EdGCM Exercise on Modern Climate Control Runs and Global Warming
Using a GCM to Explore Current and Future Climate

Mark A. Chandler, Columbia University, Goddard Institute for Space Studies
Ana Marti, University of Wisconsin – Madison, Atmospheric and Oceanic Sciences

Lesson 1: Modern_SpecifiedSST Analysis

- Explain simulation Modern_SpecifiedSST
- Visualize the data
- Examine climate basics (surface air temperature, zonal average (pole to equator gradient), seasonal temperature maps, global annual precipitation patterns, temperatures and zonal winds in vertical profile

Lesson 2: Modern_PredictedSST Analysis

- Explain simulation Modern_PredictedSST
- Visualize the data
- Compare with Modern_SpecifiedSST

Lesson 3: Doubled_CO2 Analysis

- Explain simulation Doubled_CO2
- Visualize the data
- Compare with Modern_PredictedSST (Equilibrium Climate)

Lesson 4: Global Warming Analysis

- Explain simulation Global_Warming
- Visualize the data
- Compare with Modern_PredictedSST
- Explain global warming impacts and feedback mechanisms
  - Surface air temperature
  - Ice-albedo feedback (snow and ice cover)
  - Cloud albedo feedback (low cloud cover)
  - Water vapor
  - Precipitation and Evaporation (Moisture balance)

Setting Up a Climate Modeling Experiment

1. Duplicate an existing run from the run list and open Setup Simulations
2. Set Required fields in the general information section

(fields in the General Info section with blue type are required)

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.

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 short description of the nature and purpose of each experiment. Hence, GCM simulations will not run unless the user types something in this field.

Running a Climate Modeling Experiment

Use the Play button in the Simulation Controls to start the climate simulation (they are on the EdGCM Toolbar and look like DVD buttons). The run will start up in a new window. After the first hour of the simulation the run will stop. If the first hour has completed successfully click the Play button on the run window and the simulation will proceed.

Setup for Modern Climate "Control" Experiments

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 acts like a base 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-decade period in the later part of the 20th century. 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.

Specified SST Simulations (Oceans as boundary conditions)

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 (e.g. temperatures, humidity, winds, etc.). *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 (e.g. topography, vegetation distribution, ice sheet extent). Boundary conditions in particular must be as realistic as possible and must be appropriate for the type of simulation planned. One of the most important boundary conditions is the sea surface temperature (SST) data, since SSTs directly effect 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).

Predicted SST Simulations (Using 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, climate scientists first run a short experiment (generally about 10 years), using specified SSTs. During the specified SST experiment they 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 mimicks 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, thus 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. 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. *If you haven't previously done so, begin running the Modern_predictedSST simulation.*

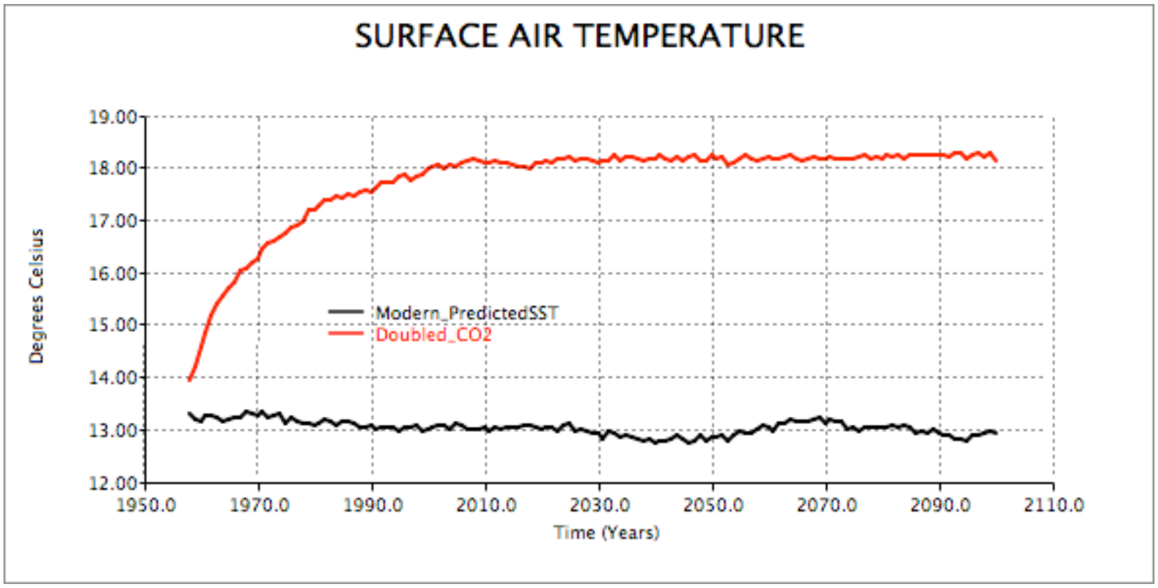
Running Simulations to Equilibrium

An example using Doubled-CO_2 experiments

You may want to introduce the concept of "equilibrium climate" during this portion of a lesson because it is an exercise that students can do while simulations are in progress. Here the concept is that a climate scientist does not want to analyze the results of a climate model simulation while the climate is still changing (i.e. still in the process of adjusting to an imposed forcing) Note that this does not apply to simulations in which the forcings are continuously changing, because, in such cases, a run is unlikely to ever reach an equilibrium state.

If you haven't previously done so, begin running the Doubled_CO2 simulation.

One of the best examples to use for showing students how a run comes into equilibrium is to compare a modern climate control run (e.g. Modern_predictedSST) to a run with an instantaneous doubling of carbon dioxide (e.g. see the Doubled_CO_2 run included with EdGCM). At any point during the simulation (even while the run is in progress) use the Analyze Output window to calculate Time Series of various climate variables. In the plot below (see figure) we show Surface Air Temperature for both modern and doubled CO_2 simulations after they have run for 150 years each. You see that the modern surface air temperature 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. The Doubled_ CO_2 run, however, was given a burst of carbon dioxide at the start (the run began with 630 ppm CO_2 instead of the 315 ppm used in the modern climate control run. By plotting the temperature change over time (red line in plot) one can see that surface air temperature increases rapidly in the simulation. But, most of the climate change is completed within 50 years, thus analysis of results from this run would be appropriate at anytime beyond 50 years. If computer resources are limited, one can see that running this experiment 150 years would be, for most analyses, unnecessary.



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

Comparing a *Transient* Global Warming Simulation to the Modern Climate

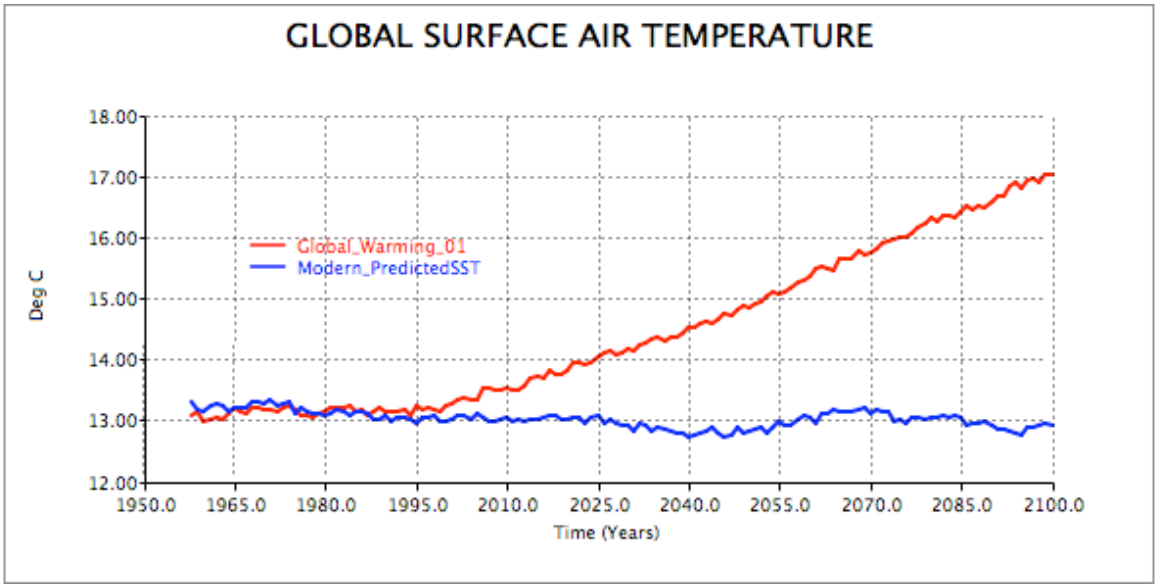
In the following exercise we want to compare the simulation Global_Warming_01 to the control run, Modern_PredictedSST.

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 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 an exponential change per year of 1% from 2000 to 2100. Use the trend creation features in the Setup Simulations window so you understand how to generate climate forcing trends.

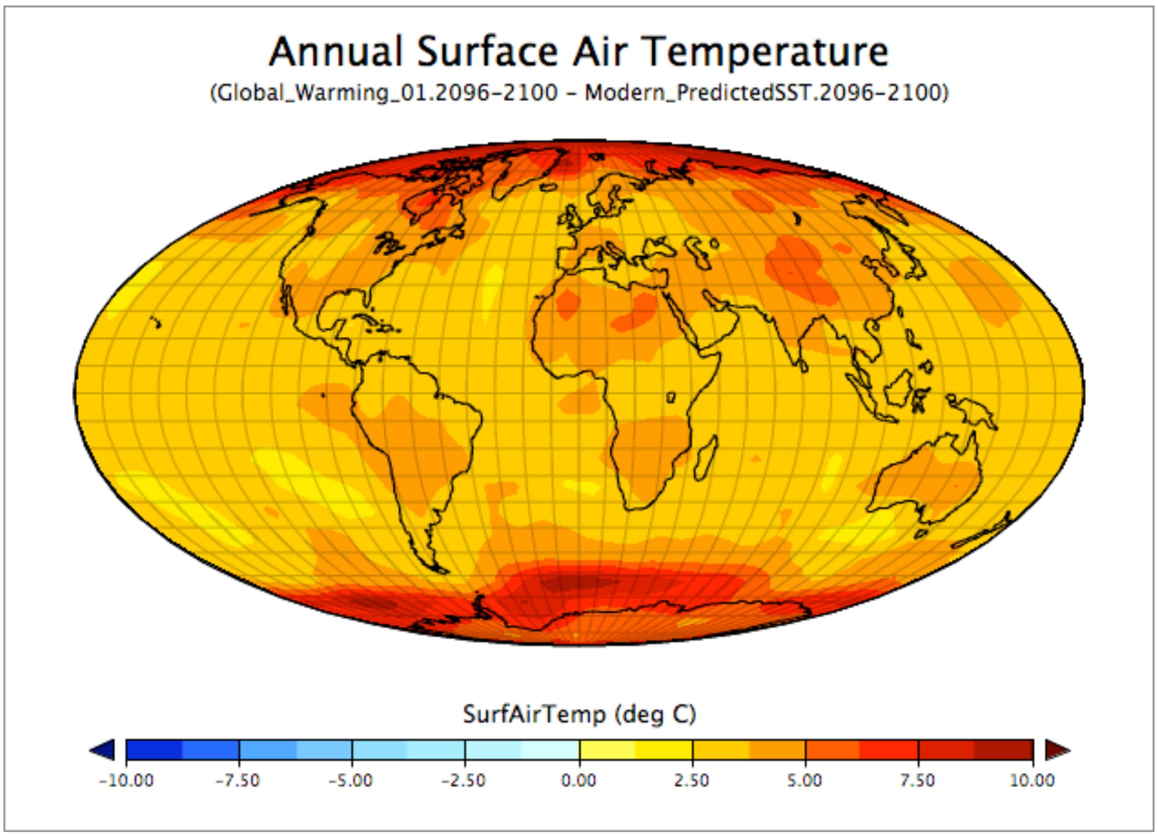
If you haven't previously done so, begin running the Global_Warming_01 simulation.

First, we compare the values of the data of the global surface air temperature. In the simulation Modern_PredictedSST the temperature is about 13ºC while at the end of the Global_Warming_01 run global surface air temperature is around 17ºC. Therefore, the global warming for this simulation is 4ºC.

Then, we compare the plots of global surface air temperature (Plot 1). In the Modern_PredictedSST curve, we can see that the global surface air temperature is almost constant at 13ºC. On the other hand, in the Global_Warming_01 graph, the global average temperature rises continuously in response to the ever-increasing CO_2 levels.



Plot 2: Global Surface Air Temperature in the Modern_PredictedSST and Global_Warming_01 simulations.

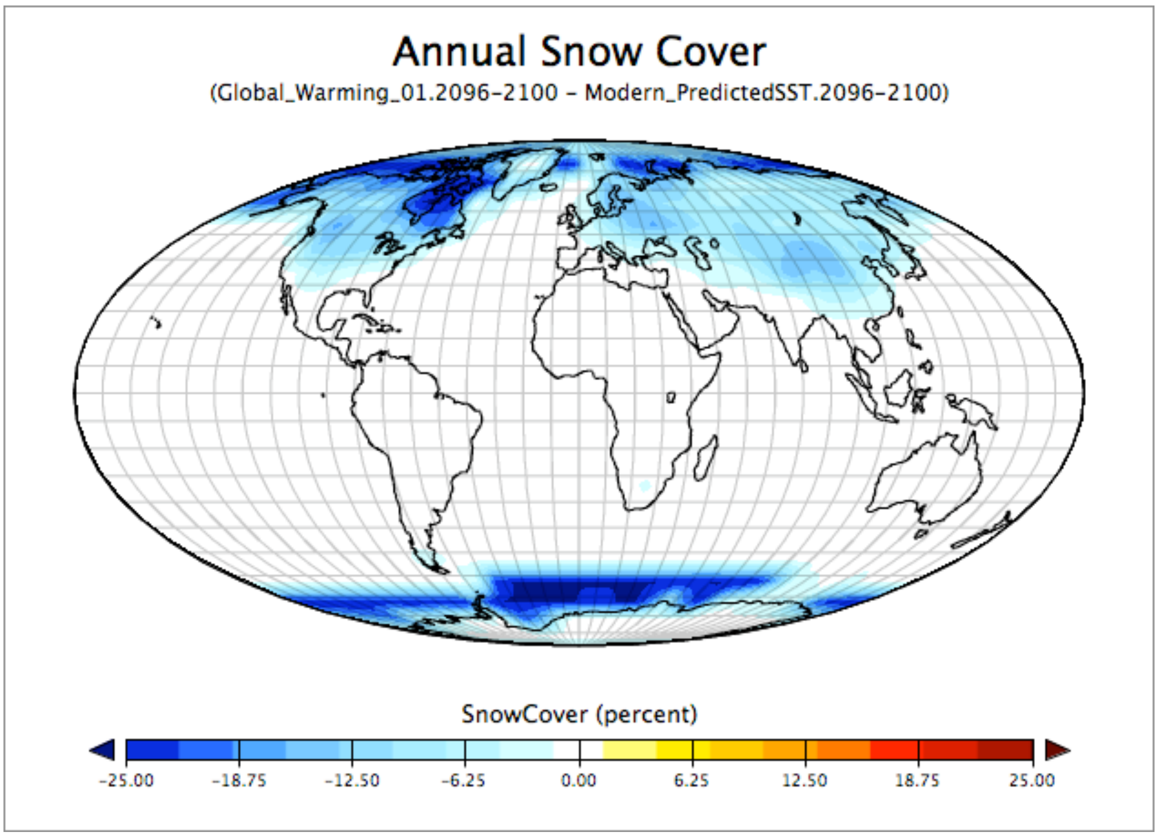


Map 1: Annual Surface Air Temperature Anomaly

If we now plot the geographic anomaly between the surface air temperature distributions in the two experiments we can see that the warming has not been uniform. Although all regions have warmed, the warming is greater at higher latitudes than in the tropics and greater over the land than over oceans. 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 increase is not also the same everywhere.

At this point you might ask students to do some "browsing" or work in an "exploration mode" to see if they can come up with hypotheses (supported by evidence) for why the planet warms in the way that it does.

One key element in the geographic distibution of warming is related to the 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 reflects far less of the sun's radiation than the highly-reflective snow and ice. The surface absorbs more energy and warms more than surrounding regions - further melting snow and ice cover. *Compare the areas of greatest snow decrease to the areas of greatest temperature increase.*

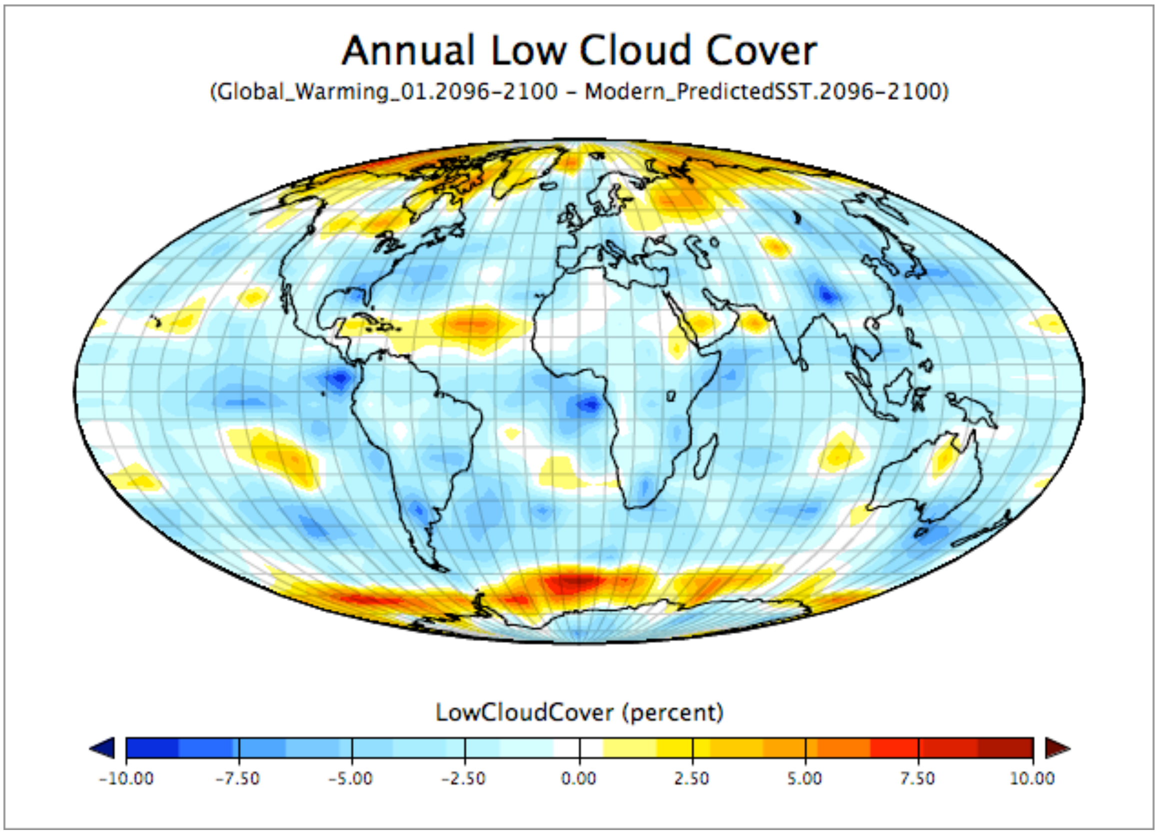


Map 2: Annual Snow Cover

Concerning the low cloud cover (map 4), the simulation shows that there is an average decrease. Since low clouds contribute to reduce the global warming, the effect of this reduction in the low-cloud coverage would produce also a positive feedback. It is interesting to note that if the cover of high clouds is also reduced, this could attenuate this feedback.

Are there other important feedbacks in the climate system that effect global warming?

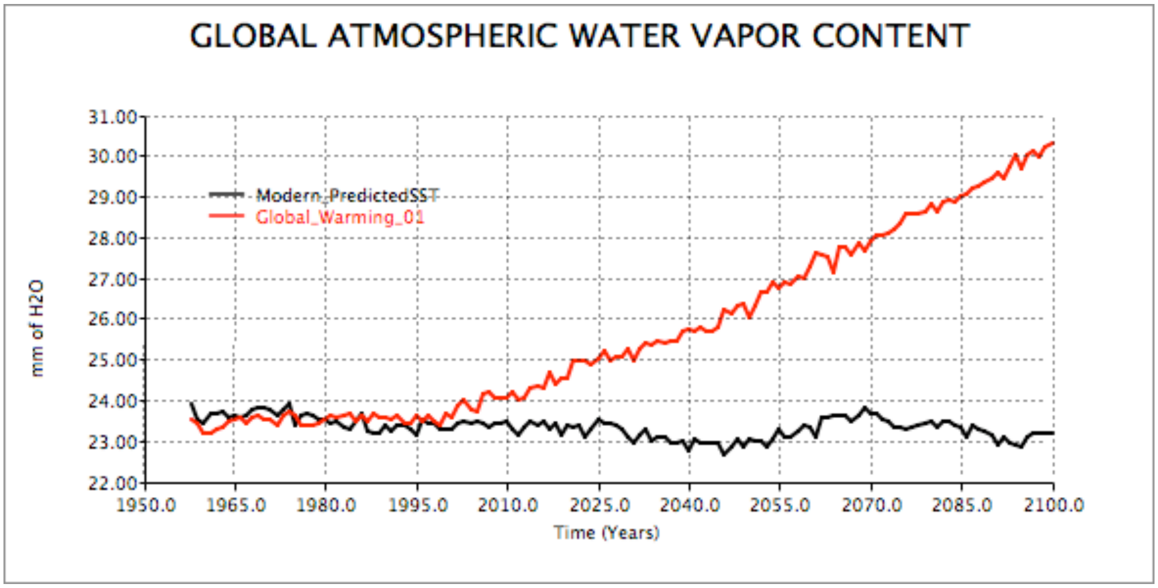
Yes. Another important feedback relates to changes in cloud cover. Below we see that low clouds, which generally act to reflect sunlight and have a net cooling effect on the planet, will decrease as climate warms. As low cloud cover decreases, less sunlight is reflected back to space, and more of the sun's energy is thus absorbed at the Earth's surface, further heating the planet…a positive feeback to warming.



Map 3: Annual Change in Low Cloud Cover

Water Vapor:

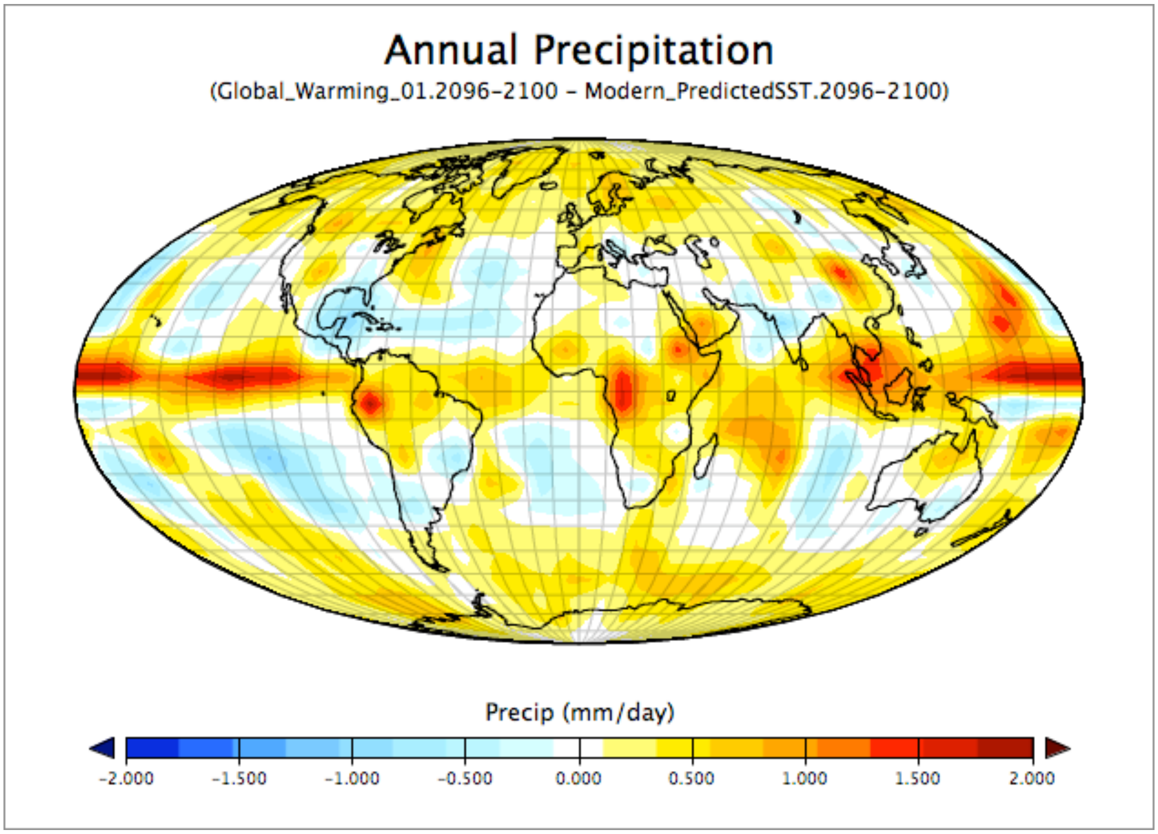
Another reason for the overall warming is that increased evaporation from the oceans causes more water vapor to accumulate in the atmosphere. Water vapor is, itself, a powerful greenhouse gas, and thus it acts as a positive feedback, which further warms the climate. We can see that the increase in the global atmospheric water vapor content in the global warming simulation is nearly 30% from 1995 to 2100 (Plot 2).



Plot 3: Global Atmospheric Water Vapor Content in Modern_PredictedSST and Global_Warming_01 simulations.

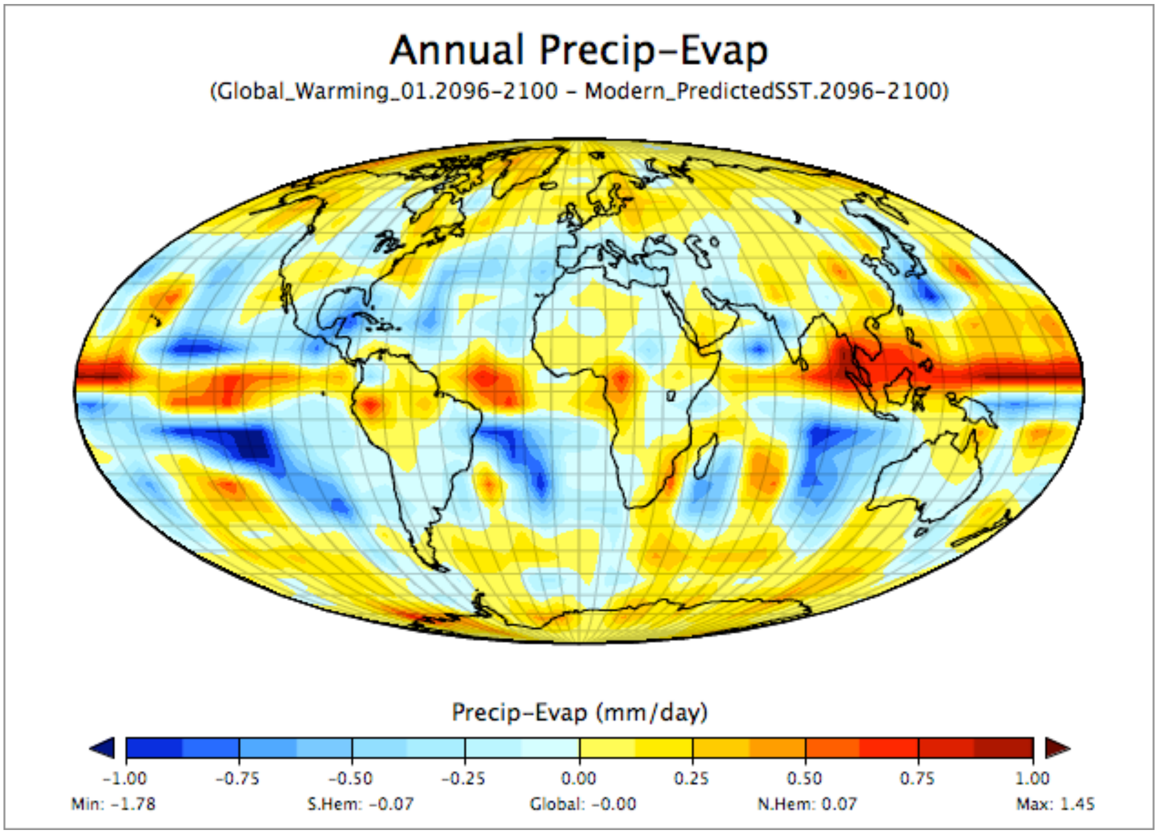
Hydrological Cycle: Moisture Balance

As one might suspect, with more evaporation, and more water vapor in the atmosphere, global precipitation tends to increase. In Map 3, we can see that the average increase in the annual precipitation, due to the increase in the global temperature, is also not uniform, with greater increases in the tropics, where energy intensifies convection systems and at high latitudes where the now open oceans are a new source of atmospheric moisture that previously did not exist.



Map 4: Annual Precipitation Change

Unfortunately, what will eventually happen to water resources in a globally warmer world is a far more difficult task, since the ultimate fate of water resources will relate to the more complex balance between regional evaporation and precipitation rates. To exacerbate the problem of determining the impact of global warming on key hydrological variables, we expect that precipitation will tend to occur more and more in short-term, intense events (the hypothesis is that convective storms will increase due to more energy in the system). GCMs, with spatial resolutions coarser than typical thunderstorms, may not capture such phenonmenon accurately enough to test such hypotheses….but you can try. *What conclusions would you draw from the climate model in EdGCM about the future of water resources on Earth in the 21st century?*



Map 5: Annual Change in Precipitation-Evaporation