Simple climate model lab 2

Climate Science

UW Program on Climate Change

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Overview

The Simple climate model lab 2 uses a simple climate model that can either be run on Excel to teach students how climate models can be tested and used to make future temperature change projections. The simple climate model is used to teach a variety of topics, including the utility of models, understanding of uncertainty, and understanding of how past temperature changes can help estimate future warming. For this lesson plan, we focus on having the students experience the process of testing their climate models , making projections of 21st century warming, and comparing their projections amongst their peers' projections. The students will be divided into groups of two or three, each representing a modeling group. Each group will provide a 21st century temperature projection based on their model that is first tuned to 20th century warming. The end product will be a graph of projected 21st century warming based on their models, much like the graph found in IPCC. This will give the students a firsthand experience of what can go on in making climate projections and show the students how climate modelers can get uncertainty in projected temperatures of the future, even when they use the same historical observations to constrain the model parameters.

Focus Questions

- What is a model? Why do we even need a global climate model?
- What is one way to test a model's performance? (How can 20th century temperature records be used to test a model's behavior?)
- Why do the wiggles exist in the temperature records and what determines how wiggly they are?
- Where do uncertainties in climate projections come from?
- Why has the temperature been rising in the last hundred years?
- What is climate sensitivity and what aspect of the Earth's mean temperature does it control?

Materials

Worksheet provided
Access to Excel
ClimateModel_presentation.pptx
3 excel spreadsheets:
climatereal2.xlsx
climatemodel_Combined.xlsx
climatemodel_GROUP.xlsx

Lesson Time

2 fifty minute class period

Prep Time

Depends on students' familiarity with using Excel (if the students are familiar with Excel, then it takes about an hour for the instructor to read the background material and test the models before the lab)

Standards

WA State:

Performance Expectations

After the lab, students should be able to look at a temperature record and understand the changes in the temperature in terms of simple forcing (anthropogenic and natural), climate sensitivity (feedback), and heat storage.

Students should understand why scientists would be interested in estimating the Earth's climate sensitivity. The students should see that depending on the value of the climate sensitivity, the warming we get in the next 100 years would substantially change.

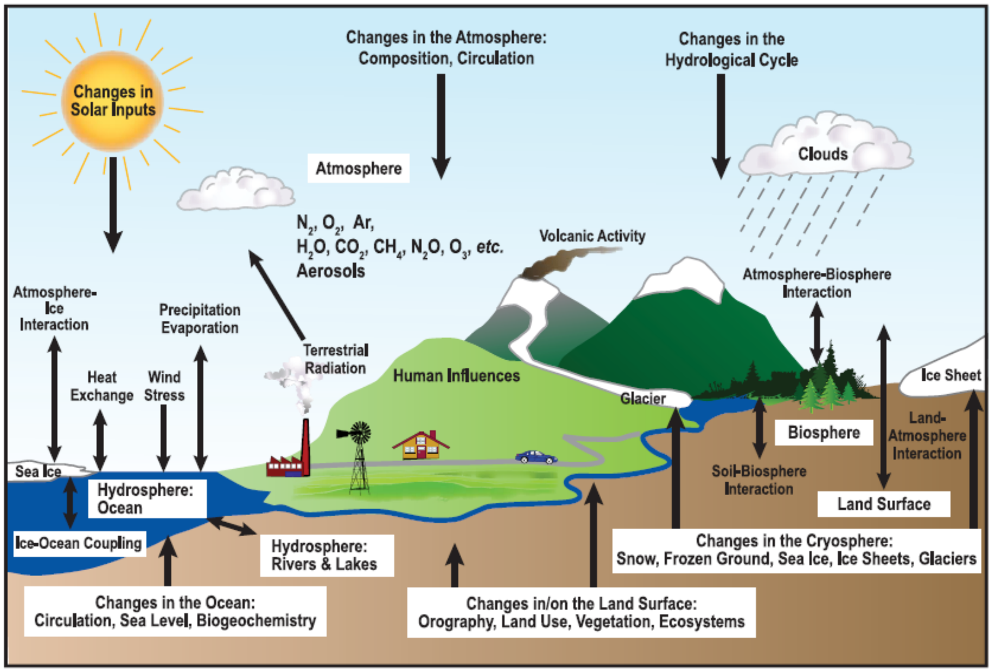
Students should be able to look at the IPCC temperature projections for the 21st century and explain the following concepts:

- Why do the A2 (RCP65) scenario projections show more warming in 2100 than the B1 (RCP3) scenario projections? *Answer: The A2 (RCP65) projections are based on emission forecasts of more greenhouse gases emissions over the course of the 21st century. Simplistically put, it is a scenario where greenhouse gas emissions are not curbed.*
- For each emission scenario, why is there a range of temperatures predicted for the year 2100? *Answer: Multiple models are used to make temperature projections, and each model is slightly different from another. The students should have found by now that even if one uses the same model and tests the model on the same 20th century temperature record, one can still come up with a range of temperatures for 2100. Therefore, this represents an inherent uncertainty in our projections for the future. Even if we knew how much emissions will exist in the future, there will still be some uncertainty to the amount of warming, given our simplified understanding of the climate in the Excel model.*

Background Information

Understanding the energy budget at the Earth's surface can take us a long way to understand recent changes in global mean temperatures. The simple climate model is essentially an energy balance model that tries to account for the major components of the climate system (feedbacks, natural variability, and an ocean) to help estimate changes in global mean temperature.

Before working with the simple climate model, some background information about models is necessary. So why do we even need climate models? Unlike many physics experiments that we can perform inside a laboratory, doing experiments on the Earth's climate is not as easy. Therefore, scientists must use computer model representations of the climate that incorporate many of the processes and attributes that are essential to simulate the Earth's climate, some of which are represented in the picture below.



However, we must test whether our models are accurately representing the Earth's climate. Therefore, many of the climate models compare their climate models with past and present observations, such as global temperatures or global precipitation fields. Now if we want our climate models to capture changes in the climate, such as what kind of temperature changes we would expect in the 21st or the 22nd century, we would need to see whether our models can even capture the warming over the 20th century. Generally speaking, many of the current state-of-the-art models used for the IPCC are tested in this way to see what areas of their model need to be improved.

In this lab, the students will have the chance to use their simple climate models to make projections of 21st century warming, given a few possible emission scenarios. In the first part of the lab, the students will tune their models so that they are better at estimating the warming that occurred over the 20th century. Then they will use the same model parameters to make temperature projections for the future. What follows is a description of the climate model. It is up to the instructor to decide how much detail to convey to the students.

The simple climate model is simply put an energy balance model. When a system (like the Earth) is in energy balance, where the energy entering the system equals the energy leaving the system, the temperature of the system will stay the same. If the system undergoes a positive forcing, like the increased intensity of the sun or increased greenhouse gases, the system will warm up until the excess energy entering the system is balanced by the energy leaving the system by longwave cooling. Among many things, the amount that the surface warms will depend on the storage capacity of the surface, which we will assume is an ocean with some depth. We can write this balance in terms of an equation

Heat storage rate = longwave cooling + radiative forcing [1]

If we want to include effects from year to year differences in the weather, then we add weather noise such that

Heat storage rate = longwave cooling + radiative forcing + weather noise [2]

When the system is in equilibrium, the heat storage rate will be on average zero, which means that longwave cooling + radiative forcing + weather noise will be zero. Since weather noise is zero on average, the system will be in equilibrium if longwave cooling + radiative forcing is zero.

Now, Eq. 2 can be written in the following form

$$\rho c_p H \frac{dT(t)}{dt} = -bT(t) + R(t) + W(t) \quad [3]$$

where

$\boldsymbol{\rho}$ is the density of sea water (1025 kg m^{-3}),

c_p is the specific heat of sea water (3985 Joules kg^{-1} $^oC^{-1}$)

H is the depth of the upper ocean where heat is absorbed (m)

T is the temperature change from preindustrial conditions (^{o}C)

t is time (seconds)

b is the climate sensitivity (Watts m^{-2} $^oC^{-1}$)

R is the radiative forcing from natural and anthropogenic effects (Watts m^{-2})

W is the year to year random weather forcing (Watts m^{-2})

Note that $bT(t)$ in Eq. 3 does not just represent longwave cooling. Although we have talked about one feedback (the Planck's feedback, which is always negative) so far, we haven't included any of the other feedbacks in our previous discussion. What we can do, however, is to combine the Planck's feedback with other feedbacks (water vapor, lapse rate, cloud, etc.) under the *b*, which is the climate sensitivity.

We can now track changes in temperature by taking the finite-difference form of Eq. 3 to look at the changes in temperature from year

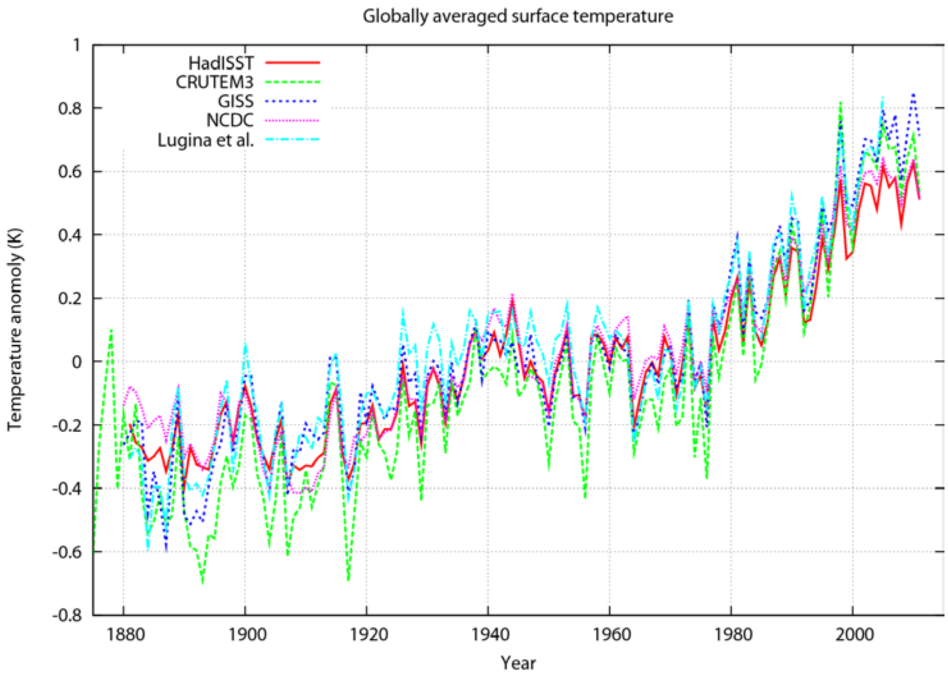
$$\rho c_p H \frac{T^{n+1} - T^n}{\Delta t} = -bT^n + R^{n+1} + W^{n+1} \quad [4]$$

Where the *n* superscript is the value at time *n* where *n* goes from 1880 through 2006 in the first sheet.

We can rearrange Eq. 4 to get

$$T^{n+1} = T^n + \frac{-bT^n + R^{n+1} + W^{n+1}}{\rho c_p H} \Delta t \qquad [5]$$

This is the equation that is in the spread sheet.



Now if we look at the 20th century global mean temperature record in this context, the temperature has been increasing, which means that the storage rate is increasing. This also means that the radiative forcing has been larger than the longwave cooling (including effects from other feedbacks). The rate of the temperature increase then is set by both the ocean heat storage capacity and the climate sensitivity. The wiggles in the temperature can be either understood as either the effect of radiative forcing or weather noise. By doing this experiment, we want the students to look at the 20th century temperature series and understand what controls the general trend, the rate of the trend, and the wiggles in the temperature.

The second part of the lab is for the students to make temperature projections based on different scenarios, called Representative Concentration Pathways (RCPs). The RCPs are meant to serve as input for climate models that capture different scenarios of changing emissions, concentrations, and land-cover change projections. Quoting the Nature article listed below, "These scenarios provide plausible descriptions of how the future might unfold in several key areas—socioeconomic, technological and environmental conditions, emissions of greenhouse gases and aerosols, and climate. When applied in climate change research, scenarios help to evaluate uncertainty about human contributions to climate change, the response of the Earth system to human activities, the impacts of a range of future climates, and the implications of different approaches to mitigation (measures to reduce net emissions) and adaptation (actions that facilitate response to new climate conditions)."(Moss et al., 2010) For our case, the RCPs will represent forcing inputs for the simple climate model.

For more information on climate models, see: http://www.realclimate.org/index.php/archives/2008/11/faq-on-climate-models/.

The Box TS.7 of the IPCC report on evaluating climate models will also be helpful: http://archive.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-4-1.html.

If you want a short article about models in general, then the following article would be helpful: http://earthobservatory.nasa.gov/blogs/earthmatters/2012/06/08/who-says-climate-models-arent-worth-talking-about/.

Further information about the scenarios can be found at

http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome#descript

Also see the Nature paper (Moss et al., 2010) for more details. This paper should be accessible to the high school students.

Moss, R. H., et al., 2010; The next generation of scenarios for climate change research and assessment, *Nature* 463, 747-756 (11 February 2010) | doi:10.1038/nature08823

Prior Knowledge and Learning Assets

Concept of energy budget and conservation

Knowledge of what models are

IPCC, climate models, and how they are being used to inform policy or understand the climate system

Some familiarity with Excel spreadsheet

Anticipated Challenges

Learning how to use the Excel spreadsheet

Understanding why we need models, and specifically climate models

Understanding of what the different components of the model represent

Understanding the difference between uncertainty in understanding of the physical processes that affect Earth's climate and uncertainty in future anthropogenic emissions of greenhouse gases and aerosols

Trying to convey what we know about future warming and not getting bogged down with what we don't know

Assessment Elements

The students will be evaluated on their answers to the worksheet.

The students' understanding will be informally evaluated during the post-lab discussion, where teacher asks questions on implications of what they've found and pushes students to speculate, based on their findings and asks the students how they would test their speculations (hypotheses). The post-lab discussion provides an opportunity for the students to recall what they'd done and put it in context of the curriculum.

Conducting the Lesson

Preparation

Read the materials above and acquaint yourself with the climate model, either the Excel version. Go through the worksheet yourself to get acquainted with the model's behavior. You can also see what kind of values of weather noise or feedback parameter to expect.

Preparation before class

- Anticipate how many modeling groups (groups of twos or threes are suggested) you will have in your class and make sure that climatemodel_Combined.xlsx is organized to accommodate that number of groups.
- Make sure the Excel model runs on every computer that will be using it. The recent version of Excel that can read .xlsx will be needed.

In class

INTRODUCTION TO THE LAB

15 min: Introduce the students to models and major components of the Earth's climate with the presentation (ClimateModel_presentation.pptx) that comes with this lesson plan. The presentation may be tailored to fit the students' level of

understanding of models, energy budget, and major constituents of the Earth's climate.

It would be good to ask the students whether they know of any models that are used to simulate different things (model airplane, model robot, flight simulator, weather forecast model, etc.) Then ask them what the models are there for. For example, why would you even need a model of an airplane or a weather forecast model? Then transition to climate models.

15 min: Introduce the IPCC (Intergovernmental Panel on Climate Change) report and the projections of future warming provided by various international climate modeling groups (graph can be found in Powerpoint presentation). Introduce the graph with temperature projections for the 21st century. Ask them what they think each line represents and what the shading behind the lines represent. You will want to circle back to this during the post-lab discussion.

10 min: (optional) Talk about how these projections of future warming are used to inform government officials on how to mitigate or adapt to climate change.

10 min: (optional) If the students have not covered energy budgets, then introduce them to the concept of energy budget. Some sample slides from the presentation may be used for this purpose.

20 min: Introduce the students to the Excel climate model. Here, varying degrees of detail may be presented. In this lesson plan, we will try to present the most basic detail that is needed to do the experiment.

GETTING STARTED

5 min: Have the students break up into groups of twos or threes. Each group will represent a climate modeling center. They may choose their own group name if they wish. They may also come up with their own logos. For our examples, we've come up with the creative group names of A, B, & C. The Excel worksheet that combines everyone's results allows for up to 5 groups. More can be added if necessary.

Handout the worksheet to everyone.

30-40 min: By the end of the lab, the students will ultimately need to come up with 3 temperature projections for the 2007 to 2100 time period. The groups' projections will then be combined using the Excel spreadsheet climatemodel_Combined.xlsx.

POST-LAB DISCUSSION

10 min: Combine the projections from all the modeling groups and graph them on climatemodel_Combined.xlsx. Then on the blackboard make a table with each group's name, noise level they chose, and feedback parameter they chose. This way allows students to see what other students came up for their climate sensitivity and

noise level. It may be good to point out that there's really no exact answer of what value is correct or wrong. Ask the students what changing the noise level did to the graphs and what changing the feedback parameter did to the graphs. If there is no response, ask them what they think a particular extreme value of noise (0 or 10) or feedback parameter (0.1 or 5) will do to temperature projections.

15 min: Plot the temperature projection from one of the scenarios. An example figure with three temperature estimates (A, B, & C) for RCP 45 is shown below.

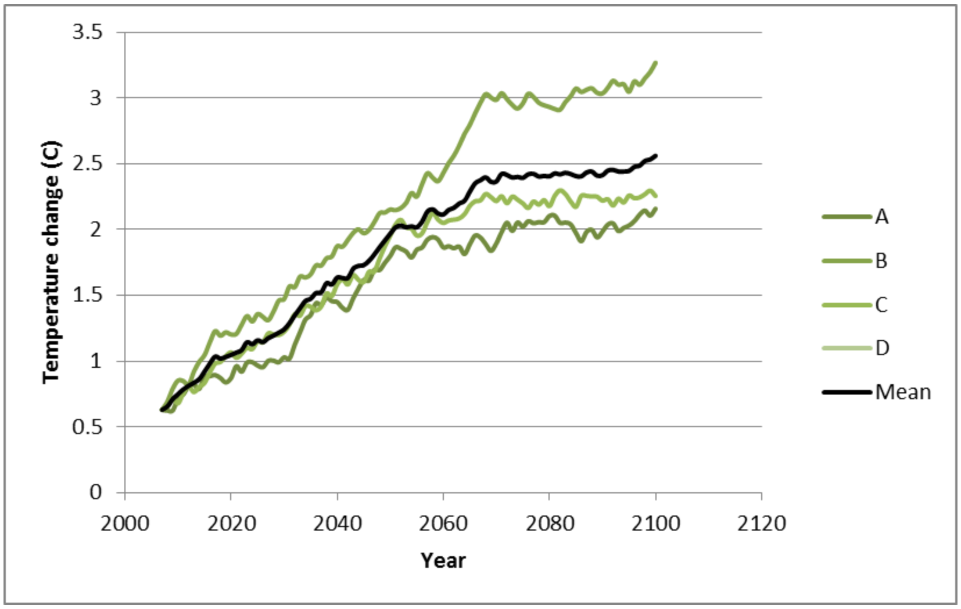


Figure: Example plot from RCP 4.5 run using 3 models (A, B, & C). The black line indicates the multimodel mean.

Here, ask the students why certain estimates appear to predict more warming than others. Then ask them about the wigglier graphs (if this is apparent). What appears to control the wiggles? This part is to reinforce the concept of how the feedback parameter and weather noise control the behavior of the temperature change. You can also ask about the line that represents the mean (average) here.

Next, show the multimodel mean plot, as shown below.

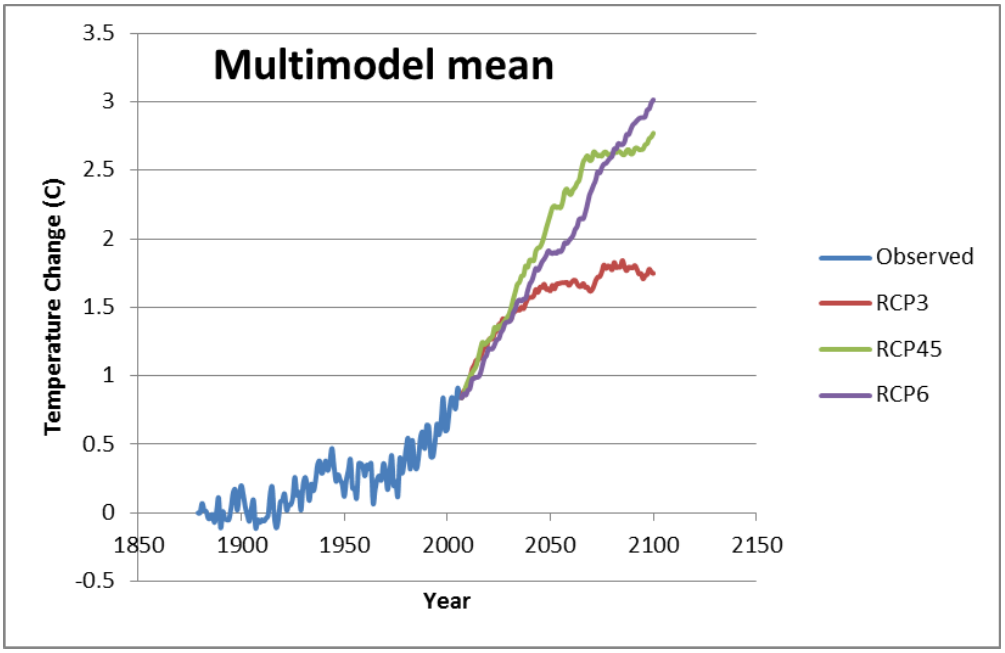


Figure: Example plot from the multimodel mean. This figure can be found under the 'All' worksheet in the spreadsheet named climatemodel_Combined.xlsx.

Here, only the multimodel means are plotted. The Excel spreadsheet may be modified so that the intermodel spread is also shown. Ask the students why they think each line ends up at different temperatures. Then if you look at the behavior of each graph, you will notice that RCP3 has actually leveled off. You can ask them why they think it's flattened, compared to say RCP6. Finish the discussion with some of the following suggested questions to get the students to start thinking about policy implications, limitations of our simple climate model, and speculation about what temperatures would look like if we ran beyond 2100.

If you want, you can ask the students some of the following discussion questions to get them thinking about implications and future scientific questions.

- What do you think the numbers in RCPXX are related to? *Answer: The XX are related to the radiative forcing values at the end of the 21st century (2100 values).*
- If we run the model to 2200, what do you think will happen to the temperature change in RCP3 and RCP45? *Answer: You can see that RCP3 is starting to flatten out, while RCP45 is increasing. Therefore, the temperatures at 2200 will be higher for RCP45, while they would stay close to 2100 values for RCP3. The follow up question to this would be, "is there a way we can test this?" And of course, you can run the models up to 2200, instead of 2100 to test this. Practically speaking, since the emission scenario for RCP3 ends at 2100, the emissions for RCP3 have to be extended to 2200 assuming a constant radiative forcing value with some noise.*
- Given the way the models are constructed, can we ever get rid of the

uncertainty (temperature range) that we find in each emission scenario? *Answer: No, we will not be able to get rid of the uncertainty, because each model will be forced with a different type of random noise. Therefore, even if two models are run with the same climate sensitivity and the same size of weather noise, they will give you slightly different temperature projections, which will show themselves as uncertainty in the temperature projections at 2100.*

- Why do the A2 (RCP65) scenario projections show more warming in 2100 than the B1 (RCP3) scenario projections? *Answer: The A2 (RCP65) projections are based on emission forecasts of more greenhouse gases emissions over the course of the 21st century. Simplistically put, it is a scenario where greenhouse gas emissions are not curbed.*
- We can talk about uncertainty in our temperature estimates. But what can we say from our modeling exercise? Are the 2100 temperatures for RCP3 and RCP65 different enough that we can say that the two alternate 'futures' would give us very different temperatures? *Answer: From the modeling exercise, the RCP3 projections should almost all lie below the RCP6 scenarios, even if one takes into account the spread in 2100 temperatures. This can show us that if we continue to emit, as projected by RCP6, we will have significantly different temperatures at 2100, compared to if we start reducing emissions, as in RCP3.*
- For each emission scenario, why is there a range of temperatures predicted for the year 2100? *Answer: Multiple models are used to make temperature projections, and each model is slightly different from another. The students should have found by now that even if one uses the same model and tests the model on the same 20th century temperature record, one can still come up with a range of temperatures for 2100. Therefore, this represents an inherent uncertainty in our projections for the future. Even if we knew how much emissions will exist in the future, there will still be some uncertainty to the amount of warming, given our simplified understanding of the climate in the Excel model.*

Teacher Note: It is important to test the model on the computers that the students will be using. In the past, there have been issues with different versions of Excel not being able to correctly run the scripts that are embedded in the provided Excel spreadsheets.

If the students are not familiar with Excel, the instructor may need to spend a class period getting the students familiar with Excel. Some of the necessary skills will be: entering data, creating new spreadsheets, copying and pasting data in excel, knowing the paste options so that the students can just paste the values, making simple scatter graphs on excel.

MORE RESOURCES:

http://serc.carleton.edu/quantskills/index.html

SERC quantitative skills portal

http://serc.carleton.edu/introgeo/index.html

SERC geosciences

http://neo.sci.gsfc.nasa.gov/Search.html

NASA earth observations

http://phet.colorado.edu/en/simulations/category/new

phET simulations

MERRA winds

http://svs.gsfc.nasa.gov/vis/a000000/a003700/a003733/index.html

For more information on climate models, see: http://www.realclimate.org/index.php/archives/2008/11/faq-on-climate-models/.

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