## Scaffolding Student Inquiry with Collaborative Visualization Tools[1]

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### 1. Introduction

A well-documented problem with science education is that students are taught science as a set of solved problems from a textbook. They have minimal opportunity to experience the open-ended inquiry that characterizes the actual practice of science. The Learning Through Collaborative Visualization (CoVis) project is attempting to address this problem by providing students with the ability to conduct their own inquiries using scientific visualization tools and to interact with scientists whose professional practice consists of exploring similar questions using similar tools. Through advanced networking technology and new collaborative software environments, CoVis has been able to create a virtual community of practice that includes students, teachers, practitioners of informal science education, and practicing research scientists (Pea, 1993, in press; Pea, et al., 1994).

### 2. Scientific Visualization

Scientific visualization received its definition from a landmark NSF report (McCormick, DeFanti, & Brown, 1987) that defined the field by linking disparate elements from the disciplines of science, computer science, and the visual arts. Overall, the significance of scientific visualizations is highly specific to the domains that produced them, since they portray the phenomena studied by that scientific field. However, they can be distinguished by the following characteristics (Gordin & Pea, 1993):

1. Usually incorporate massive amounts of data.
2. Aim for verisimilitude with the phenomena they represent.
3. Aim to represent entire phenomena holistically by interpolating from data.
4. Extensive use of color to encode the magnitude of variables.
5. Animate sequences to show the progression over time.
6. Rely on high speed computation (supercomputers).

Scientific visualizations are similar to digital photographs in that they also are stored as a set of values that can be rendered by mapping each number to a particular shade. However, the values composing a scientific visualization image are not necessarily formed from the intensities of visible light; rather, the numbers represent abstract quantities. For example, the data set might be collected from temperatures all over the world. These temperatures are then viewed as a digital image, where each number is mapped to a specific shade. This "temperature portrait" allows one to discern patterns

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and contrasts much as figure and ground are seen in a photograph. The extensive use of *color* is a hallmark of scientific visualization. Colorful palettes can be used, such as a full rainbow of colors or the color spectrum of molten metals, where the order of colors in the palette correspond to successive numerical values. Different palettes serve to bring out distinctive features of an image, thus encouraging an association with the phenomena under study. Through use of color and motion (i.e., animation, typically used to convey the dimension of time), scientific visualizations exploit areas of human perceptual strength. Further, scientific visualizations provide a graphic referent around which to base discussion and argumentation. This is seen even in the popular press which recently used a Landsat photo to demonstrate the extent of flooding in the Midwest and to show the areas of a gene said to be responsible for aggressive behavior.

## 2.1 Scientific Visualization for Education

The same advantages that scientific visualization holds for scientists also offer promise for students of science. While students' naive conceptual models of a science model figure prominently in the challenges of science teaching, many of the troubles that students experience in science come from difficulty in understanding abstractions, formalisms, and quantitative terms. Because it takes advantage of powerful human visual perceptual capabilities, scientific visualization offers a different route to scientific understanding from other techniques. This offers the possibility of reaching a group of students that have not been well-served by traditional science tools and techniques. Scientific Visualization also offers the possibility of opening up new domains for study that have been considered too complex for high school students because of their heavy reliance on formulae and abstract representations.

Besides these opportunities to reach a broader range of students more effectively, scientific visualization offers 3 advantages for high school science education. First, scientific visualizations can give students the ability to conduct direct investigations in areas to which they have only had indirect access before. For example, students typically study weather phenomena by observing laboratory simulations, e.g. a tornado in a bottle, or limited and isolated field observations. In contrast, scientific visualization can give students access to extensive data collected from actual events, such as tornadoes, and can allow them to conduct their own investigations using these data. Second, inquiry using scientific visualizations can link students with the authentic practice of scientists. This step toward reducing the distance between the practices of scientists and those of students in the classroom will allow students to better understand the practice of science and interpret the results emerging from scientific research. Using the same visualization techniques and data sets as scientists gives students a motivating common ground with them. In the context of the CoVis Project where student have direct access to practicing scientists through telecommunications networks, this common ground can support effective communication and scientist-student mentoring relationships. Third, understanding the uses of visualization is becoming an increasingly important skill for both practicing scientists and informed citizens. On the one hand, the use and manipulation of visualization is growing across a broad range of scientific disciplines, mathematics, information processing, and finance. On the other, images and animations produced through the techniques of scientific visualization are becoming increasingly common in both the print media and on television. Whether or not students go on to careers in the sciences, an understanding of the nature and source of the visualizations they see in the media will help them to be informed citizens and decision-makers in modern society.

2.2 Challenges of Scientific Visualization for Education

Scientific visualization as it is practiced by researchers depends critically on the researcher's ability to identify appropriate data sets and convert them into formats in which they can be used. Our empirical studies of the practices of scientists using visualization tools have shown that these two steps consume an enormous amount of a researcher's time (D'Amico, Fishman, Gordin, McGee, O'Neill, & Polman, in preparation). To be effective, the visualization environments used in educational settings must simplify the process of identifying appropriate data sets and remove any concerns over data format from the user. This places the burden of identifying relevant data sets and dealing with incompatible formats on the developers of the scientific visualization tools. Fortunately, there are similar large-scale efforts underway in the scientific community to make data sets more available to scientists (Calvo & McDonald, 1993; Gershon & Miller, 1993; Short, Lowman, Freden & Finch, 1976), and we hope, in future, to leverage these other efforts.

However, making data and tools available to students is just the first step, since they must also learn how to interpret scientific visualizations and learn what questions can meaningfully be asked with them. Beyond making scientific visualizations materially available to students lies the harder task of making them meaningful in the students' learning processes. We call this the distinction between *availability* and *accessibility* of scientific visualization. Providing accessibility requires that developers of visualization tools understand the connection of the data sets to primary processes in the world, how these processes can be "seen" in visualizations, what questions can be legitimately asked of the data, and what operations can be performed on the data to yield answers. These goals require an understanding of scientific practices, namely, the background knowledge that scientists use to understand the data sets, what scientists "see" when they look at the data, and how they manipulate the data to discover new results or to test their conjectures. With an understanding of the operations and cognitive processes that scientists use in scientific visualization, we believe we can construct visualization environments that will support students through the process of learning to perform those same activities.

## 3. Scientific Visualization in the CoVis Project

In the first eighteen months of the CoVis project, we have made substantial progress toward our goal of developing scientific visualization tools for atmospheric sciences that are accessible to high school students at diverse levels of academic ability. Our progress has taken the form of 1) a methodology for constructing visualization environments and 2) actual scientific visualization environments that have been deployed. Using a knowledge-engineering approach similar to that used in the development of artificial intelligence systems, we have developed a methodology for working with practicing domain experts and adapting their visualization tools so that students can investigate the same questions using the same data sets as scientists. Currently we have made three visualization environments available for the high schools that are participating in the CoVis Project. Two of those environments are described in this paper. Finally, we have adopted a development strategy that places a heavy emphasis on formative evaluation. Through careful observation of the software in use and direct feedback from students and teachers, we have been able to identify important sources of conceptual difficulty in the subject matter, to increase the functionality of the visualization tools in response to user's needs, and to incrementally improve the design of the user interfaces.

In the remainder of this paper, we describe in more detail the methodology we have developed and two prototype visualization environments we have deployed as products of this methodology. In addition, we describe the classroom environments in which these tools have been used and some examples of investigations that students have conducted using these tools.

## 4. Development Methodology

The process by which we have developed our visualization tools reflects the pedagogical goal of CoVis to enable students to learn through the process of authentic scientific inquiry. This means that we must provide students with the ability to use scientific visualization tools to answer meaningful questions in ways that are similar to those used by researchers. The process we have adopted for achieving this goal relies heavily on the role of the content area scientist. The development of the CoVis visualization tools is a four step process:

1. <u>Investigate science practice</u>. Observe the use of visualization tools and data sets by scientists. This step requires our development group to become reasonably expert, with the support of scientific advisors, in the content area and its research questions. The result of this step is a characterization of the sorts of questions the visualization tools and data sets can be used to investigate, and the ways in which the tools are employed in the course of inquiry.

2. <u>Identify tacit knowledge used in science practice</u>. Determine the tacit knowledge employed by scientists in their use of the visualization tools. This knowledge includes scientific principles, understanding of the limitations of the data collection process and the models used to enhance the data, and how-to knowledge concerning the use of visualization tools.

3. <u>Scaffold the science practice for students by making the tacit explicit</u>. Adapt these visualization tools so as to make the tacit knowledge exposed in the second step explicit, structuring the software interface and affiliated pedagogical activities to assist students to pursue meaningful questions.

4. <u>Refine the visualization tools in response to formative evaluations.</u> Through a combination of observation and direct user feedback, evaluate the patterns of use that emerge and use these evaluations to inform the redesign of the software.

In pursuing this four-step process, we have been able to obtain considerable leverage in our development efforts by incorporating existing scientific visualization software instead of building our own tools from scratch. We have done this through a process we call “front-ending.” Using different forms of inter-process communication, we have created new user-interfaces for pre-existing commercial or public-domain software. In each case, the front-end provides an accessible interface to the pre-existing software. The back-end software operates either in the background or on a remote computer as an engine that generates visual images from data. By constructing front-ends, we have achieved enormous savings in time and resources. We have been able to assemble and deploy systems in a drastically shorter time frame than we would have been able to if we were constructing these environments from the ground up.

## 5. The Visualizers: Scientific Visualization Environments for High School Students

The first generation of visualizers developed under the CoVis Project are devoted to the atmospheric sciences. The Weather Visualizer provides access to up-to-the-hour data about weather in the U.S. The Climate Visualizer provides access to temperature, pressure, and wind data for most of the northern hemisphere over a period of more than two decades.

## The Weather Visualizer and Weather Graphics Tool

The Weather Visualizer is a unified set of tools for examining current weather conditions throughout North America (Fishman & D'Amico, 1994). Using the Weather Visualizer students are able to view the following:

- Satellite images of the U.S. in the visible and infrared spectrums.
- Customized weather maps displaying clouds, temperature, pressure, wind direction, wind speed, dew point, weather symbols, visibility, radar, severe weather watches, fronts, isobars, isotherms, isodrosotherms, and names of reporting stations, as well as wind speed at five different altitudes (850, 700, 500, 300, and 200 mb). Students can choose any subset of these features for display on their weather maps and can selectively view any region or city in North America at any zoom factor.
- Six-panel preconstructed visualizations displaying temperature, pressure, wind speed, wind direction, dew point, and moisture convergence for North America.
- Textual reports providing local conditions and local and state forecasts for all reporting stations.

The Weather Visualizer utilizes a client/server architecture. The tool itself resides on students' Macintosh computers, and the data resides on various servers, primarily the "Weather Machine" at the University of Illinois at Urbana-Champaign. When commands are issued, the Macintosh sends an information request to a Sun workstation at Northwestern. If the machine at Northwestern contains the necessary information, it is sent back to the Macintosh where it is displayed. If, however, more or updated data is needed, Northwestern's computer sends an information request to the Weather Machine at UIUC. All of this network access takes place in the background, without any student intervention, allowing students to focus on the task of thinking about the weather, instead of thinking about network access tools.

In addition, we have supplemented the Weather Visualizer with the Weather Graphics Tool. This tool allows students to draw their own weather maps with traditional weather symbols used in WxMaps (thus constructing their own visualizations) to make predictions and explain their understanding of weather.

In order to best understand how the CoVis weather tools can be integrated into classroom practice, consider the following scenario, adapted from Fishman and D'Amico (1994). In CoVis, the teaching of meteorology begins with the belief that all students have a naive understanding of the weather, generated from their life experiences. It is important to begin from this naive understanding, allowing students to formalize their beliefs and then use the computer tools as the means of gaining alternative perspective on the natural phenomena they witness every day of their lives.

### Satellite Images

The images most students choose to look at first are satellite images (see Figure 1). Using a check-box palette interface, the Weather Visualizer provides both visual and infrared satellite images of the United States as taken by the GOES-7 weather satellite. The same clouds that the students observed from the ground are now seen from Earth orbit — an engaging shift in perspective. Not only can they see the cloud cover above their current location, they can also see cloud cover over the rest of the nation. The infrared images allow students to gauge how high the cloud tops are, a good indicator of potential precipitation. Large-scale weather patterns, such as mid-latitude cyclones, become visible in satellite images. Students begin tracking and making predictions about the formation and life cycle of these large-scale weather patterns.

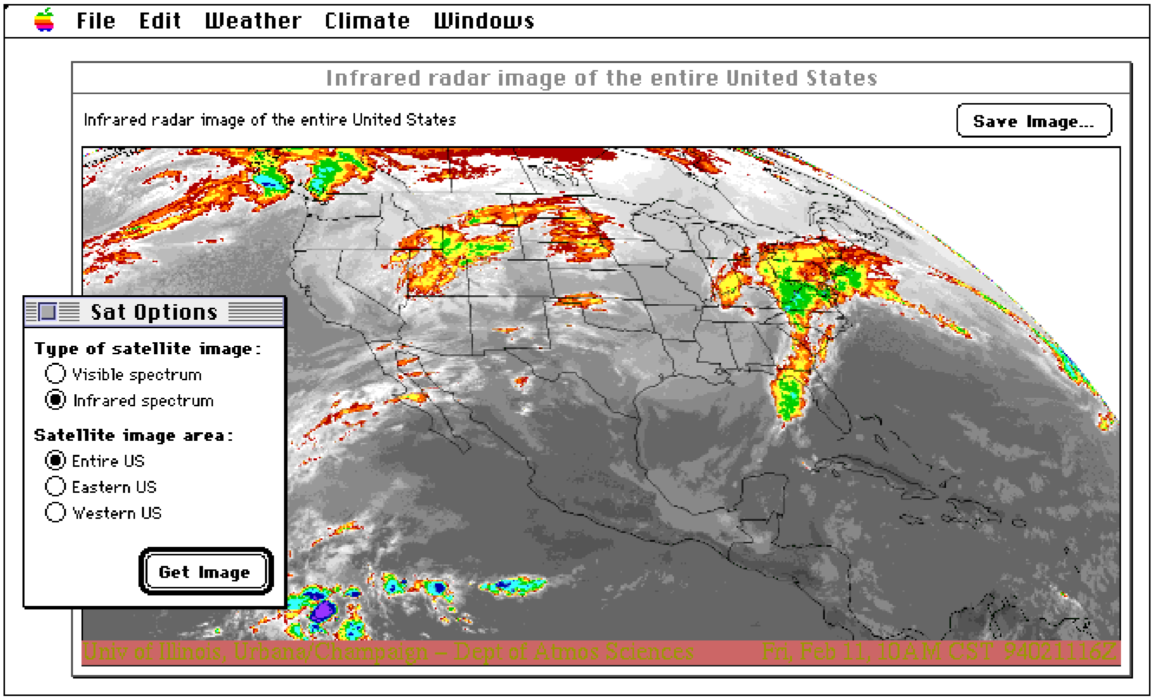


**Figure 1:** The satellite palette and resulting satellite image.

<u>WxMaps—Customized Weather Maps</u>

WxMaps are specialized weather maps produced by software written at the University of Illinois. These maps are generated by a UNIX program using data from the National Weather Service called Domestic Data Plus (DD+). The UIUC software, although very powerful, has a difficult to use command-line interface. The Weather Visualizer puts a graphical front end on this UNIX software, allowing students to construct their own WxMaps by checking off various options (see Figure 2).

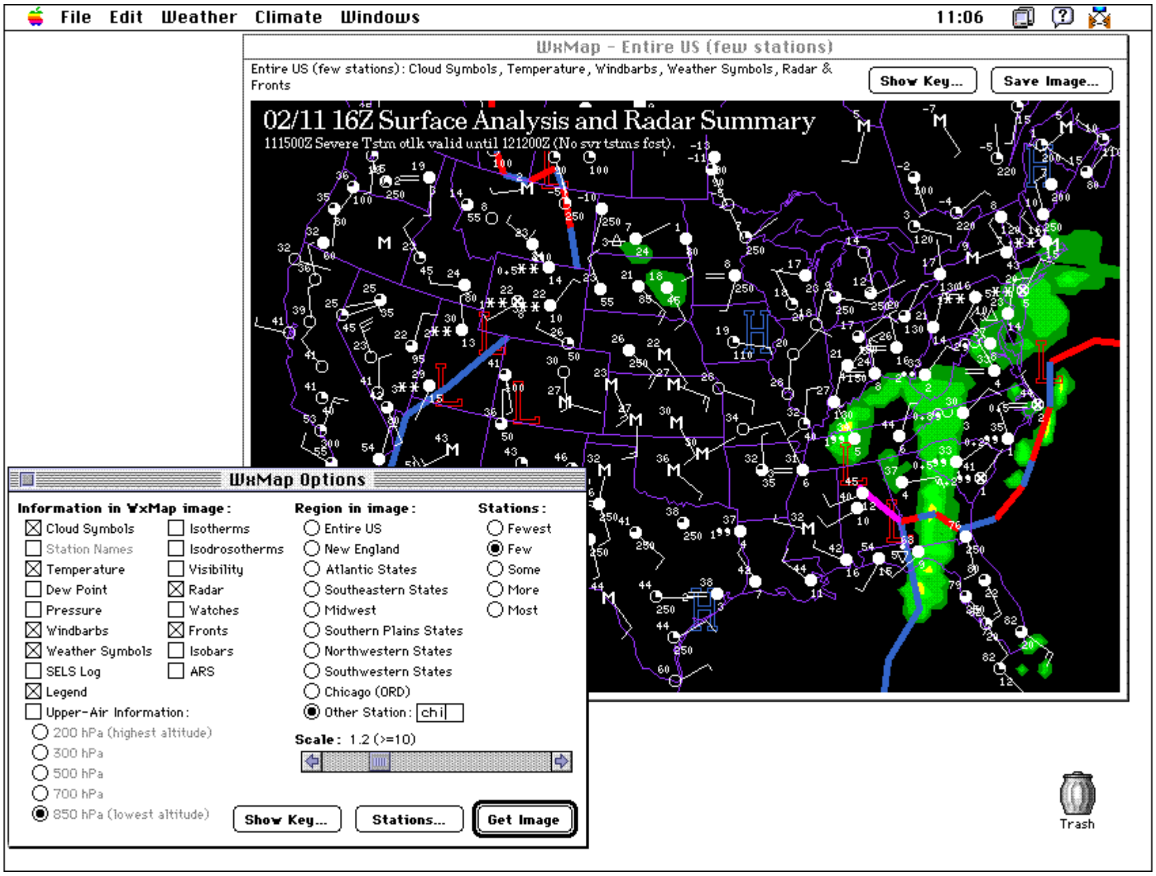


**Figure 2:** The WxMap palette and resulting weather map.

Wxmaps provide information from weather reporting stations across North America, allowing students to compare weather data from across the continent to the local report, which can be confirmed with a glance out the window. They can explore the relationship between large-scale weather patterns and local weather conditions.

WxMaps are capable of showing upper air conditions, such as jet stream wind patterns, using data gathered by weather balloons released twice a day at each station. The teacher asks the students to compare these upper air maps to the surface maps so that they may begin to think of the atmosphere as a three-dimensional space. Through exploring this three-dimensional space, the students learn that patterns of atmospheric phenomena occur not only in horizontal directions, such as the general west-to-east movement of the jet-stream over the U.S., but also in vertical patterns such as rising and sinking masses of cold and hot air.

The ability to generate custom WxMaps is an important attribute of the Weather Visualizer that sets it apart from other weather information services that are increasingly becoming available on the Internet (e.g., Ramamurthy & Kemp, 1993; Samson, et al., 1993). For the most part, those services provide access to precompiled weather images. The Weather Visualizer gives students the ability to create their own weather maps by specifying the region of interest, the height in the atmosphere, the number of stations to include, and particular variables of interest. This capability gives students the ability to tailor their investigations in order to pursue questions of particular interest. Such tailoring of visualizations is characteristic of the practice of professional scientists using these tools.

The Weather Graphics Tool

The CoVis teachers, seeking ways to support WxMap-based prediction activities, requested a tool that would allow students to make maps representing their predictions. In response, the CoVis team developed the Weather Graphics Tool. This tool is actually a plug-in extension to Aldus SuperPaint 3.5, a widely used graphics program for the Macintosh. Our plug-in provides SuperPaint with a palette containing “stamps” for all the weather symbols represented in WxMap, as well as a special stamp that can be student-configured to represent a complete station reporting model (see Figure 3). In order to make accurate predictions with the Weather Graphics Tool, students must consider the relation of various atmospheric conditions and processes to future weather at any given time and location. To do so, they must begin to integrate the knowledge they have gained thus far, and like professional weather forecasters, make decisions about which weather indicators have more weight in any given weather scenario.

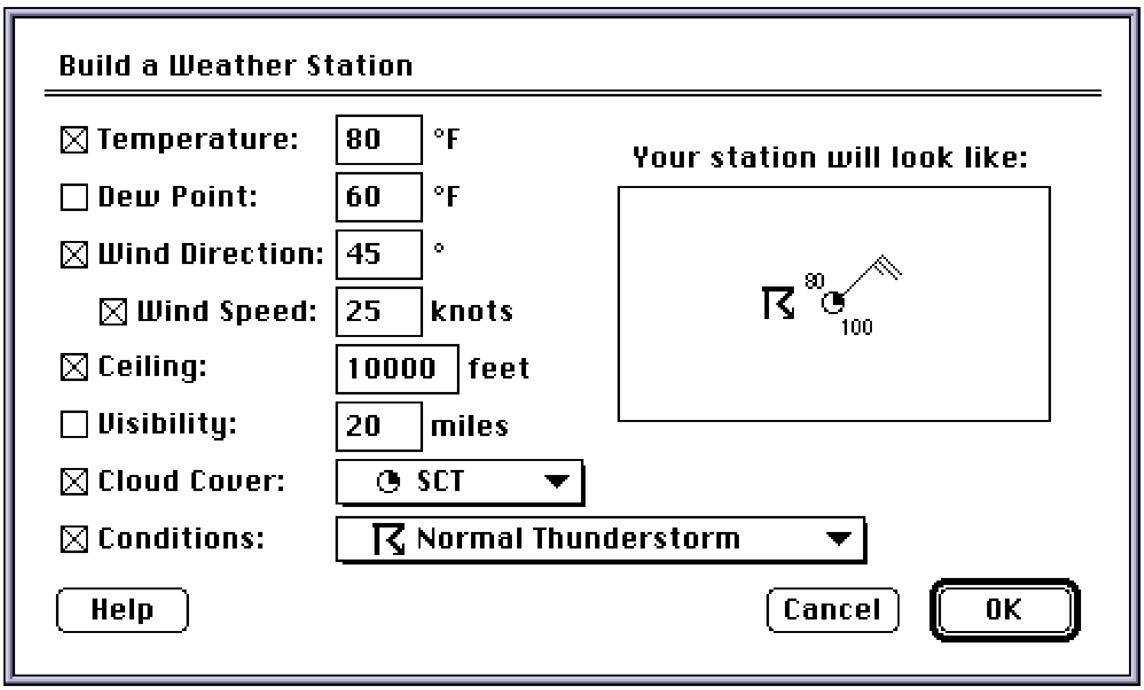


**Figure 3:** The station construction palette from the Weather Graphics Tool.

Six-Panel Images

As students learn how to make more accurate weather predictions, they are also learning more about the representational language of atmospheric science. This learning is driven by the higher-level goal of improving their forecasts, and thus happens in the background of the learning activities. For students who have mastered the interpretation of WxMaps, there is one more type of image available from UIUC. This image, commonly referred to as a “Six Panel” image, displays six atmospheric variables mapped as color across a map of the United States (see Figure 4). The six panels represent a great deal of information presented in an efficient manner. As a result, they are difficult for novices to interpret. There are, however, direct benefits to investing the time to learn how to interpret the Six Panel image. Moisture convergence is a particularly useful variable, because it indicates where there are gathering “pools of moisture” in the atmosphere that could contribute to future precipitation.

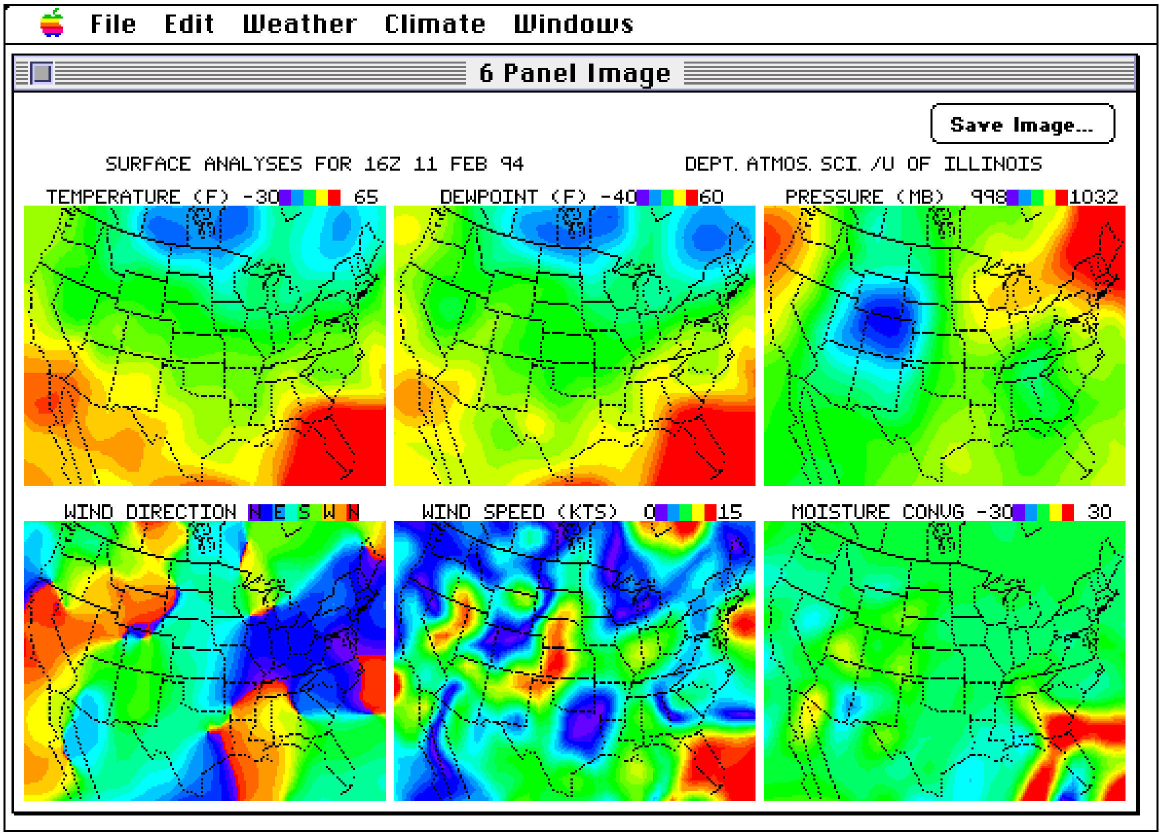


**Figure 4:** A Six-Panel Image showing temperature, dew point, air pressure, wind speed and direction, and moisture convergence

<u>The Climate Visualizer</u>

The Climate Visualizer (Figure 5) provides a learning environment for students to explore scientific visualizations that display important climatic variables (see Gordin, Polman & Pea, in press). For example, the Climate Visualizer allows students to easily produce scientific visualizations of temperature over most of the northern hemisphere for any day or month in a twenty-five year period. The aim of this section is to present the initial design of the Climate Visualizer. In this context, design refers not only to the learning environment itself, but also to the models of its use.

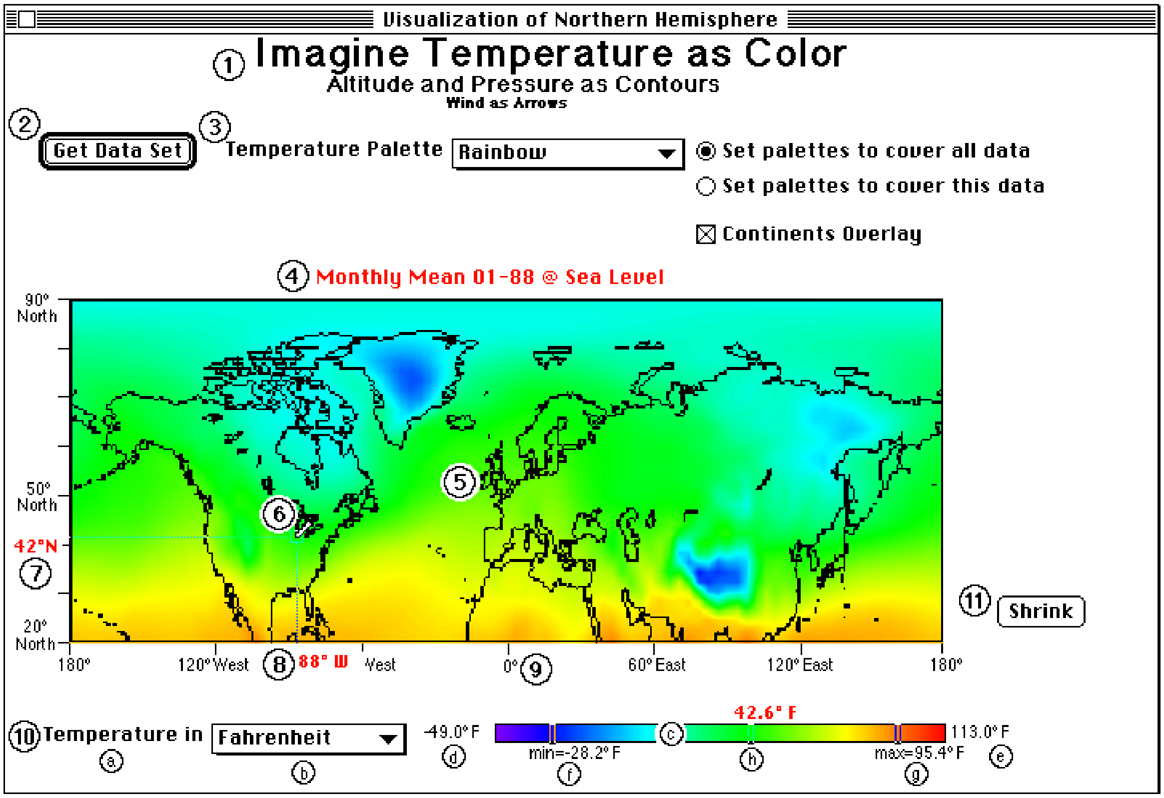


**Figure 5:** The Climate Visualizer shown displaying temperature in the Northern Hemisphere. **(1)** Title of View - describes the basic representations this view may display. **(2)** Get Data Set - provides the controls for obtaining the visualization for a specific date. **(3)** Means to manipulate the use of color palettes and overlays for the image. **(4)** Title of the visualization - describes the date, time, and variables currently displayed. **(5)** Current Scientific Visualization. **(6)** Query Box - indicates the currently selected grid point. **(7)** Latitude of current query. **(8)** Longitude of current query. **(9)** Background grid showing latitude, longitude, and local times at selected longitudes. **(10)** Display- palette. **(a)** Variable shown in this display-palette. **(b)** Units Popup - shows currently selected units for this variable, and allows switching to other units. **(c)** Current Palette for this variable. **(d)** Value of minimum color for this palette. **(e)** Value of maximum color for this palette. **(f)** Value and position of minimum value in this data set. **(g)** Value and position of maximum value in this data set. **(h)** Value and position of the current query selected on the visualization (indicated at point 6). **(11)** Shrink button - allows user to shrink current visualization and display-palettes into a small window.

In the Climate Visualizer, temperature is encoded as a raster color image. The student can choose which color palette to use to render the visualization. Different color palettes dramatically change its appearance and what features or patterns are most salient. There are sixteen different color palettes to choose from, ranging from rainbows of colors to gray scales to shades of red. Specific locations on the visualization can be selected and their temperature appears on a "display palette." This palette shows the range of colors used in constructing the image and the minimum and maximum values for the data set. Temperatures (with appropriate units) appear as highlighted numbers above the color palette, thereby presenting the relationships between the colors and the temperature. When a student clicks on any point in the display, its latitude and longitude are given through cross-hatching. Geographic context is also provided through an overlay that shows continental boundaries. Other variables can be similarly displayed. In particular, wind speed, wind direction, and the altitude of constant pressure levels (i.e., isobars). Wind speed and direction are shown as arrows and altitude as contours, instead of colors.

The range of dates available in the Climate Visualizer extends from January, 1964, to June, 1989[2]. The data set contains two sets of values per day, one at noon and one at midnight Greenwich Mean Time, and a monthly mean for each month. For each time interval, data is available at a variety of pressure levels (i.e., 850 mb[3] , 700 mb, 500 mb, 250 mb, and 200 mb). Most of the northern hemisphere is covered, from the North Pole to 20° North. The resolution of the data is two degrees latitude by four degrees longitude. From this description certain strengths and weaknesses of the data can be observed. The main strength is in the length of time covered and the detail: twenty-five years of twice daily measurements. Weaknesses are in the granularity of the data (relatively coarse since a two degree by four degree area includes hundreds of kilometers) and in the limited spatial coverage—specifically, the whole world is not included.

Currently, the data sets for the Climate Visualizer are retrieved from a CD-ROM attached to a Sun Sparc10 UNIX workstation. The appropriate scientific visualizations are then generated by a commercial application called Transform from Spyglass, Inc. This application is controlled through the use of Apple Events by the Climate Visualizer. The visualizations are then imported to the Climate Visualizer which presents them to the user. These underlying processes are concealed from the user who is only aware of the Climate Visualizer interface.

In addition to the data available, and the means for viewing the data, the third important attribute of a scientific visualization environment are the operations that can be performed on the data. The initial operation supported by the Climate Visualizer is subtraction. For example, temperature data sets from any two days can be subtracted from one another. A use for this operation in conducting an investigation might be to subtract the January monthly mean of temperature from the July monthly mean of temperature for any year. The resulting visualization of the difference between the summer and winter seasons[4] typically shows striking differences in how much certain areas increase or decrease in temperature.

The visualization of the differences in temperature between January and July provides a good starting point to describe the model of use that we anticipated for the Climate Visualizer. Primarily, we expected that students would look to interpret the patterns of color that emerge in the visualization. Two processes would interweave in this examination: first, finding patterns that confirm their intuitions about climate, and second, finding patterns that were inexplicable or contradicted their assumptions about climate. For example, a visualization of a July monthly mean of temperature largely shows warmer temperatures than January (remember only the upper part of the Northern Hemisphere is being shown). This coincides with our North American students'

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[2] The Climate Visualizer uses data from the National Meteorological Center's Grid Point Data Set (file ds195.5 Version 1.4).

[3]*Mb* is the abbreviation for *millibars*, the standard meteorological unit for air pressure. Average surface air pressure is around 1000 mb, so 850 mb corresponds to the point below approximately 85% of the weight of the atmosphere. Readings at 1000 mb is rarely used in large-scale climatology because of common surface distortions to temperature and other variables due to buildings, hills, and other surface-level anomalies.

[4]This follows standard meteorological practice of using the monthly mean of January as a exemplar of winter, the monthly mean of July as an exemplar of summer, and their difference as the seasonal range.

experience of July as warm and January as cold. However, the patterns that emerge from subtracting these visualizations might not be as comprehensible. Certain areas have large shifts in temperature while other areas hardly change at all. An important underlying climatic principle that underlies this differences is the extent to which land stores heat energy as compared to oceans. While many students would not know about this difference initially, observation of such patterns coupled with teacher guidance would enable them to observe it. Further project work could consist of measuring the extent of this difference, its dependence on latitude, and the secondary role of geographic features such as deserts and mountains. We anticipated other similar uses such as employing visualizations of temperature and wind to investigate how large cyclones form and effect the weather. These uses are largely consistent with the investigative processes of practicing climatologists and meteorologists who in large part served to provide the basic recommendations for the design of the Climate Visualizer.

<u>Integration of Visualizers with the CoVis Collaboratory Notebook</u>

The Collaboratory Notebook (Figure 6) is a central and unique element of the CoVis software environment. It serves several roles in support of science learning (Edelson & O'Neill, 1994a, 1994b; O'Neill & Gomez, 1994). The Collaboratory provides a place for students to record their activities, observations, and hypotheses as they perform scientific inquiry. It provides capabilities for planning and tracking the progress of a project, and it provides a means for collaborators to share and comment upon each other's work. The notebook has been designed to support authoring and reading equally, and to allow teachers to monitor and guide student inquiry.

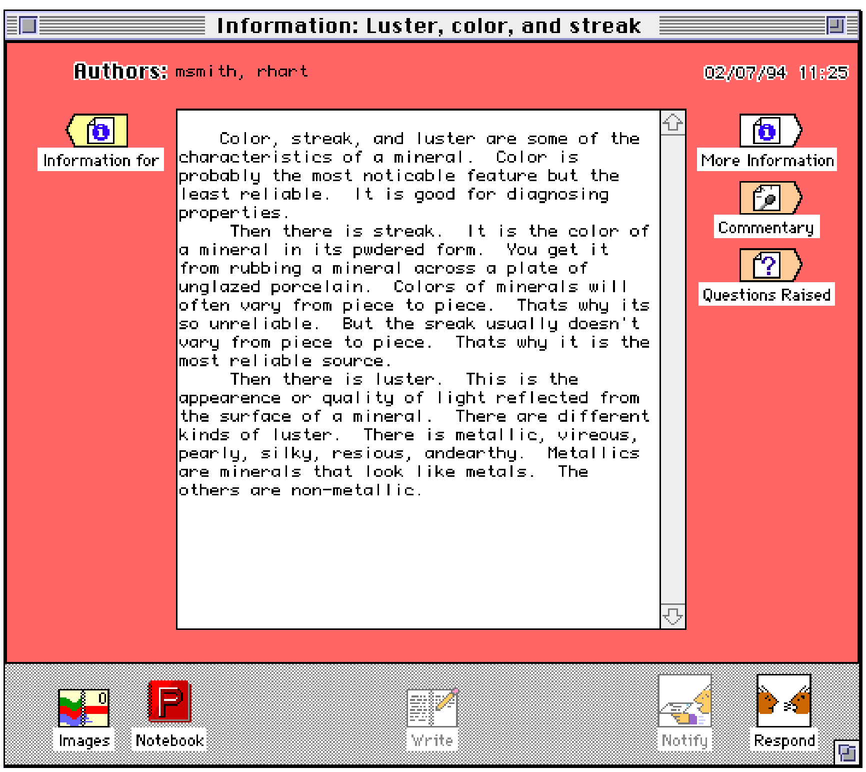


**Figure 6**. A page from the Collaboratory Notebook.

The Collaboratory Notebook is implemented as a structured hypermedia database. A particular notebook can be private or shared among a group of collaborators. The table of contents of a notebook is displayed in a way that is similar to files and folders in the Macintosh operating system. When the user displays a page from a notebook it appears in a window with buttons that represent links to other notebook entries. There are several types of links that can be used to indicate different relationships between notebook entries. For example, a question can be linked to a hypothesized answer to that question, which in turn, can be linked to evidence for or against that conjecture. These link types provide a structure for students to organize their open-ended scientific inquiry.

The Collaboratory Notebook is tightly integrated with the Visualization software that has been developed under the CoVis Project. For example, when a student uses one of the CoVis visualization packages, the visualizer maintains an activity log for that visualization session. This log records significant activities conducted by the student. For example, an activity log might record the data sets that a student loaded in and the manipulations conducted on that data set. The student can take the contents of this automatically generated activity log and copy it into the Collaboratory Notebook. Once there, the student can annotate this log with comments that elaborate on the process that was just completed. This activity log can serve as a trigger for reflection on the inquiry process. In addition, users can store the images produced in the course of a visualization in the Notebook. Through the “cut and paste” metaphor of the Macintosh user interface, the user can take an image that he or she has generated and store it as part of a notebook entry.

## 6. The CoVis Classroom Context

The development of the CoVis visualization environments have been influenced significantly by our close collaboration with classroom teachers and our experiences in their classrooms. Currently there are six teachers in two Chicago area public schools participating in the CoVis Project. These earth and environmental science teachers are in the process of transforming their teaching from traditional textbook, lab, and lecture approaches to a project-enhanced science learning (PESL) approach (Ruopp, Gal, Drayton & Pfister, 1993). In this approach, students engage in projects that provide them with the opportunity to perform open-ended, self-directed inquiry. A large proportion of the learning in a successful PESL classroom occurs because of the demands of this inquiry, as opposed to following from a prescribed curriculum in a traditional classroom. The PESL approach is designed to derive the benefits that come from well-motivated, self-directed learning.

The two participating high schools, Evanston Township High School and New Trier High School, are located in suburban Chicago, within 15 miles of Northwestern University. There are 262 students in twelve different classes involved with the CoVis Project. They both asynchronous and synchronous networking technologies available to connect the schools to each other, to collaborating scientists, and to the Internet. Teachers, students, and scientists use e-mail and the Collaboratory Notebook to support asynchronous collaboration on project-work. In addition, they have access to desktop video teleconferencing and screen sharing software to support synchronous collaboration.

We have worked closely with our collaborating teachers as they go through challenging transformations in teaching and as we develop innovative software to support learning and teaching. In the reciprocal evolution of tools and practices achievable in participatory design (Allen, 1993), the technology we are providing has been designed to support them in their transition, and their experiences in the classroom are being used to inform the design of the software.

## 7. Some Classroom Examples

In order to illustrate the potential of the visualizers within the classroom, we will describe some of the projects students in CoVis have worked on this year that have incorporated these technologies.

Several groups of students have used the Weather Visualizer to investigate an issue of importance to the weather patterns in their region: the effect that the Great Lakes have on the weather. For instance, one group contrasted areas near the lake with areas further away, by collecting WxMaps with temperature, wind speed and wind direction at weather stations in the Midwest region for several weeks in November and December. They created tables and graphs of the temperature at some of the stations to show that over their time period the temperature is higher near the lake. Their tables of wind speed and direction did not show any consistent pattern regarding distance from the lake. After looking at other weather conditions on the WxMaps, they concluded that wind speed and direction seemed to be more affected by weather patterns such as pressure systems and fronts than by the lake. Another group of students collected weather maps for the Midwest to look at the relationships between temperature, dew point, and cloud cover near the lake and further away. They also constructed tables and graphs of these variables for several stations at varying distances from the lake, and they found that clouds were more likely when the temperature and dew point were close to one another, and this happened much more often near the lake. In order to make sense of the lake effects, these and other student groups had to learn and use general principles about the weather—for instance, that a close temperature and dew point indicates a high relative humidity, and that high relative humidity is associated with fog and clouds. They also benefitted from looking at the combination of factors available in WxMaps in the Weather Visualizer.

One of the CoVis teachers designed an activity in which all the students in his class predicted the local weather in the local region two days after the day when they were making their prediction. The students used the current weather maps to look at current conditions such as wind, temperature, and pressure at different stations, as well as the location of areas of precipitation, high and low pressure systems, and fronts. Several of the groups used wind speed and direction information from upper air maps to project where the fronts and pressure systems might be 48 hours later. The groups then recorded their predictions—most in text, but one in the form of their own map made with the Weather Graphics Tool—with their justifications for the predictions. Two days later they checked the actual weather maps, and tried to explain any discrepancies.

Some of the students' projects have made use of historical weather data that is not currently provided in the Weather Visualizer. Currently, the Weather Visualizer only provides up-to-the-hour weather maps and satellite maps for the past forty-eight hours. With the help of our partners at UIUC, our students have been able to do projects with the same kind of data we hope to provide within the tool itself in the future. Several student groups, for instance, have investigated the relationship between the paths of major hurricanes and other phenomena. By tracing the paths of Hurricanes Emily, Hugo, and Andrew on animations of satellite images and weather maps, students have been able to show how high pressure systems over the land can alter the path that hurricanes take, and the importance of the Coriolis effect on the path that hurricanes take.

One group of students decided to look at the effect of the weather on the recent firestorms around Los Angeles, California. They also used archival weather maps and satellite images, in this case from the time period and region near the fires. With the help of researchers from UIUC, these students were able to collect evidence that dry winds coming off the desert due to the existence of a pressure system had helped to spread the fire. They also pointed out that a shift in winds corresponded to the time when the fires were able to be controlled. The data they used for this experiment seemed to have promise as an item of general interest, so it was made available on UIUC's Weather Machine Gopher server, a popular resource on the Internet that provides weather images and data. In the future, we plan on making archival weather data such as that used by these students looking at events such as hurricanes and fires directly available in the Weather Visualizer.

Many students have expressed interest in the eruption of Mt. St. Helens in their earth science classes. This is a topic which naturally comes up in discussions of volcanism, but some students have been interested in looking at weather and climate effects the eruption may have caused. One particularly interesting study made use of the Climate Visualizer. The students began by trying to find relationships between the temperature anomaly of May, 1980, when the volcano erupted, from the normal temperature in May over the 25-year period covered by the data, and the path that the volcano's dust cloud had taken according to other sources. They predicted that the area under the dust cloud would be colder, but did not see any significant change. Then, they began looking at daily maps, and found a warming trend around the volcano as the month went on. They attempted to offer some possible explanations for this finding, but in the end they sided with one book's assertion that Mt. St. Helens did not effect the weather.

Another group of students used the Climate Visualizer to look at coastline temperatures in comparison to inland temperatures. They predicted, based on their textbook, that the ocean would cause the coast to be warmer in winter than inland areas and cooler in summer than inland areas. They chose several months out of the year, and looked created visualizations of the monthly mean temperature for those months over several years. They were able to find support for the theory in the summer months, but not in the winter months.

Another group of students attempted to characterize why thunderstorms were more common in the spring than in the fall, and in some regions than in others. They had to find out about some of the factors that contributed to the formation of thunderstorms, such as temperature and pressure, and relate them to this data as is is available in the Climate Visualizer. Making the connection between the abstract ideas they were able to collect on thunderstorm formation and the Climate Visualizer maps proved difficult for the students, but helped us to see possible project uses we hadn't recognized before the students began working with the tool.

A concept that sometimes crops up on the nightly weather reports as an explanation of weather patterns is "El Niño." El Niño is a cyclic occurrence of ocean current patterns off the coast of South America that typically begins near Christmastime (thus the name, which refers to the Christ child in Spanish) and affects the jet streams and other factors relating to weather in North America. Some of the students in Covis classes used the Climate Visualizer to look at one way El Niño years differed from non-El Niño years. By looking at maps of the difference between January during El Niño years and the average of January over all the years, students were able to show that those years were in fact consistently warmer than average.

## 8. Conclusion

One of the guiding principles in the formation and design of the Learning Through Collaborative Visualization Project has been that authentic science as it is practiced today is not an isolated endeavor. We believe that the practices of science are fundamentally collaborative, so we attempt to foster collaborative inquiry in the high school classroom. It is perhaps fitting to note the extensively collaborative nature of our own inquiry into the most constructive design of visualization tools for use in educational settings. As the above discussion illustrates, a large number of constituencies have contributed to the design of these tools and their uses. Our own fascination with the compelling possibilities of visualization were transformed into initial designs through extensive interaction with atmospheric scientists. The initial designs went through many transformations in our own development, but even more once students and teachers began to use the tools themselves. As even these early examples show, appropriate scientific visualization tools used in a collaborative environment that includes students, teachers, and scientist experts, can enable students to perform meaningful investigations of the same sorts of scientific questions being asked by leading-edge researchers.

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