The *Ed*GCM Project

Teachers' Guide to Exploring

Future Climate Change

NASA Climate Modeling and Data Applications Workshop

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Teachers who are new to climate modeling often ask *how*, specifically, they can use EdGCM with their students. Because that answer depends so much on an array of factors – such as course focus, grade level, and time and computing resources available – we don't offer a one-size-fits-all classroom plan for EdGCM. Instead, we provide some information and a framework of ideas for teaching about climate modeling and climate change, to allow teachers to decide what aspects of the EdGCM experience to emphasize with their students.

This guide presents some fundamentals of climate modeling and analysis with EdGCM, using a pre-prepared global warming experiment as an end point for discussion. The guide is divided into sections that can be used individually, or combined to create a lab-length exercise. We have also included a some suggested questions for your students (shown in blue italics) to get you started.

Happy modeling!

The EdGCM Team

An EdGCM Teacher's Guide:
Exploring Future Climate Change Using a Global Climate Model

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Outline

Part 1: Setting Up a Climate Modeling Experiment

Part 2: Modern Climate Control Runs
- a. Specified SST Simulations (Oceans as Boundary Conditions)
    - Explain simulation Modern_SpecifiedSST
- b. Predicted SST Simulations (Using a Mixed-Layer Ocean Model)
    - Explain simulation Modern_PredictedSST

Part 3: Running Simulations to Equilibrium: An Example Using Doubled CO2 Experiments
- Explain simulation Doubled_CO2
- Visualize the data
- Compare with Modern_PredictedSST

Part 4: Comparing a *Transient* Global Warming Simulation to the Modern Climate
- Explain simulation Global_Warming_01
- Visualize the data
- Compare with Modern_PredictedSST
- Explain global warming impacts and feedback mechanisms
    - Surface air temperature
    - Ice-albedo feedback

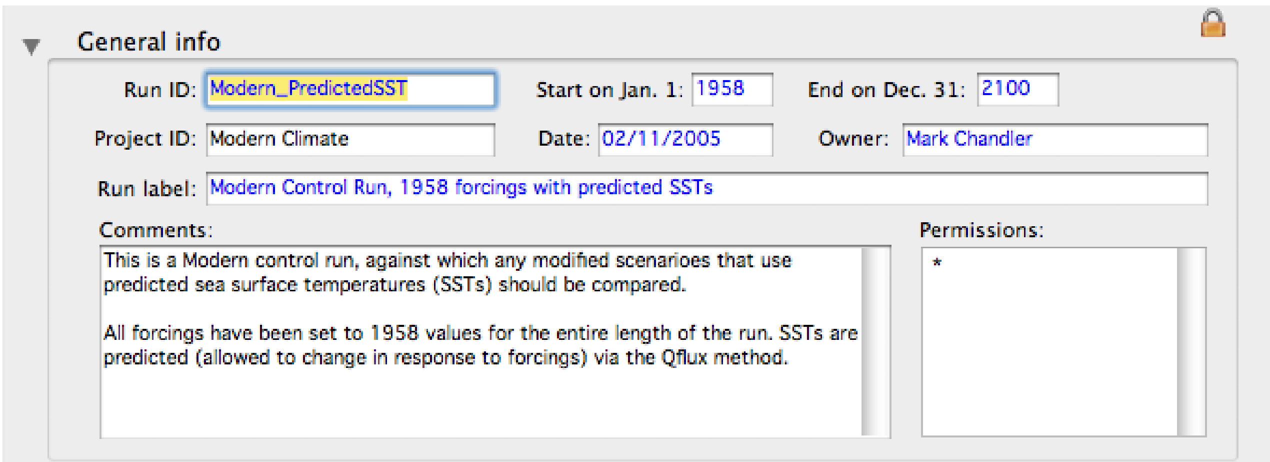
Significance of "Rediscovery"

Suggested questions/activities are given in bold blue italics.

Part 1: Setting Up a Climate Modeling Experiment

Step 1: Open the Setup Simulations window and duplicate an existing run from the run list using the button on the toolbar.

Step 2: Fill in the required fields in the general information section.



Run ID: Each run needs a unique identification name associated with it.

Start / End Dates: Set a date for your run to begin and end. For example, the run Modern_SpecifiedSST starts on the first hour of 1/1/1958 and ends on the last hour of 12/31/1967. Thus, the run simulates the climate of a 10-year span. Note that the years in these fields do not represent actual calendar dates, unless the forcings and input files are specific to those dates. Otherwise, the dates are used as counters and to establish a meaningful reference frame for seasonal climate cycles.

It is also standard practice that the simulations begin one month before analyzable data begins to be produced (12/1/1957 in our example). This is referred to as a "spin-up" period, during which numerical noise in the atmosphere subsides. This noise is associated with the fact that the initial conditions and boundary conditions are not in perfect equilibrium with each other at the start. Within a month this noise is "ironed out" and meaningful output begins to accumulate.

We start many simulations in the year 1958, which holds special significance because it was the first year that direct measurements of greenhouse gases were taken. By 1958 the level of carbon dioxide in the atmosphere was 315 ppm (parts per million), which was already an increase of more than 10% over pre-industrial values.

Project ID: The project ID can be used to group several simulations under one project title.

Date: The date is entered automatically when a new simulation setup is created.

Run Label: Each run needs a short (<60 character) description that will be used to tag the raw digital output that is produced by the model.

Owner: A user name is required so that simulations in the database can be attributed to a person (or group).

Comments: It is good practice to include a description of the nature and purpose of each experiment. Hence, GCM simulations will not run unless the user types something in this field.

Provide an example of a useful run label and comment.

Step 3: Set up a modern climate "control" experiment.

No computer model of a complex system is a perfect representation of that system in the real world. Unfortunately, assigning error bars to the output of such complex process models is also not possible in any straightforward sense. Thus, climate simulations are generally compared to a "control run", which is a baseline against which all other simulations can be compared. For future climate experiments the control runs are nearly always some type of simulation of the modern climate. The term "modern" is defined differently by various modeling groups, but is nearly always a representation of the average climate of a multi-decadal period from the 19th or 20th centuries – before significant climate change had occurred. EdGCM has preset modern climate control runs that use characteristics of the atmosphere and oceans that are representative of the period 1951-1980. We use 1958 values for the greenhouse gases in our control runs since that was the first year that regular and continuous measurements of atmospheric CO_2 were begun.

In order to start a climate model simulation it is necessary to supply the model with "initial conditions" and "boundary conditions" that define the initial state of all factors in the model that effect the climate calculations. An *initial* condition is prescribed at the start from a file on the computer, but such conditions change as the experiment proceeds. *Boundary* conditions are also supplied from a computer file, but they are distinct from initial conditions in that they are not affected by subsequent model calculations. Boundary conditions in particular must be as realistic as possible and must be appropriate for the type of simulation planned. Choosing initial conditions that lie beyond the model's intended range, or selecting mismatched boundary conditions, can result in the model producing unrealistic output or simply crashing.

Identify boundary conditions and initial conditions used in global climate models in the list below, and justify how you categorize each variable. Why does a model need both boundary and initial conditions?

Topography
Precipitation
Surface air temperature
Greenhouse gases
Land-Ocean distribution
Lake distribution
Wind speed
Specific humidity
Clouds
Snow cover
Atmospheric Pressure
Vegetation distribution
Land ice extent
Greenhouse gas levels
Solar luminosity
Wind direction

Step 4: Start a climate modeling experiment.

Click the play button in the Simulation Controls to start the climate simulation. (These controls are at the top of the EdGCM Toolbar and look like DVD player buttons). The run will start up in a new window. After the first hour of the simulation the run will stop, and a message will be displayed: "First hour completed successfully." Then click the play button at the bottom of the run window, and the simulation will proceed.

What might the purpose of this model stop be?

Part 2: Modern Climate Control Runs

a. Specified SST Simulations (Oceans as Boundary Conditions)

One of the most important boundary conditions is the sea surface temperature (SST) data, since SSTs directly affect the moisture and energy fluxes over 70% of the Earth's surface. Supplying the climate model with long-term averages of the ocean temperatures is not adequate. In order for the climate model to accurately simulate the heat and moisture exchange from the ocean to the atmosphere we must also supply the geographical and seasonal distribution of SSTs. The climate model used by EdGCM can use various types of SST boundary condition files, but the most common form uses 12 monthly-average SST arrays that contain information about not only sea surface temperature distributions, but also sea ice distributions (which forms at temperatures below -1.6°C in the NASA/GISS GCM).

b. Predicted SST Simulations (Using a Mixed-Layer Ocean Model)

In order to run experiments in which the sea surface temperatures are allowed to warm or cool in response to atmospheric changes, we must first determine the proper energy fluxes for an experiment. To do this, we first run a short experiment, generally about 10 years long, that uses specified SSTs. During the specified SST experiment, we collect information about the fluxes of energy at the atmosphere-ocean interface that the model produces as the days, seasons and years progress. In a follow-up simulation we supply the previously collected energy fluxes to the ocean, allowing the sea surface and atmospheric temperatures to adjust to each other. When run in this mode the SSTs are free to adjust to changes in other forcings (e.g. increasing CO_2) and the oceans are capable of storing heat and, in a crude way, transporting energy horizontally in a manner that mimics ocean currents. Such ocean models are generally referred to as "Mixed-Layer" models, since they approximate the essential characteristics (from a climate standpoint) of the well-mixed upper layers of the ocean.

The simulation Modern_PredictedSST, which runs from 1/1/1958 to 12/31/2100, uses a mixed-layer ocean model, so it allows SSTs to vary in response to energy fluxes from the atmosphere over the course of the run. With the greenhouse gas concentrations and the solar luminosity fixed at the values of 1958, this simulation is our modern climate control run. It provides a basis for comparison to climate change runs (such as global warming simulations) and is a key test of the GCM. With constant forcings, if this run were to exhibit large changes over time in its climate state then we should be suspicious of the model's output.

Part 3: Running Simulations to Equilibrium: An Example Using Doubled-CO_2 Experiments

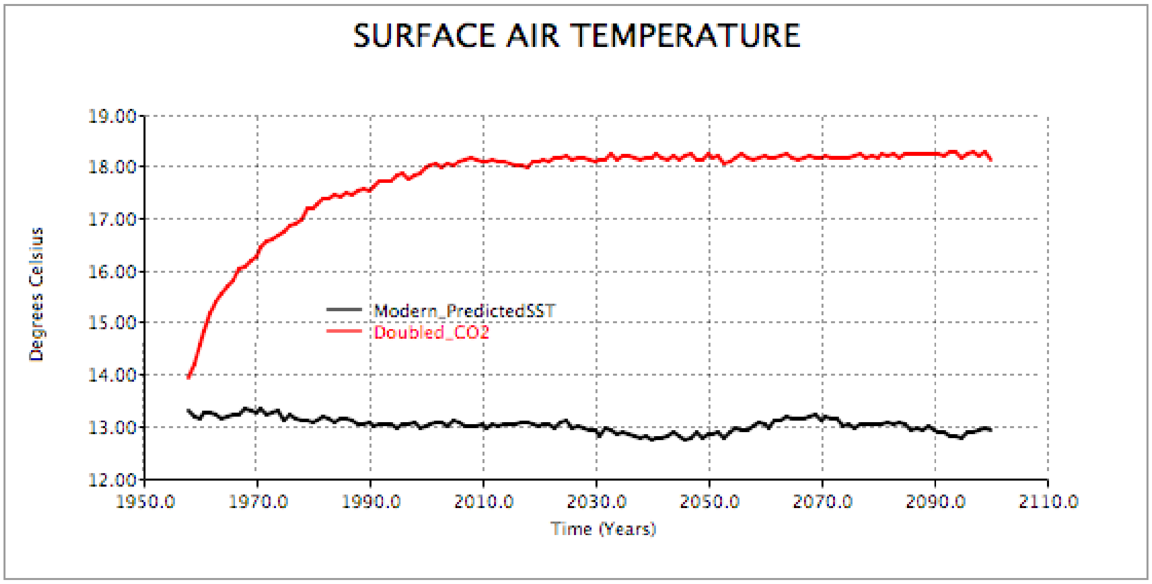
At this point in the exercise it is important to introduce the concept of an equilibrium climate state. You may have covered equilibrium, or stability, in a context other than the climate system – for example, in physics, chemistry or earth sciences. A key point for students to understand is that the climate system is generally stable on human time scales, even though some properties of the climate system – i.e., climate forcings – may be oscillatory or episodic (e.g., seasonal greenhouse gas fluctuations, solar luminosity, volcanic eruptions, El Niños and La Niñas, etc.) Furthermore, when changes do occur in these climate forcings, the system responds through feedback mechanisms that may act to mitigate the change (negative feedback) or to amplify it (positive feedback). However, feedback mechanisms generally operate on time scales that are slower than the initial forcing, thus adding time lags that delay the full response of the climate system. Global Climate Models attempt to simulate not only the detailed components of the climate system, but also the correct time responses of the feedbacks. Thus, when a forcing is altered in a global climate simulation, the response of the model is not instantaneous, but instead takes place over some extended interval.

One of the best ways to show students how a run comes into equilibrium is to compare a modern climate control run such as Modern_PredictedSST to a run with an instantaneous doubling of carbon dioxide, i.e., the Doubled_CO2 run included with EdGCM. At any point during the simulation, even while the run is in progress, you can use the Analyze Output window to calculate time series of various climate variables.

What does a time series plot show?

In Plot 1, we show Surface Air Temperature time series for both modern and doubled CO_2 simulations after they have each run for 143 years. The modern surface air temperature (black line) is relatively stable over time, because the climate was essentially in equilibrium with the forcings at the beginning of the run. A large drift in the results from a modern climate simulation would make one suspect of the quality of the model being used. In contrast, the Doubled_CO2 run was not initially in equilibrium, since it was initiated with an instantaneous carbon dioxide increase (630 ppm instead of the 315 ppm used in the modern climate control run). By plotting the Doubled_CO2 surface air temperature time series (red line), we can see that the temperature increases rapidly while the model adjusts to new CO_2 level. Eventually the model achieves a new stable state that is in equilibrium with the increased CO_2 level in the run.

Identify the point on the plot at which the Doubled_CO2 experiment reaches an equilibrium state. How many years did it take the model to reach equilibrium? What is the difference in surface air temperature between the modern control and the Doubled_CO2 runs when both are at equilibrium? What component of the climate system contributes the most to the delay in the temperature response to an increase in CO2?

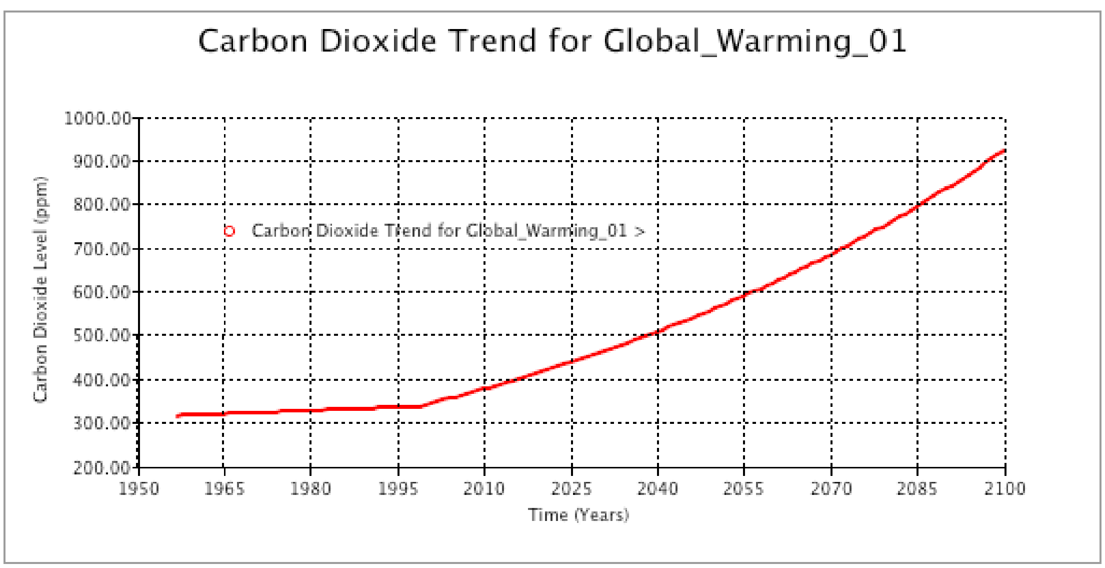


Plot 1: Exploring the length of time it takes for the climate to adjust to an instantaneous doubling of CO_2

Part 4: Comparing a *Transient* Global Warming Simulation to the Modern Climate

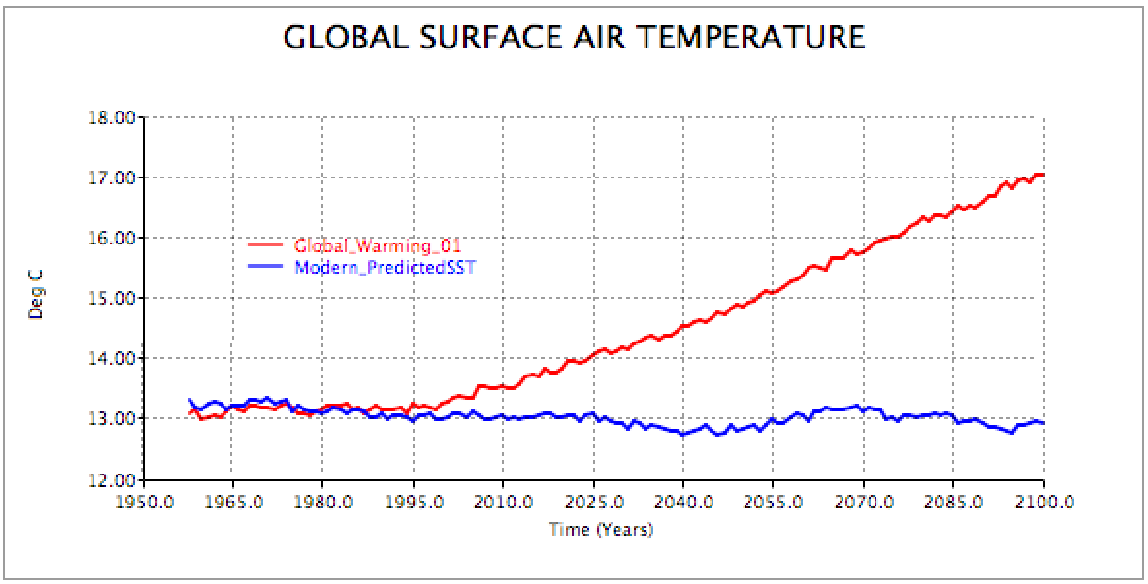
An equilibrium climate may never be completely achieved if any of the climate forcings themselves have long-term, continuous trends. To explore what happens under such a circumstance, we will next compare the simulation Global_Warming_01 to the control run, Modern_PredictedSST.

Like the modern control run, our global warming simulation (Global_Warming_01) also begins in 1958 and ends in the year 2100. The global warming run is identical in all respects to the Modern_PredictedSST run, except that atmospheric carbon dioxide (CO_2) increases steadily over time. In this particular global warming experiment, the CO_2 trend involves a linear increase of 0.5 ppm per year from 1957 to 2000, and then an exponential change of 1% per year from 2000 to 2100.



Plot 2: CO_2 forcing trend in Global_Warming_01.

Compare the CO2 input trends in Plot 2 above with the Global_Warming_01 surface air temperature time series in Plot 3 below. How does the change in CO2 input relate to the change in temperature over time? What does the Global_Warming_01 temperature curve tell you about the strength of the CO2 forcing in this simulation?

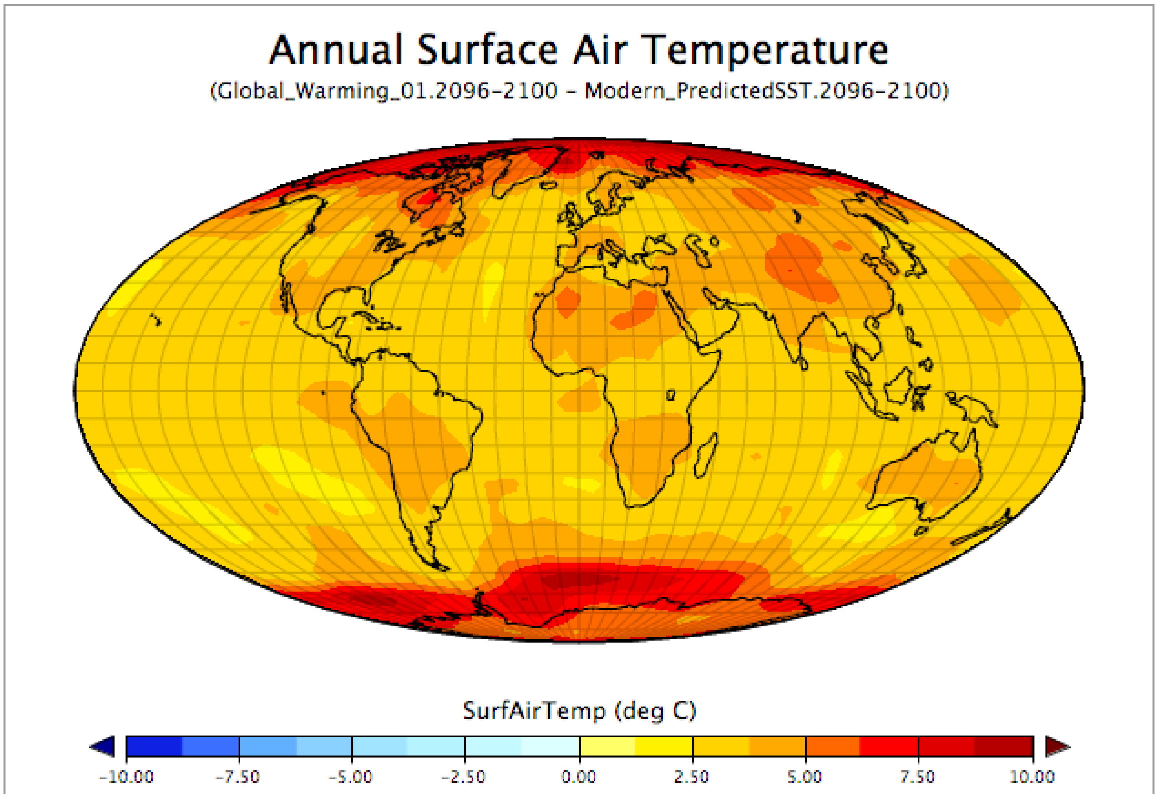


Plot 3: Global Surface Air Temperature in the Modern_PredictedSST and Global_Warming_01 simulations.

Surface Air Temperature

Compare the values shown in Plot 3 for the global surface air temperature at the end of each run, in the Year 2100. In the modern control run the temperature is about 13ºC, while in the Global_Warming_01 run the temperature is around 17ºC. Therefore, the total amount of global warming at the end of this transient simulation is 4ºC.

Suppose we extended the Global_Warming_01 run another 100 years, while holding carbon dioxide steady after the year 2100 (i.e., no further increases in CO2 levels). Sketch an extension to Plot 3 above that shows what you think the surface air temperature would do from the years 2100 to 2200. Explain your reasoning.



Map 1: Annual Surface Air Temperature Anomaly

In addition to comparing time series between the modern control and Global_Warming_01 simulations, scientists are interested in examining the geographic changes in climate. To do this they make images called anomaly maps, in which the climate of the control run (our baseline) is subtracted from the climate of the run with altered forcings. What the anomaly map shows, then, is the amount of climate change produced by those altered forcings.

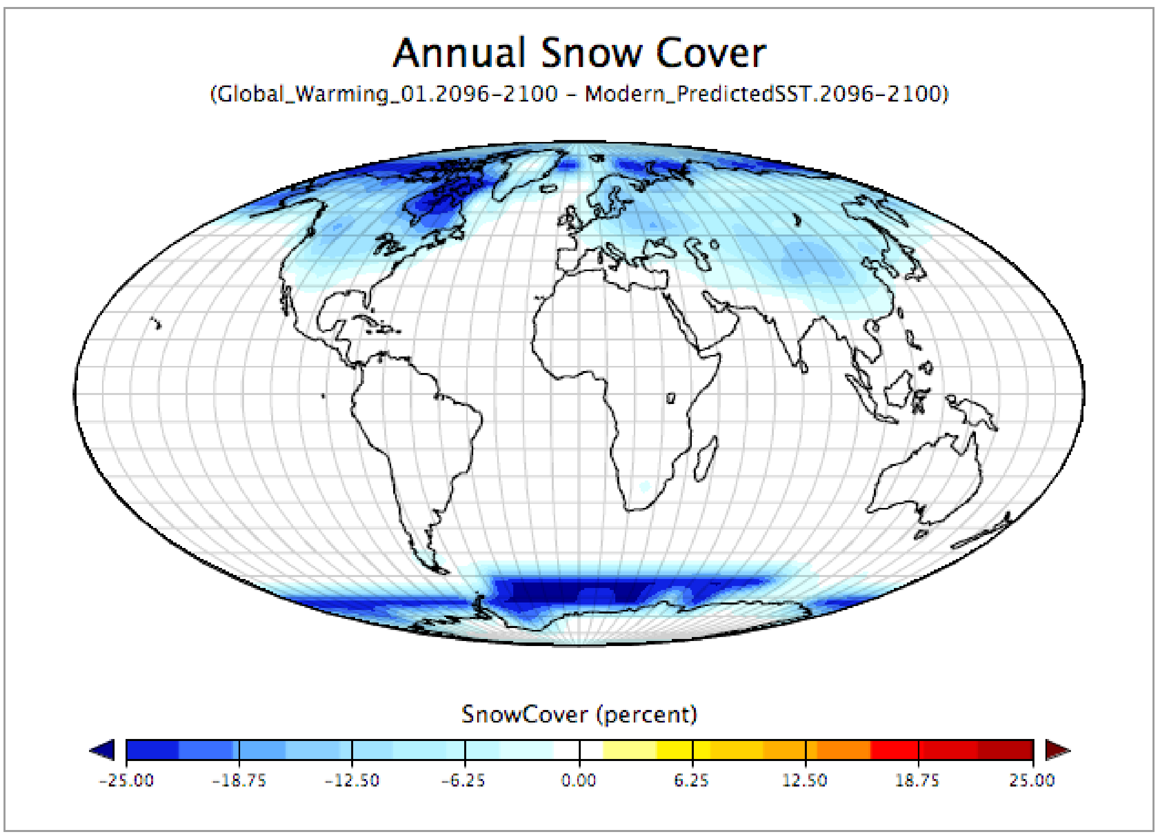
What does the surface air temperature anomaly shown in Map 1 tell you about the Global_Warming_01 run in general compared to the modern control run? Why do you think the temperature change is greater at high latitudes? What other geographic patterns do you notice in the temperature anomalies?

Since the carbon dioxide increase was uniform (CO_2 is a well-mixed gas in the atmosphere), we must examine other climate variables to explore why the temperature change is not also the same everywhere.

Ice Albedo Feedback

One key element in the geographic distribution of warming is related to the snow and ice-albedo feedback mechanism. This feedback is related to the fact that, as the climate warms, snow and ice begin to melt. As they do, the underlying surface – be it bare land, vegetation, or water – reflects far less of the sun's radiation than the highly reflective snow and ice. This newly exposed, darker surface absorbs additional energy and warms more than surrounding regions, further melting snow and ice.

Describe the geographic relationship between decreased snow cover in Map 2 and temperature increase in Map 1. How do you account for those areas in Map 2 that show little or no change in snow cover?



Map 2: Annual Snow Cover Anomaly

Signficance of "Rediscovery"

The ideas and activities that you have just reviewed in this global warming exercise are fairly typical of those that climate scientists perform using Global Climate Models in their own research. This exercise falls into a broad category of projects that students can pursue with EdGCM that we call "Rediscovery Experiments." Rediscovery experiments, as the name implies, allow students to recreate both the scientific process and scientific results that have been published by climate researchers from NASA, universities, and other institutions around the world. Because EdGCM includes an actual research version of NASA's global climate model, there are thousands of professional publications, scientific presentations, and reports that have detailed its use for various purposes – from the study of future climate change to climates of the geologic past. Many of these studies, including the activities you have just completed, are actually very famous experiments that lead to not only a new understanding of our Earth's climate system, but actually are responsible for much of the current debate over how government's worldwide should deal with future climate change.

The global warming experiment you just did, using the GCM you just employed, was directly responsible for the first-ever testimony to the U.S. Congress on the issue of global warming, and it heavily influenced the creation of the IPCC - now the preeminent body advising governments on the future of our planet. By participating in this global climate modeling exercise, whether you knew it or not, you just became a climate scientist. The issue of climate change is complex, and involves many more variables, including significantly those relating to hydrology. Hopefully, you will be inspired to pursue further study about simulating Earth's future and past climates, and to understand better the models that we will all be relying upon to plan for the 21st century.