The greenhouse effect visualizer: a tool for the science classroom

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THE GREENHOUSE EFFECT VISUALIZER: A TOOL FOR THE SCIENCE CLASSROOM

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1. INTRODUCTION

The Greenhouse Effect Visualizer (GEV) is designed to help students visualize data sets related to the earth's energy balance. This work was inspired by the benefits scientific visualization have provided to scientists in discovering patterns and presenting the results of their work to broad communities. The hope is that scientific visualization can provide equal assistance to students trying to learn science. The philosophy underlying this approach links learning with practice. Hence, students are encouraged to learn science initiating and pursuing scientific questions and through interacting with the scientific community. This approach is by no means new, the difference is the attempt to ease the task through the assistance of selected technologies. This framework is basic to the Collaborative Visualization Project (Pea, 1993) of which the GEV is a part. This paper describes the GEV, including its data sets, models and visualizations, supported operations on data, and suggested uses. In addition, since the GEV is still very much under development, current shortcomings are described along with potential remedies.

2. WHY THE GREENHOUSE EFFECT?

The greenhouse effect has become the focus of an international research effort in the scientific community that views the earth and its atmosphere as a unified system affected by the fuel policies of industrial and emerging nations (Silver and DeFries, 1990). This intertwining of scientific and social concerns is useful since it provides diverse *hooks* or entryways for students to become involved with science. Optimally, this variety allows students to choose an angle that combines with their existing interests, yet relates to a common topic. For example, one project might propose a cap on carbon-dioxide emissions, while another evaluates the cap's impact on developing nations. Projects of this type involve substantial amounts of science, yet are not traditional science projects, since they integrate social and political concerns. It is hoped that integrated projects like these will help students to view science within a social context, rather than as isolated formulas.

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3. WHY SCIENTIFIC VISUALIZATION?

Students need specialized resources in order to participate in scientific practices. This need is documented by sociologists of scientific knowledge who have analyzed the role of specialized representations in negotiating scientific questions (Latour and Woolgard, 1979). Their findings show that when a scientific community adopts a new representation, it signifies an important change in the field. Arguably, scientific visualization is such a change for atmospheric science. Hence, giving students usable access to it can help them to understand and perform atmospheric science. In practice, the most common usage of visualizations is to portray scientific processes that vary spatially. This allows increasing or decreasing values to be easily picked out through noticing distinctive colors and patterns. As detailed below, these observations can help students to understand processes involved in the greenhouse effect.

4. DATA SETS IN THE GEV

The GEV data is based on the Earth Radiation Budget Experiment (ERBE; Barkstrom, 1984) data sets. These data sets provide monthly means of the quantities involved in the radiation balance through which the earth system reflects, absorbs, and re-emits radiation. In addition, surface temperature is provided from European Common Model World Forecast (ECMWF) data. The data sets provided by the GEV are:

1. Sunlight coming to earth (insolation)
2. Reflectivity of Earth-Atmosphere system (albedo)
3. Reflected sunlight (reflected shortwave radiation flux)

4. Absorbed solar radiation (insolation minus reflected sunlight)
5. Surface temperature
6. Outgoing terrestrial radiation (longwave radiation flux)
7. Net radiation (outgoing minus net incoming radiation)
8. Greenhouse effect amount (amount of energy retained in the atmosphere)
9. Greenhouse effect percent (percent of terrestrial radiation flux that is retained in the atmosphere)

These data sets were selected to help students understand how increased greenhouse effect could increase surface temperatures.

4.1 *Models in the Greenhouse Effect Visualizer*

The GEV offers three models under which to view the above data sets:

1. Earth without atmosphere
2. Earth with atmosphere but no clouds (i.e. clear atmosphere)
3. Earth with atmosphere and clouds

This sequence of models is motivated by order of magnitude effects involved in producing our climate. This is demonstrated by calculations that show that the global temperature of an atmosphere-free Earth would be around 254° Kelvin.. Adding an atmosphere brings this chilly average up above freezing, to around 276° Kelvin (freezing is 273° Kelvin). The effect of clouds is to refine this number still further (exactly how is still being debated). The main point is that the models provide successive approximations to the Earth climate. The primary basis has been the black-body model which relates energy to the fourth power of temperature. The specific formulas used are listed in Table 1. Each model is now analyzed in turn, by discussing the derivation of the data sets, current limitations, and potential remedies.

4.2 *Model 1: Earth without an atmosphere*

An earth without an atmosphere would have a simple energy balance where the amount of incoming radiation would equal outgoing radiation. This allows the calculation of surface temperature using a black body model as follows:

$$T = \sqrt[4]{\frac{(1-\alpha_{CLR})S}{\sigma}} \qquad (1)$$

where σ is the Stephan-Boltzman constant, S is the solar constant and α_{CLR} is clear sky albedo, so $(1-\alpha_{CLR})S$ is the absorbed solar radiation. The use of α_{CLR} to model albedo without an atmosphere is a substantial simplification, since α_{CLR} includes atmospheric gases, such as, water vapor and carbon-dioxide. However, it is useful in identifying high albedo areas, such as, polar caps and deserts. The full set of derivations used to calculate GEV data sets from ERBE data, for this model and the others, is in Table 1. Note that the greenhouse effect amount and percent are zero for this model. This is definitionally true, since greenhouse effect refers to the energy trapped by the atmosphere and this model specifically excludes an atmosphere. Similarly, the net radiation is zero as the outgoing radiation is assumed to equal the incoming radiation.

The primary problem with this model is that it does not take into account thermal inertia; this is particularly significant for the poles and oceans, since ice and water retain significant amounts of heat. A possible solution is to use the current monthly mean radiative calculation for land (due to its low thermal inertia) and use annual mean radiative calculations for water (due to its high thermal inertia). The poles are more complicated because of the latent heat of ice. The overall temperature cannot rise until the ice has melted. A several month moving average could be used to smooth out the excessively quick changes, thus taking into account the time needed to melt and freeze polar ice.

4.3 *Model 2: Earth with an atmosphere, but no clouds*

The presence of an atmosphere increases the surface temperature, since the atmosphere traps outgoing terrestrial radiation, but allows incoming solar radiation to pass through. The atmosphere is here modeled as a black body, thus all terrestrial radiation is assumed to be caught. Further, when the atmosphere re-emits the trapped terrestrial radiation half is sent to outer space and half back to the earth. This means the measured outgoing longwave radiation flux equals incoming longwave radiation. This allows the surface temperature to be calculated using a black body model as follows:

$$T = \sqrt[4]{\frac{(1-\alpha_{CLR})S + F_{CLR}}{\sigma}} \qquad (2)$$

where F_{CLR} is incoming longwave radiation flux (taken as equal to observed outgoing longwave flux) and $(1-a_{CLR})S$ is again the absorbed solar radiation. This model uses a very simplified view of the atmosphere. In particular, the atmosphere is modeled as a single layer, hence the temperature profile (or lapse rate) of the atmosphere is not taken into account. This leaves little room to answer a natural question from students: "If surface temperature is based on a radiation balance and your model already assumes a black body atmosphere (i.e. one that absorbs all terrestrial radiation), why would increasing amounts of CO_2 make any difference?" Indeed, in this model it would not cause a difference (Horel and Geisler, 1993). Rising levels of CO_2 in the

	Model 1 Earth without atmosphere	Model 2 Earth with atmosphere but no clouds	Model 3 Earth with atmosphere and clouds
Insolation	S	S	S
Albedo	α_{CLR}	α_{CLR}	α
Reflected Shortwave	$\alpha_{CLR}S$	$\alpha_{CLR}S$	αS
Absorbed Shortwave	$(1 - \alpha_{CLR})S$	$(1-\alpha_{CLR})S$	$(1-\alpha)S$
Outgoing Longwave	$(1 - \alpha_{CLR})S$	F_{CLR}	F
Net Radiation	0	$(1 - \alpha_{CLR})S - F_{CLR}$	$(1-\alpha)S - F$
Surface Temperature	$\sqrt[4]{\frac{(1 - \alpha_{CLR})\,S}{\sigma}}$	$\sqrt[4]{\frac{(1-\alpha_{CLR})\,S + F_{CLR}}{\sigma}}$	T
Greenhouse Effect Amount	0	$(1 - \alpha_{CLR})\,S$	$\sigma T^4 - F$
Greenhouse Effect Percent	0	$1 - \frac{F_{CLR}}{(1 - \alpha_{CLR})S + F_{CLR}}$	$1 - \frac{F}{\sigma T^4 - F}$

<u>Key to data sets (source):</u>

S:	Insolation (ERBE)
α:	Cloudy albedo (ERBE)
α_{CLR}:	Clear albedo (ERBE)
αS:	Cloudy outgoing shortwave radiation flux (ERBE)
$\alpha_{CLR}S$:	Clear outgoing shortwave radiation flux (ERBE)
F:	Cloudy outgoing longwave radiation flux (ERBE)
F_{CLR}:	Clear outgoing longwave radiation flux (ERBE)
$(1-\alpha)S - F$:	Cloudy net radiation (ERBE)
$(1-\alpha_{CLR})S - F$:	Clear net radiation (ERBE)
T:	Surface temperature (ECMWF)

Table 1: Formulas used to calculate data sets

solution to these problems is to use a more sophisticated model of the atmosphere provided by NCAR. This model

atmosphere make a difference because as they raise the temperature of the atmosphere, the temperature at the surface of the earth also rises due to the vertical temperature profile of the atmosphere (i.e., a lapse rate of around 6.5°C per kilometer). The proposed on to these problems is to use a more sophisticated model of the atmosphere provided by NCAR. This model parameterizes outgoing longwave radiation flux based on atmospheric temperature, relative humidity, and CO_2. The plan is to use tropical, mid-latitude, and polar reference profiles for temperature and humidity. This would provide a surface temperature data set that a student could adjust based on the CO_2 level. In addition, the model-based result should differentiate between temperature increases caused directly by CO_2 and the forced increase due to water vapor which is the feedback mechanism that occurs when surface temperature increases. Separating out the direct temperature increase from the forced increase allows students to differentiate direct effects from feedback effects. Further, the forced effects only occur after a timelag, due to the earth's thermal inertia. It is this lag that provides a window for compensating effects that could reduce the predicted surface warming (e.g., increased albedo from clouds)* .

4.4 *Model 3: Earth with an atmosphere, including clouds*

Although considered here as a model, this category is closer to observations. The surface temperature is not calculated from ERBE data sets, but based on data from the ECMWF. A strength of using observed data is that these data sets can be used by students to study a wide variety of projects. For example, by supplying several years more of data (currently only 1987 data is provided) El Niño effects could be studied. More detail on using the GEV for activities is provided below.

4.5 *Greenhouse Effect Data Sets*

Measurement of greenhouse effect is given in two ways (for the models with an atmosphere which produce a greenhouse effect). First, a measurement of the energy contained in the atmosphere due to greenhouse effect is provided by subtracting the top of the atmosphere longwave radiation flux from terrestrial longwave flux. This is called the greenhouse effect *amount*. Second, the greenhouse effect is shown as the fraction of energy leaving earth that is retained in the atmosphere, calculated by subtracting from one the ratio of top of the atmosphere longwave radiation flux divided by terrestrial longwave radiation flux. This is called the greenhouse effect *percent*. Figure 1 shows the greenhouse effect percent for July, 1987; equations for these data sets are listed in Table 1.

5. VISUALIZATION AND MANIPULATION OF DATA SETS

The GEV provides visualizations of all the data sets described for the three models, see Figure 1 for an example*. Several features have been included to increase comprehensibility. In particular, the color palette, located below the visualization, records the minimum and maximum data set values keyed to their respective colors. Further, all numbers are listed with their appropriate units (e.g. watts per meter squared). Specific data values pop up on the color palette when the student clicks on the visualizations; the latitude and longitude are given by call-out lines.

A number of enhancements are planned to allow further manipulation of the visualizations and their underlying data by students. First, is the ability to compute the average on parts of the data by sweeping out an area. This provides a mean to convert part or all of the visualization to a scalar number, thus assisting quick comparison, summary, and calculation (for examples of student projects of this sort see McGee, 1995). Second, is the ability to zoom in on a portion of the visualization, so as to focus in on a selected section. For example, a student might want to zoom in on a single continent or the poles. Third, is the ability to look at data over time by averaging multiple data sets of the same quality, extracting point data over time, and creating animations. At a minimum, annual means should be provided for the all the data sets. Fourth, we would add arithmetic operations on the data sets including addition, subtraction, multiplication, and division. These operations could be subjected to some semantic checking (e.g. to ensure that only like units are added or subtracted). The intention is to provide for flexible analysis of the data sets. Providing these arithmetic functions would allow students to calculate the amount of cloud forcing* as detailed by Ramanathan et. al (1989). Fifth, is the ability to spatially correlate data sets. This would provide a means to help determine the relationship that holds between two data sets (e.g., is one data set a linear or exponential function of another). Such patterns can help in understanding the underlying causality. Several means to perform such a correlation are being investigated, in particular, a multi-dimensional histogram or scatter plot could be created where the values in the two data sets provide the x and y coordinate axes and points are plotted from the values at the latitude and longitude positions in the two data sets (e.g., the values at location 42°N, 88°W would compose the x,y coordinates of a point). The correlations are detected by the way the points cluster (e.g., in a linear correlation the points would line up).

6. USING THE GEV WITHIN THE SCIENCE CLASSROOM

Studying the greenhouse effect provides an integrated approach to science, since its understanding relies on atmospheric chemistry (e.g., spectral

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* Thanks to Roy Jenne of NCAR for emphasizing this distinction and its pedagogical value.

* Visualizations rendered in color can be found on the Collaborative Visualization World Wide Web Server (http://www.covis.nwu.edu).

* Cloud forcing refers to the overall effect of clouds on temperature, that is, do clouds cause a net increase or decrease in surface temperature.

characteristics of greenhouse gases and their interactions in the environment), physics (e.g., electro-magnetic spectrum and relating temperature and radiation through the black-body model), biology (e.g., role of forests and plankton in carbon cycle), and earth systems science (e.g., consideration of the earth, atmosphere, and oceans as an integrated system). In addition, using models is essential, as is assessing their limitations. A general goal for any greenhouse effect curriculum is helping the student to understand why so many uncertainties persist. The GEV can aid inquiry in these areas by exploring specific processes and use of models.

6.1 *Learning about radiation balance and greenhouse effect*

Using selected visualizations from the GEV a variety of topics can be explored in the classroom. In general, the suggestions are either to compare differing data sets within the same model or to compare the same data set visualizations in different models. The following are example investigations:

- Compare insolation for January and July to observe the change over seasons. Ground the source of this change in the rotation of the earth around the sun and the earth's tilt off the ecliptic.
- Deduce how insolation would differ when earth is in different stages of the Milankovitch cycle. It might be attractive for this variability to be incorporated into the GEV when calculating surface temperature.
- Examine insolation, albedo, and shortwave reflection to find their relationship. Use this to explain why the poles stay relatively cool during their summer.
- Compare clear and cloudy albedos to see the impact of clouds. In particular, examine how the lack of the intertropical climate zone (ITCZ) affects the tropics.
- Compare the absorbed solar radiation with the surface temperature in order to see the effects of atmospheric heat transports.
- Observe the differing thermal inertia of ocean and land by subtracting January's surface temperature from July's. Explore the interaction between land and ocean by contrasting a El Niño with a La Niña year.
- Contrast the surface temperature between the three models to see the effects of an atmosphere and of clouds.
- Look for a correlation between greenhouse effect amount and percent.
- Explore the effect of increased CO_2 on surface temperature by varying the amount present. Note and explain which areas of the globe are most affected.

6.2 *Learning about Models through the GEV*

The GEV models exemplify several important practices in the use of models by scientists that are of value to students:

- Use of multiple models to understand a single phenomena, where each model is differentiated by order of magnitude effects.
- Importance of feedback loops (including forcing agents) in describing effects of a change.
- Use of balance to describe a complex ecology. For greenhouse effect the essential balance is of energy; for a wetland the essential balance is of water -- in both cases the ecology is analyzed by tracing out a balance.

6.3 *GEV in the classroom*

During the 1994-1995 school year, we will be including the GEV as a new educational resource in a number of high school classrooms in the Chicago area, and formatively improving its interface and educational utility through learner and teacher feedback and re-design. Earth science and environmental science teachers and students will be studied in their use of this visualization package, and how it is complemented by print and video resources, in service of completing their curriculum. We will be particularly concerned to determine what forms of support are needed to guide students' use of their physical intuitions and prior knowledge about heat, temperature, sunlight, reflectivity, feedback, and balance as they bear on the relationships among radiation, atmosphere, clouds, and the electro-magnetic spectrum as used in service of understanding the greenhouse effect. Since key conceptual relationships in the models are defined in terms of mathematical formula involving algebraic relationships and new kinds of semantic units (e.g., watts per meter squared), we will identify how the requisite knowledge for understanding these underlying mathematical considerations may be effectively built up through instruction around examples, when students do not have the proficiencies required. While section 6.1 outlines some investigations the GEV will enable, the relative difficulties of such projects for high school students, and modifications of their design required for student success in their inquiries, remain to be determined through this fieldwork and curriculum design with teacher guidance.

7 CONCLUSION

The international focus on greenhouse effect can serve to form a nexus for a course of study in science by providing a single issue that combines fundamental material from diverse scientific areas and is of crucial importance to world wide economic policy. The GEV can help to explore some of this phenomena. In particular, the GEV allows:

- physical processes to be shown, discovered, and analyzed visually
- exploration via a succession of models that isolate order of magnitude effects
- student investigation of state-of-the-art research data sets

The goal is to enable science students to successfully engage in the practices of science, rather than memorizing a simulacrum of its products. We welcome feedback and use of the GEV as it develops from both the scientific and educational community.

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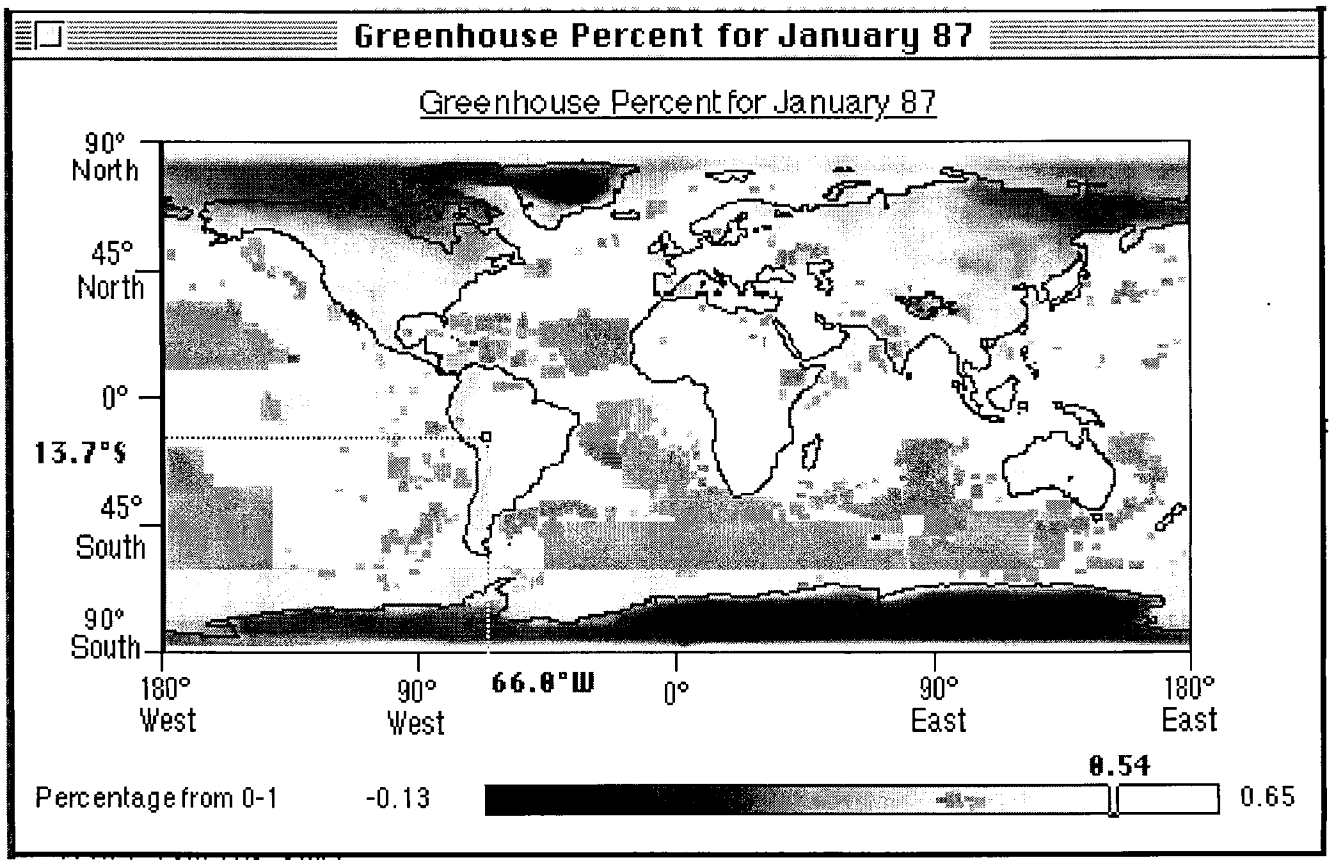

Figure 1: Example GEV Visualization