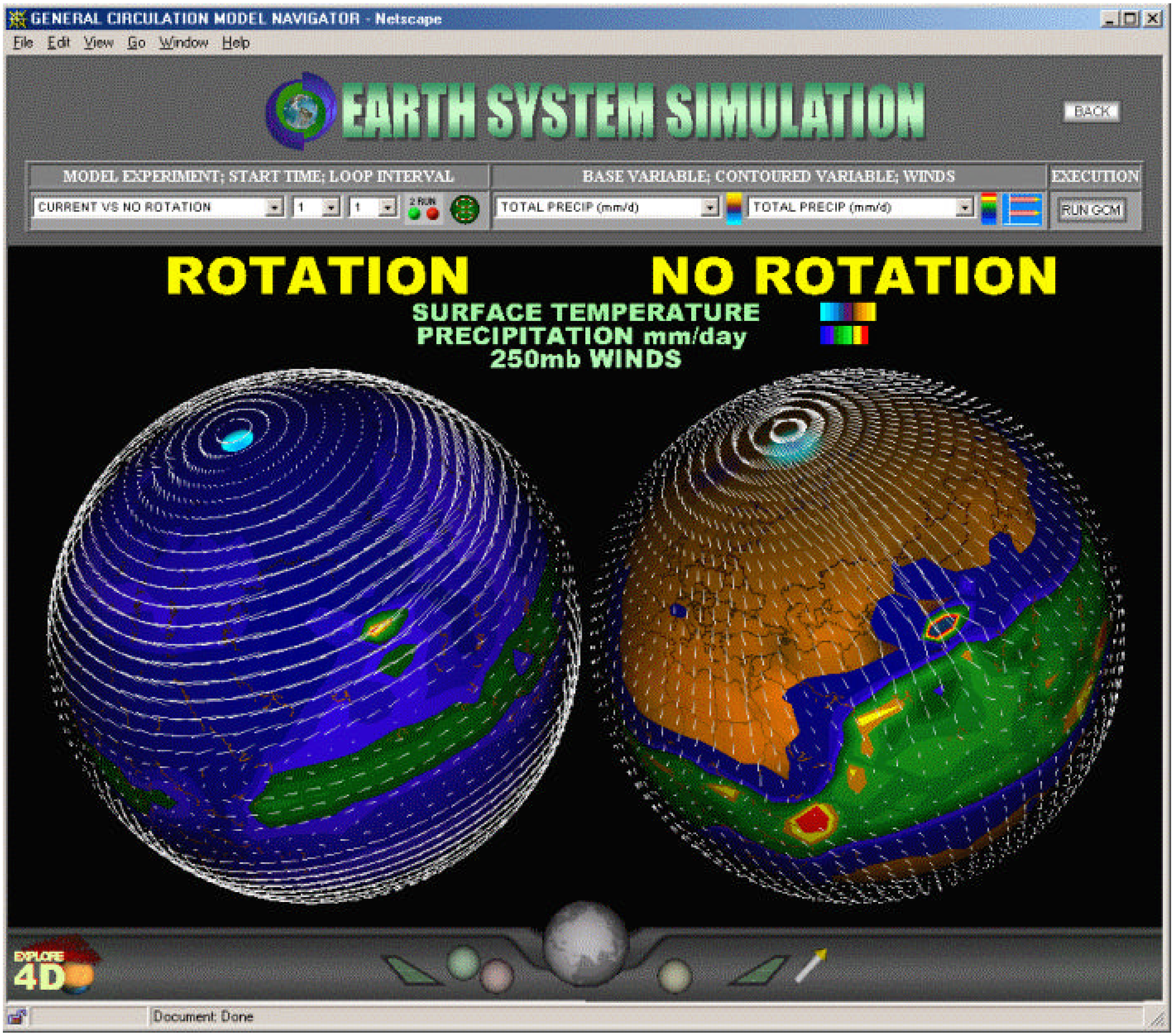

COMPUTATIONALLY INTENSIVE MODELS IN THE CLASSROOM

Earth System Science Education, 2001

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Abstract

We present a strategy to put modern earth system numerical modeling and data fusion into the hands of teachers and students investigating weather, climate and global change. There are four key aspects of this strategy: (1) Configure and run computationally intensive earth system models; (2) Design experiments with fundamental educational value which reveal unifying concepts of earth system science; (3) Deliver interactive, 3D time-dependent visualizations of model runs to student desktops; (4) Integrate all components into pedagogical designs to develop knowledge and intuition about earth system science. Prime target groups are: Undergraduate college students pursuing earth system science as a major area; Pre-service and in-service science teachers; professional colleagues who might also become engaged in pursuits of modern, technology-enabled educational developments.

1. Introduction

The current generation of pre-college and college age students are far ahead of their adult mentors in computer and Internet savvy. After playing high performance three-dimensional interactive war games in hangouts beyond the school yard, they sit down in educational computer labs to a lot of static two-dimensional educational materials. Their hunting skills are not being challenged by our science educational hunting grounds. Bringing the privileged domain of advanced research inquiry and discovery to their desktop environment provides an exciting opportunity for improving education. Developing useful, inquiry-based, intuition-driven educational modules from research accomplishments requires quite a bit of scientific and pedagogical design work. Subject lessons may be supplemented by computationally simple scientific calculation and visualization to focus on underlying concepts and principles.

Modern research endeavors in earth system science (ESS) cover the range of time-space scales from global climate change to the regional and urban scales of advanced mesoscale numerical weather prediction (NWP). Educational products derived from ESS research can have enormous currency to students. Work, classroom, and leisure activities all proceed in the earth system environment that is under study. The National Science Foundation's (NSF) long-range planning document, NSF GeoSciences Beyond 2000, defines the need for ESS research and education and the commitment to developments that benefit both researchers and educators. From NSF's Geosciences Directorate, the report Geoscience Education: A Recommended Strategy also encourages the science community to initiatives "... bringing cutting edge research into the educational mainstream." Those challenges stimulated the initial developments for year 2001 described herein.

The principal goal of this article is to demonstrate a few examples of how modern research-produced results in ESS can be brought into a virtual, interactive learning environment for today's students. Developments to produce the 21st Century science content for the national "Digital Library for Earth Science Education" (DLESE) are objectives of the demonstrations cited. Such materials are produced from computationally intensive earth system models and massive databases. The learning environments for students include both classroom community involvement and individual self study. In our view, education in the future should proceed through a scientific intuition-building process using interactive virtual laboratories, modules, and tutorials. Authors needed to integrate the following processes:

- Science: Configure and run modern numerical models of earth's weather and climate behavior that directly support educational goals.
- Technology: Deliver the model and data realizations as interactive advanced scientific visualizations on remote desktop PCs common to classrooms and student computer labs. Develop diagnostic tools to help understand the vastly complex results.
- Pedagogy: Imbed tutorials and documentation into a tightly integrated student-learning system patterned in the style of intuition-driven inquiries, hypothesis building, and virtual hypothesis testing.

To stimulate interest in what is to follow, readers can take a quick look at the science and technology components of our journey in a browser-based advanced 3D visualization of Hurricane Andrew created from the Penn State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (i.e. "MM5"). This demonstration is on-line for JESSE readers at http://meto.umd.edu/~owen/JESSE/HurrAndrew.html

Our demonstration will show the process of bringing advanced science into the classroom. The key to this demonstration is to carefully design a selection of virtual laboratory experiments, computational model simulations, and data excursions in order to build student intuition about how some aspect of ESS phenomenology works. The design involves structuring a process of scientific discovery, and building scientific intuition within each virtual laboratory experience. Building intuition for young students is substantially different than extending it for seasoned professional researchers. It is not sufficient to post a complex graph of a late-breaking scientific result on the web with the hope that research colleagues - and their children - will each receive the same important lesson.

Johnson, Manduca and Snow (1999), Co-Convenors of the August 1999 Coolfont Workshop on DLESE, write *"... the Digital Library will also facilitate the development of tools for the visualization and analysis of on-line datasets. Electronic delivery will provide imagery of the Earth system in 3 and 4 dimensions, and access to archived or real-time large datasets in support of research-like experiences for all students."* To achieve such a digital, educational context, a technology transfer system involving complex "client-server" software is needed. Performing scientific model computations and preparing advanced visualizations are most efficiently conducted on powerful computational servers at research/educational centers. Delivering the results of this computational heavy lifting to desktop PCs around the world is best done across the Internet. Client-server technology directed at computational models in the (remote) classroom are now in hand. Examples are demonstrated here. They provide for highly interactive virtual realizations that encourage students to examine, manipulate, and discover; then to request new data fusions and views for further learning.

The Internet technology design provides for 2 kinds of research interaction for students: decide what model/data server you want to visit, and what data you want to get; interact with rendered visualizations of requested data, and tutorial materials appropriate to your request. The first of these is an important key to learning, for it stimulates thought-provoked curiosity. The natural progression of professional research includes crucial "what if" experiments that often reveal new behaviors and concepts. No one would disagree that education should also provide such opportunities for students. But no one has ever been able to give their students their very own earth system which would allow them to, say, rotate the earth backwards; raise and lower the sun's radiational energy load; move the continents back to their "Pangea" configuration. Such "what if" experiments help guide students in discovery of new concepts for *their first time*. Designing research experiments for students that parallel professional research practice is fundamental to the goal of this work.

2. Interactive Educational Module Design

The results to be shared in this paper initiate our search for a durable design for 21st Century educational modules built around advanced science and technology achievements. The most important part of the design is pedagogical. Our educational module template consists of a coordinated set of student research experiment components. Each component of the module should have certain basic properties:

1. Introduce one or more new concepts which build upon previous components in a coordinated way.
2. Emphasize the discoveries and findings of the research project.
3. Stimulate articulation of new questions raised by the research experience.
4. Stimulate the formation of one or more hypotheses concerning the questions raised.
5. Stimulate the formation of one or more "What If" conjectures to encourage intuition development.
6. Help focus questions, hypotheses, and conjectures towards a new experiment.

In our view, the importance of "what if" experiments for students cannot be overemphasized. Our Earth climate is the result of a complex and delicate balance: the sun heats the atmosphere, the oceans and the land, more in the tropics than in high latitudes, and more in the summer than in the winter. Water evaporates, is transported by the wind, and condenses into clouds and precipitation. The winds develop because the earth rotates around its axis once a day. When the authors of this paper were young students, we all dreamed about being able to answer questions such as:

> *The seasons are due to the tilted axis of rotation of the earth. What would happen if the earth did not rotate? What if the axis of rotation was not tilted? What if there were no oceans? Why is there a Sahara desert in Northern Africa and not in Southern Africa? Would it be different if the African continent had a different shape? Can we try to change the shape of the continents and see how climate would develop?*

One of the most important problems that faces mankind is climate change. We frequently hear about the "greenhouse" effect, and the impact of "greenhouse gases", as well as the reduction of "good ozone" and increase of "bad ozone". It would be ideal if students, and even politicians, would be able to answer experimentally questions such as:

> *What would be the major changes if we allow CO2 to double, or even to quadruple? What is the greenhouse effect anyway? How will the sea surface temperatures change? And the temperature over land?*

Our dream is coming to pass. We demonstrate here the ability to integrate computationally intensive modeling into the classroom using massive model databases stored on remote servers. Our next goal is to configure computationally intensive *educational* models available to the classroom in active computation mode using client-server technology. Finally, we seek to develop user-friendly earth science computational models which execute and visualize on desktop computers. Students will be able to change the local configuration easily so that they can conceive model experiments and research questions by themselves. For example, to be able to change the shape of the continents, or to change the axis of rotation, or to double the amount of CO2 in the atmosphere. They would be able to run a "control" run with the present system, and an "experiment" run with the changed continent, rotation or shape of the continents. The system will provide students with modern, visualization output that summarizes the main changes.

As the new century progresses, we anticipate a large number and variety of computational model runs, data analyses, and discovery modules explicitly geared toward education. A large pyramidal matrix of targeted modules will develop from that community effort. Ideally, every point of a student's curiosity will lie somewhere in the middle of such a matrix. Opportunities for review and refinement of concepts already met by the student will appear within its broad base with new discoveries and enrichments appearing just above within easy reach. This educational module matrix will have been delivered by an expanding number of research-educational teams around the country organized around emerging "digital libraries". A large module matrix would allow student groups to pursue almost any rational "what if" scenario (that is, selecting an available educational module designed for their particular line of inquiry). In our view, such an integrated matrix does not yet exist. In this paper, therefore, a single, exemplary module was designed to illustrate the pedagogical features described above. Students are led to speculate on questions which are, in fact, addressed in the next component of the module. Even with this extremely narrow pyramid of choices, the strategic design of module template, and development of an integrated series of intuition-driven experiences, illustrate an educational strategy for the future.

3. Effects of Earth's Rotation

Example of an Educational Module Incorporating Computationally Intense Models

An educational module on the effects of earth's rotation on weather and climate was built around the collective research contributions of the named authors. The module covers basic concepts of the Coriolis effect, and proceeds to demonstrate its effect on circulations in the atmosphere. This subject was chosen for educational development because:

1. In a young student's first engagement with a weather map, they are told that air circulates around pressure centers rather than from the highest to lowest pressure. While this may go into their "fact bank", it is not at all intuitive, and registers with no child's life experience other than watching swirls around bathtub drains.
2. When the student first engages Newton's laws of motion in a non-accelerating frame of reference, weather and climate data in their empirical science data bank represents huge hurdles to intuition-building.
3. The fraction of the earth's inhabitants who have actually played catch on a Merry-Go-Round is vanishingly small. This common educational admonishment therefore generally fails to build anyone's intuition about science.
4. A subsequent life-long engagement with earth system behaviors will rest on this insecurity about the effects of earth's rotation: Are they real? Under what circumstances are they important?

The design of our educational module on the Coriolis effect makes no assumption about a student's intuition of the matter. The release version contains no mathematical notation, seeking to treat the subject entirely inductively through interactive "hands-on" research and experimentation. The Coriolis effect educational module incorporates 9 interactive research projects for high school or college students, each utilizing 3D web browser interactivity to simulate an elaborate experimental environment. About half the projects involve simple computational simulation of rotating turntable experiments in a virtual physics laboratory. The remaining projects involve observed data or computationally intensive model simulations brought to the same virtual lab experiment bench. These latter projects embrace the theme of bringing computationally intensive models into the classroom. Moving a student from reasonably simple and intuitive rotating turntable experiments onward to atmospheric simulation model experiments is admittedly a very large leap. The strategy here is to reinforce simple lessons by providing additional experience in an earth system science context in which that lesson is relevant. The Coriolis effect module may not be a perfect instance of this strategy, but the strategy itself is very important we believe. Each project is carefully constructed with tutorial information designed to build intuition about non-inertial reference frames and the effect of earth's rotation on global weather and climate. The tutorial material in the release version of the Coriolis effect module is extensive, following what we hope is a logical, intuitive pathway through concepts. It may be ponderous for some students and shallow for others. Discussion among JESSE readers about the style, level, and utility of tutorial materials is encouraged.

Our educational module begins with establishing basic scientific intuition about rotating reference frames using a *virtual physics laboratory*. Various experiments which could be constructed and deployed in a science laboratory (budgets permitting) are instead implemented in a virtual reality browser lab. In this virtual laboratory, a student is presented with a number of research projects with rotating turntables and frictionless pucks to build intuition about non-inertial frames of reference.

The starting point is a simple, intuitive demonstration that an object undergoing uniform motion in an inertial frame of reference exhibits startlingly different behavior when viewed from a uniformely rotating reference frame. This experiment <u>is</u> the traditional Merry-Go-Round example brought into a controlled, virtual laboratory environment. A workbench with coordinate markings sits stationary in a virtual science laboratory. A device fixed to this workbench launches a frictionless puck which moves at constant velocity across the workbench. A transparent plane with its own coordinate markings rotates at constant angular velocity above the workbench and moving puck. A rotating camera is located in the ceiling of the lab and looks straight down on the benchtop. Another rotating camera is arranged to "orbit" around the workbench keeping its view trained on the workbench and puck. Both rotating cameras have angular velocity equal to the rotating reference plane. The ceiling camera implementation allows a student to view the experiment from a viewpoint directly above, and rotate in synch with the turntable. The orbiting camera provides the opportunity to "grab" the rotating turntable from any perspective viewpoint in the lab environment and "hold on". Students then orbit the lab apparatus as though they were riding the turntable itself. The lab appears to rotate around them, as if everything were happening on a Merry-Go-Round. The rightward deflection of the moving puck in the rotating reference frame is readily appararent. The uniform puck motion relative to the inertial, lab reference frame coordinate markings is also in view. This "stationary" coordinate system appears to rotate backwards, of course, while the student rides the rotating turntable. Any prior experience with how the world looks from a Merry-Go-Round rationalizes what the student sees during this very intuitive experience. The student is provided with interactive controls to: view the workbench from a fixed position in the lab; view the workbench from the orbiting camera; view the workbench through the rotating camera in the ceiling; turn the rotating coordinate grid on and off; toggle the rotating coordinate grid to cartesian or polar coordinates; speed up or slow down the rotation rate of the rotating reference frame (and cameras). Through these interactive controls, the student can systematically compare the motion of the puck relative to both the fixed and rotating reference frames. What a student observes in this virtual experiment is extraordinarily intuitive. While viewing the Coriolis effect for the first time using this module, even uninitiated students might describe it in the same way that college majors deduce it from the differential equations of relative motion.

Figure 2 below illustrates the module interface, and screen captures of various aspects of student research.

In the course of the first four research projects, the student moves from the simple demonstration of the essence of the Coriolis effect, to its extention to a 3D earth. During the course of that research experience, the student meets issues of the rotational deformation of earth, true and apparent gravity, even the basic concept of *inertial oscillations*. These experiments are conducted with carefully designed interactive visualizations and tutorial materials to guide the student independently, or in a class setting with a teacher's guidance.

Next, the student engages a research experience with atmospheric wind data (Arkin, *et al.*, 1976) illustrating oscillations of the winds at Fort Worth, TX (latitude ~ 30N) suggestive of inertial oscillations in nature. The data visualization is "mounted" on the workbench with interactive controls to animate or step a sequence of vertical wind profiles through an averaged diurnal cycle, and to toggle between actual wind vectors and vector departures from mean winds at each level.

Next, the student engages a research project where the computationally intensive PSU/NCAR MM5 model (see Grell, *et al.*, 1993; Zhang, 1992) is brought onto the virtual lab workbench for examination of basic geostrophic and gradient wind concepts in a regional scale setting. Scientific material for the educational module was generated from a selected real-time 36 hour mesoscale forecast produced daily by Zhang and colleagues at Maryland. For the module, the relationship between wind and pressure is visualized using a 3D-shaped pressure surface; gridded wind vectors; and a jet streamline. Fixed and time animated visualizations have been prepared for this student research project to assure an appreciation for the systemic coupling between atmospheric pressure and winds in earth's atmosphere.

Next, the student engages a research project investigating global scale weather circulations to discover whether earth's rotational effects are global, or merely local. This research project brings a 20-level global NWP model (See Johnson, *et al.*, 1994) into the virtual lab workbench for student investigation. Whereas Johnson's model provides a full set of variables at many time steps, the student experiment is limited to the surface level and a single upper level showing relationships between global winds (gridded vectors) and pressure (geodynamic height). Interactive controls allow students to toggle between surface and upper air data. A single time step is currently used in the module, although 3D time animation can be easily provided.

Finally, students interact with the 2-level atmospheric general circulation model (GCM) of Held and Suarez, (1978), on the lab workbench. Two experiments using the Held-Suarez model were conceived and run by co-authors Kalnay, Cai, and Suarez to show expected environmental situations on earth for non-rotating conditions compared against current rotational conditions. (The non-rotating case was powered by latitudinally varying solar heating distributed all around the globe so as to simulate classical Hadley cell circulation to contrast with baroclinic westerlies in the rotating case. This provides a simulation which would be comfortably accomodated by professional researchers but would need to be discussed and rationalized to students.) As with Zhang's MM5 simulations and Johnson's NWP model, the Held-Suarez GCM model also provides an extensive set of primitive and derived variables. However, only visualizations of the surface temperature, precipitation, and surface and upper-level winds are integrated into the current version of the educational module. Lessons about the interplay between large-scale thermal circulations, and rotationally-influenced baroclinic effects emerge for the student from interactions with this virtual lab experiment on the workbench.

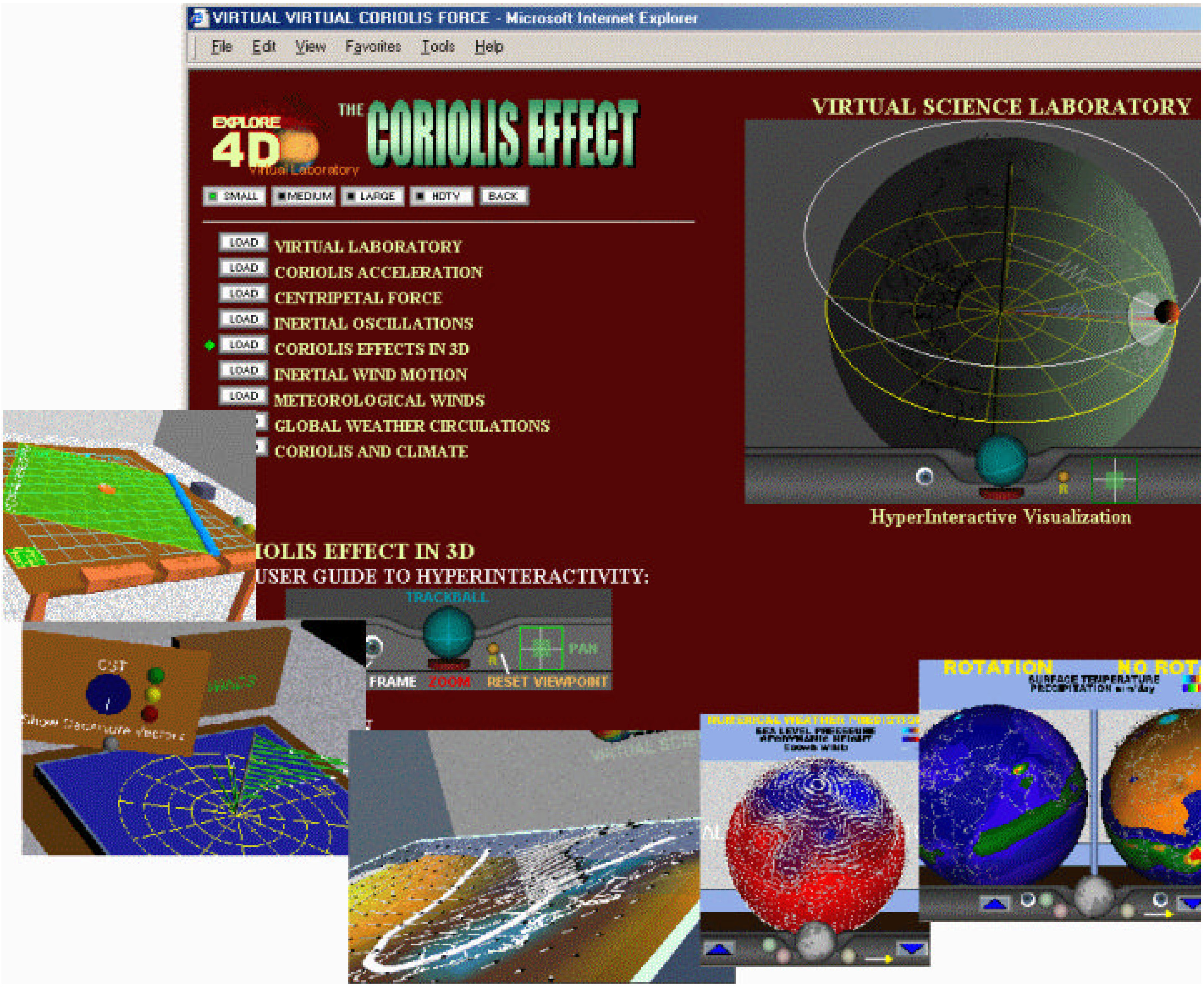

Figure 2. The Virtual Coriolis Lab. Interactive virtual research lab for investigating the Coriolis effect, designed for desktop PCs and Macs. The first four experiments are digitally simulated interactive physics lab devices for studying the basic mechanics of the Coriolis effect. The fifth experiment extends the 2D Coriolis effect concept to 3D, as shown in the module window. The last four experiments are interactive research projects utilizing atmospheric data and computational models from ESS research. These projects provide a modern, ESS context for the Coriolis effect. The complete Coriolis effect educational module has been put on-line for readers who wish to further investigate our experiment with student research using simple and computationally intensive models in the classroom. The URL is: http://meto.umd.edu/~owen/CHPI/CFLAB/

4. Technology to Transfer Scientific Research into Science Education

4.1 *Computation and Visualization Processes*

The enabling Internet technology underpinning the hyperinteractive Coriolis effect module nicely supports the goals of intuition-driven science education. This section briefly describes the technical bases for delivering educational materials and virtual labs to students interactively derived from sophisticated research models and massive databases. The technology incorporated into this project are known to be the research and developmental goals of some well-known national labs and agencies.

The Coriolis effect module incorporates two types of computational modeling. First, the power of modern desktop computers is now sufficient to perform a spectrum of relatively simple science computations on a student's own computer in a time frame that preserves student engagement with a module. For example, the computations required to execute the virtual lab experiments with rotating turntables and spheres in the first four module projects are well within the power of ubiquitous desktops today. But the power required to produce interaction with computationally intensive models, such as the MM5, global NWP models, and modern climate and global change models are way outside the domain of student desktops. Bringing these models into the classroom requires sophisticated client-server software which integrates a student into a modern high performance research computing environment.

Producing interactive 3D and 4D scientific visualization displays in a web browser can be done in a variety of ways. Many approaches require separate applications which render pre-made, proprietary file types, but which may not provide a dynamic "authoring" capability for that proprietary file format. The technique used in the examples here are based on the open, international standard "Virtual Reality Modeling Language" (VRML). Such a language is amenable to integration with numerical computation models to produce visualizations directly from the results of those models. This provides a convenient "authoring" environment for earth system scientists where advanced visualizations may be dynamically created from a computationally intensive model or massive observational database. The strategy for interactive, cross-Internet educational materials built around computationally intensive models and massive databases is discussed in sections to follow.

On the computationally simple end of the spectrum, quite a lot can be done using programs and calculation functions that reside and execute on the desktop computer itself. Integrating calculation and 3D visualization into a self-contained web page involves some innovation*, but is well within current HTML, JavaScript, VRML, and web standards. The concept is to use JavaScript math functions to compute something of interest, and other JavaScript functions to produce tailored VRML visualization code to dispay the results of the calculation in the form of an interactive 3D visualization. The HTML, JavaScript, and VRML instructions are all in "open source" languages. Each instance of such a stand-alone calculator/visualizer therefore provides an open source template for customization, or new module development. As an example of computationally simple modeling for educational goals, Figure 3 shows a client-side satellite orbit calculator/visualizer which is a self-contained web page program and operates entirely off-line.

The program uses just two data entry windows where students can enter the altitude (above earth's surface) and inclination angle (relative to the equator) to launch their very own synthesized earth orbiting satellite. Choice of scientific units encourages students to face up to an important difference between science and pure math. The "EVALUATE" button computes and displays numerical attributes of their satellite's behavior. Orbital characteristics are computed on the student's computer from JavaScript mathematical algorithms internal to the web page file. The "VISUALIZE" button invokes a VRML file creation function that produces an interactive, animated 3D visualization of the student's satellite in orbit about earth. Browser controls provides capability to examine the scene from different viewpoints. Even very young students can *empirically* determine some very interesting things using this client-side calculator/visualizer. In fact, this tool was built for an eight year old scientist on a vacation tour of Russia who wondered why satellite dishes in St. Petersburg seemed to droop at a lower angle than those in his home town of Frankfurt, Germany. Using it, he discovered geosynchronous earth satellites (although was not the first person to do so); something about satellite receiver dish elevations relative to satellite orbits; and went on to investigate the Wisconsin SSEC web site to learn how they are used for coherent weather observations. Work is underway to refine this module for public release.

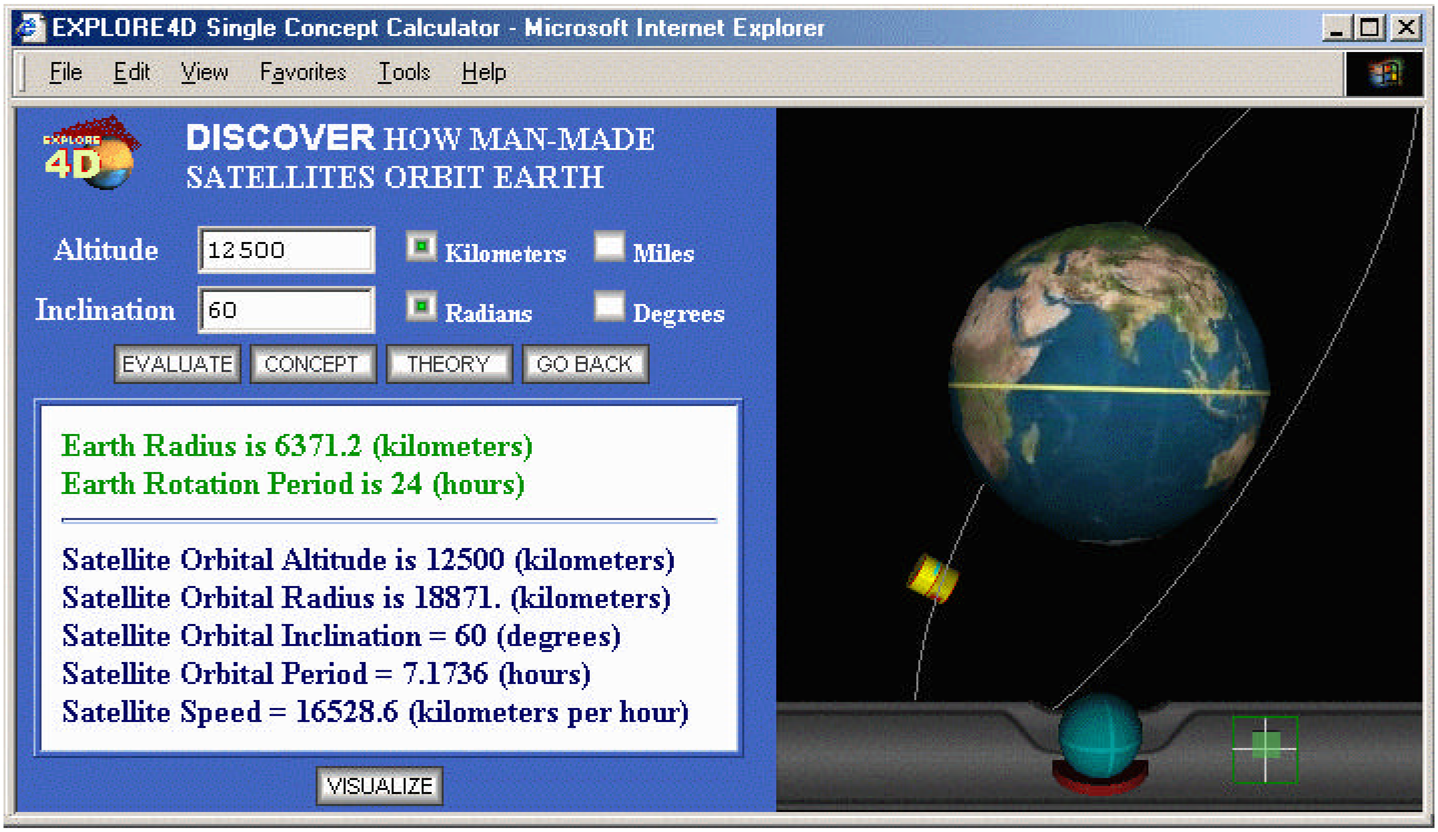

Figure 3. Hyperinteractive, client-side satellite orbit calculator/visualizer for science education. This web program operates as a calculator, taking satellite altitude and inclination input data from the user and producing a table of simple orbital parameters. Buttons provide for interactive 3D visualization of a satellite in the computed orbit about a globe. Additional buttons produce concepts, figures, and theory of satellite orbits geared towards pre-college and entry-level college students.

4.2 *Client-Server Processes*

Producing hyperinteractive educational materials from an on-line computational server is considerably more complicated. In the case of modern weather and climate modeling, for example, it is immediately clear that neither the model computation requirement nor the massive output database should be transferred across the Internet to a classroom desktop computer. Instead, the following model is put forward:

1. A client-server interface to a remote, high performance compute server is developed;
2. A custom request for computations and/or data visualizations is formed on the interface, and submitted to the server;
3. Requested computations are performed on the computational server;
4. Data mining software is then implemented on the server to pull out only that information requested by a user;
5. Advanced visualization files of requested data products are then formulated and fused into a file;
6. The fused file is returned to the student desktop across the Internet;
7. A plugin or Java application on the student desktop renders an advanced visualization on screen;

This approach is orthogonal to that used in advanced scientific visualization laboratories where powerful visual workstations engorge entire massive databases into memory, and produce interactive visualizations at ultrahigh bus speeds. Instead, the bus is replaced by the Internet, heavy computation is relocated on a high performance server, data mining and advanced visualization software prepares visualization files of modest size on the compute server for rapid return using the communication bandwidth of the Internet. The difference in bus speed and Internet speed is more than compensated by the coupling of supercomputing technology to the student desktop, and the assembly of small, query-specific data files for return across the Internet.

For preparation of educational materials by teachers and scientists, more general versions of user interface to complex models and databases is useful. Educational design teams can then experiment with models to determine the most effective simulations and visualizations to support their module designs. The advanced cross-Internet interfaces used to develop the components of the Coriolis effect module are discussed in the next section.

4.3 *Regional Numerical Weather Simulation and Prediction*

The scientific research for the next generation of advanced high resolution NWP is maturing in the domain of research universities and national laboratories. Such models provide the powerful engines for modern education about atmospheric behavior. Figure 4 shows a web browser interface to the PSU/NCAR MM5 model suitable for both research and educational development.

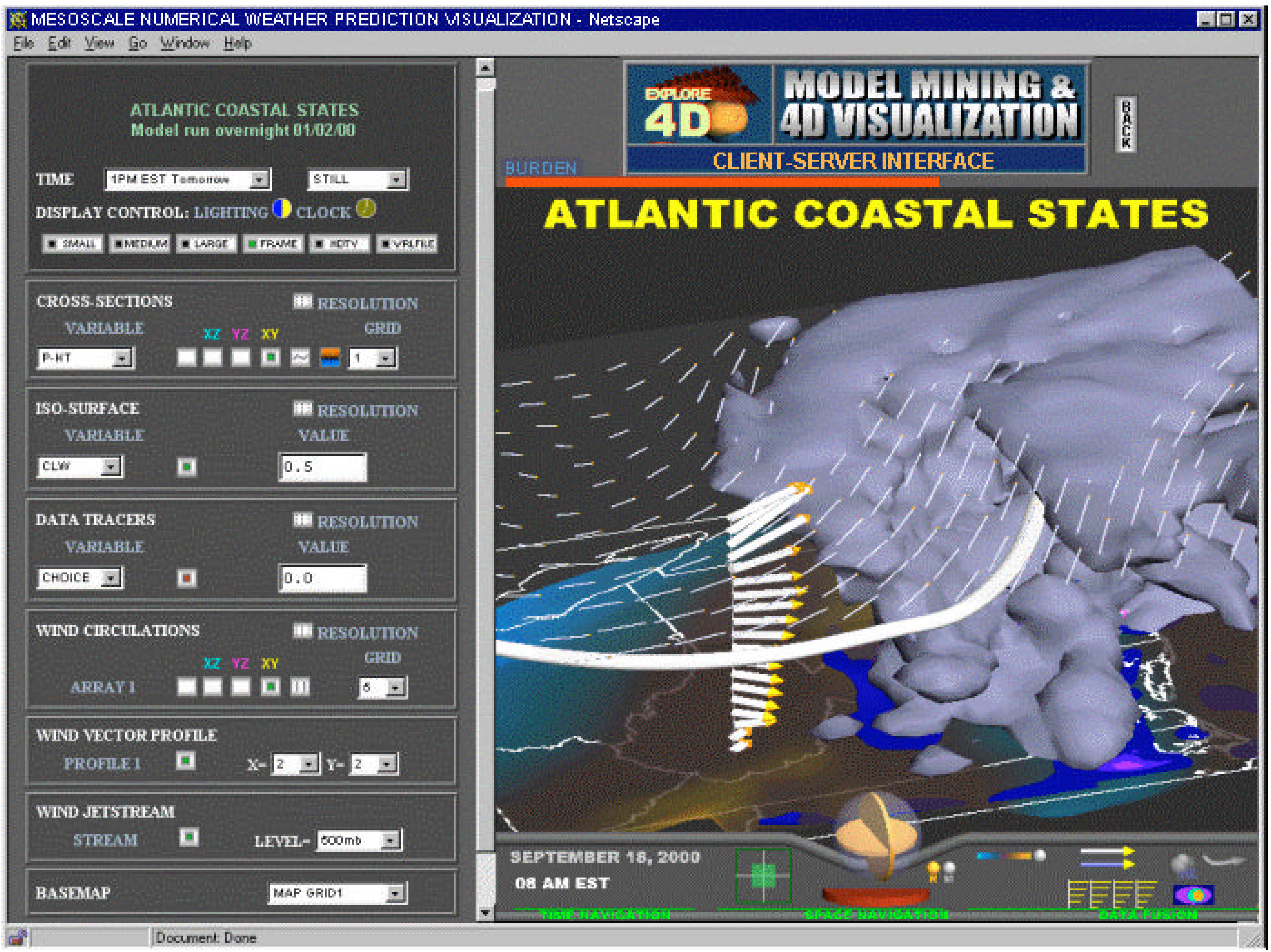

Figure 4. Advanced 3D web browser interface to the PSU/NCAR MM5 model. Buttons and menus in the left panel control the initial time, loop duration, lighting and time display options, and a variety of selections of model variables and data rendering styles. The right panel shows a requested visualization which fuses a 1000 mb pressure surface, 750 mb (off) and 500 mb (on) wind maps, 250 mb jetstream, four vertical wind profiles (one on), an isosurface of cloud water content, and a terrain-following isocontour display of surface precipitation. Dashboard controls allow individual data components to be toggled on and off; and to control zoom, pan, and examination of the visualization. Two pre-designed viewpoints for educational focus are included as explicit dashboard buttons.

The Cartesian model visualization interface is an advanced, client-server software system suitable for professional research scientists, educational designers, and, possibly, advanced science majors. The portion of the client-server software that loads onto the desktop computer consists of an HTML/JavaScript web page providing many user selection choices. User selection choices are sent to a computational server which manages the model and databases, mines requested data, and fuses everything into a VRML visualization file which is returned to the client desktop PC. Enabled with a VRML plugin, such as the free Cortona VRML client, the visualization file is then rendered in the visualization window to the right.

Scientists and developers assisted by such client-server software tools can experiment with various attributes of model output, variable selections, visualization geometries, data fusion, and visual information content. Among the user controls is the capability to write a conceived visualization to a VRML file for incorporation into web-based research briefs and educational modules. The design of the interface is easily adaptable to other computational models and databases rendered in Cartesian coordinates. Virtually all model variables, and many types of 3D visualization of scalar and vector variables, can be produced using this advanced interface. The educationally strategic fusion of different variables into an advanced visualization can be easily designed using this cross Internet technology. This interface was used on a laptop PC to design the MM5 visualization used in the Coriolis effect module discussed earlier.

4.4 *Global Scale Environmental Simulation and Prediction*

Figure 5 shows an advanced web browser interface to the global NWP model of Johnson, *et al.* (1994) at the University of Wisconsin. The design of the interface is adaptable to other computational models and databases rendered in spherical coordinates. This interface is an advanced, client-server software system suitable for professional research scientists, educational designers, and advanced science majors. The interface provides a user choice of model variables and geometry modes which, in the case illustrated, provided an interactive 3D-stereo visualization of scalar and vector data at 2 selectable pressure levels; and zonal and meridional cross-sections. Client choices of scalar and vector variables are mined from the remote model database and fused into a customized static or time evolving visualization. Dashboard controls are imbedded into the visualization file, and provide means of manipulating the visualization within a web browser on a user's desktop or laptop computer.

Although not explicitly realized in Figures 4 and 5, such interactive visualizations can incorporate interesting dynamic features such as the ability to zoom into a region and have higher resolution data swapped in upon zoom, or to include clickable icons in the visualization [acting as active hyperlinks] to produce additional information about a local scenario. Marrying computationally intensive scientific models with advanced web visualization technologies produces levels of user engagement hardly imagined by today's students (most teachers and researchers as well, we suspect).

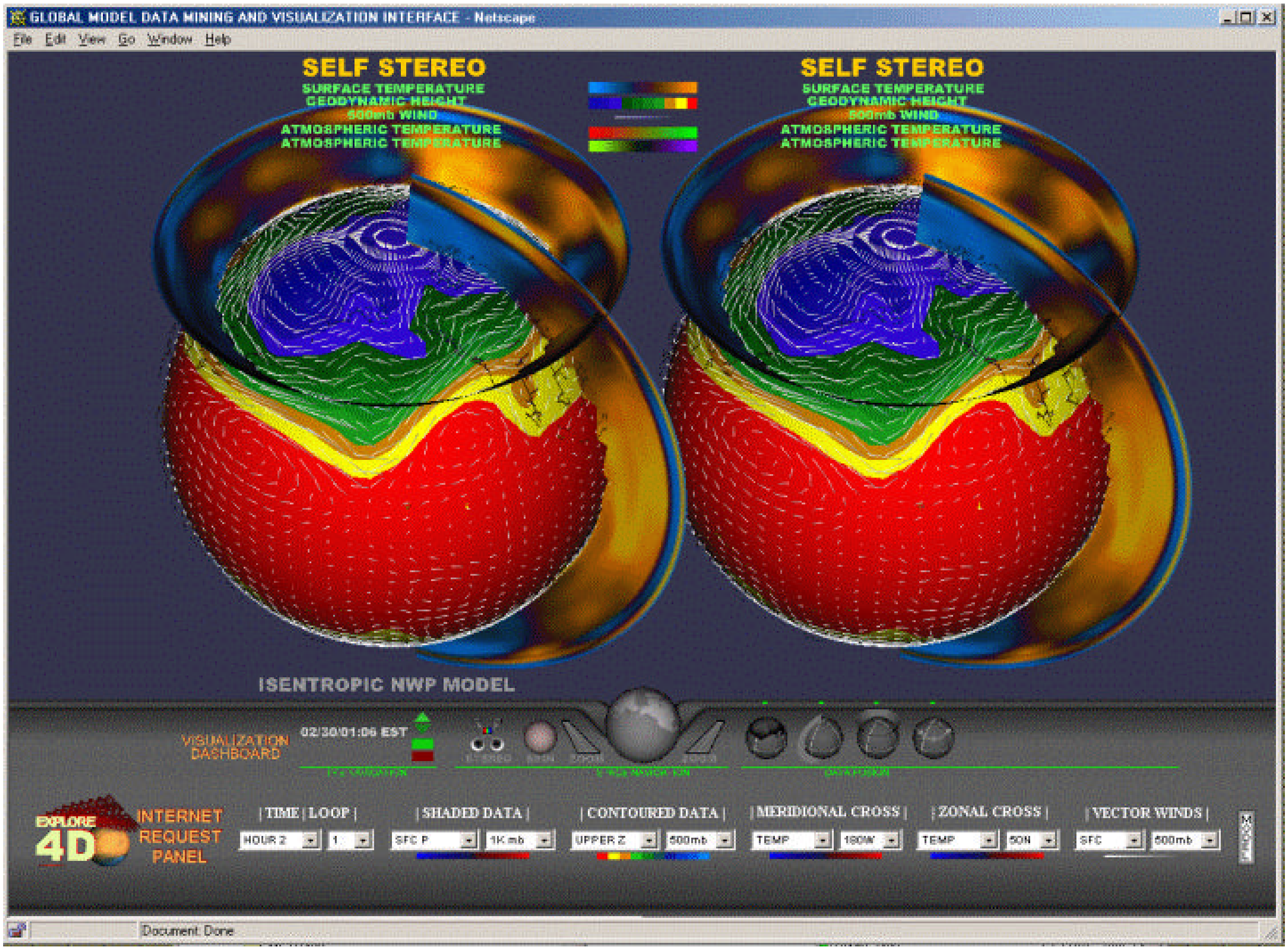

Figure 5. Global, 20 level numerical weather research model. The browser-based visualization is in 3D self-stereo with left eye view on the right, right eye view on the left. Crossing the eyes slightly produces a visualization which emerges from the computer screen. Global map, zonal and meridional vertical cross-sections of selected scalar variables are shown along with global winds at a specified vertical level. "Visualization Dashboard" controls immediately below the visualization provide for interactive engagement with the data. Dashboard controls in the "Internet Request Panel" provide buttons and menus for fetching new fused visualizations from a remote computation server.

4.5 *Climate System Simulation and Visualization for Students*

Marrying research-level computational models with advanced Internet technology opens the wide spectrum of *"What If"* environmental simulations tailored to key themes of earth system science education. The title page figure in this report emphasizes this point by showing a browser-based client-server interface to the previously discussed dual climate simulations using the Held-Suarez atmospheric general circulation model. The model runs were inspired entirely by educational interest in the question *"What if earth didn't rotate?"*. The educational goal of the limited interactive visualization incorporated into the "Coriolis effect" module was simply to demonstrate the essence of baroclinicity in earth's rotating atmosphere against the backdrop of 18th century Hadley cell concepts. Hadley-like thermal circulations on a non-rotating planet are fairly easy-to-take, intuitive discoveries for young students. Extending this intuition to large scale thermal circulation on a rotating planet is less intuitive, and is a principal theme of weather and climate education.

The experiment-control comparison scenario using complex modeling allows students to discover the rotational effects on climate in a somewhat empirical way to supplement study of the underlying science concepts. Interface technology designs can range over the spectrum from simple, student oriented educational interfaces with a few, pre-made "experiment-control" runs to investigate, to doubly interactive versions which conceive a "what if" experiment using an elaborate set of selection controls and dynamically retrieve results from a dedicated on-line computation server. Advanced, interactive browser interfaces to joint model computations provides a more extensive opportunity to select primitive and derived variables for comparison, providing a much deeper engagement with earth system simulations for professionals and advanced students.

5. Conclusions

This report demonstrates current science and technology achievements for numerical modeling and simulation, data fusion, and interactive visualization of global, regional, and local data in digital scalar, digital vector, and pre-textured [image/movie] form. Data representations can be freely mixed into a coherent educational product. These advances can erase the traditional boundary between earth system science research and earth system science education. With such digital tools in hand, educators can design learning adventures for the next generation of scientists that embodies the methods by which professional researchers now educate each other. Computationally explicit, observationally rich discovery is how we professionals learn about earth system science. Let us share our methods with students along with our findings. Let us also join together to erase the boundary between learning something for the very first time, and helping students learn it for their very first time.

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