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Lesson 5 - Modeling of the Climate System, part 2

The links below provide an outline of the material for this lesson. Be sure to carefully read through the entire lesson before returning to Canvas to submit your assignments.

Introduction

About Lesson 5

In this lesson, we will continue with our investigation of climate models. We will investigate more complex models of the climate system than in the previous lesson. We will first investigate a slightly more complex version of the EBM encountered in Lesson 4, where we explicitly insert an atmospheric layer above the Earth's surface. We will consider models that represent the full three-dimensional geometry of the Earth system, and model atmospheric winds and ocean currents, patterns of rainfall, and drought, and other key attributes of the climate system. We will also explore the concept of 'fingerprint detection'—a method that allows us to compare model predictions against observations to discern whether or not the signal of anthropogenic climate change can already be detected.

What will we learn in Lesson 5?

By the end of Lesson 5, you should be able to:

- describe the hierarchy of theoretical climate models, the underlying assumptions, caveats, and strengths and weaknesses of various climate modeling approaches;
- discuss both the strengths and limitations of current-generation climate models;
- speak to the issue of how climate models have been 'validated';
- assess the relative roles of human vs. natural impacts on climate, based on experiments with climate models;
- assess the state of our current knowledge regarding the equilibrium climate sensitivity of Earth.

What will be due for Lesson 5?

Please refer to the Syllabus for specific time frames and due dates.

The following is an overview of the *required activities* for Lesson 5. Detailed directions and submission instructions are located within this lesson.

- Read:
  - IPCC Fifth Assessment Report, Working Group 1 [1]
  - Summary for Policy Makers [2]
    - D. Understanding the Climate System and its Recent Changes: p. 15-19
  - Dire Predictions, v.2: p. 36-37, 100-101, 110-111, 148-149
- Problem Set #4

Questions?

If you have any questions, please post them to our Questions? discussion forum (not e-mail), located under the Home tab in Canvas. The instructor will check that discussion forum daily to respond. Also, please feel free to post your own responses if you can help with any of the posted questions.

One-Layer Energy Balance Model

We can increase the complexity of the zero-dimensional model by incorporating the atmospheric greenhouse effect in a slightly more realistic manner than is embodied by the *ad hoc* gray body model explored in the previous lecture. We now include an explicit atmospheric layer in the model, which has the ability to absorb and emit infrared radiation.

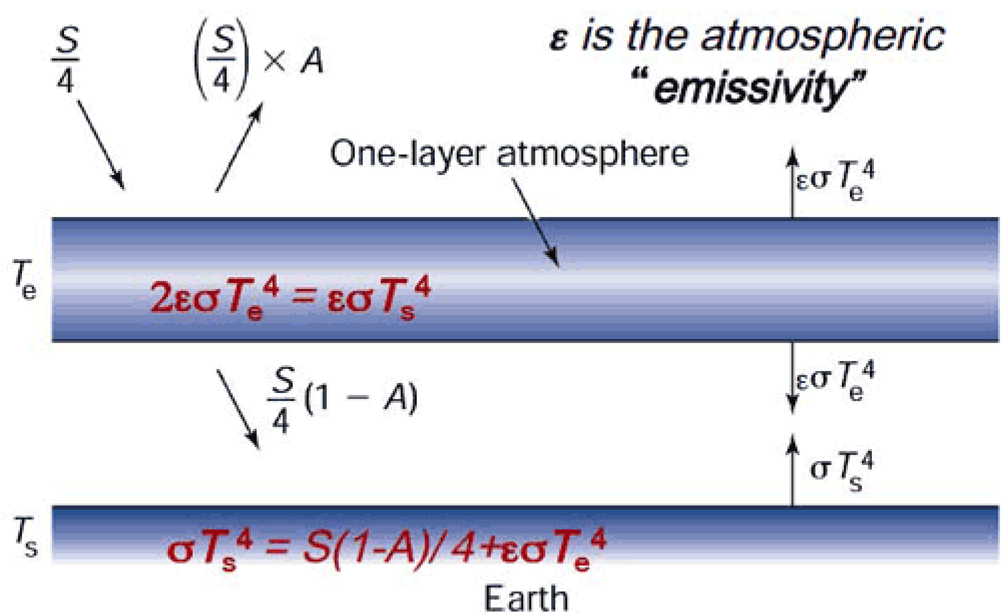


Figure 5.1: One Layer Energy Balance Model.
Credit: M. Mann modification of a figure from Kump, Kasting, Crane "Earth System"

We will approximate the emissivity of Earth's surface as one, that is, we will assume that The Earth's surface emits radiation as a black body. The atmosphere itself has a lower but non-zero emissivity, i.e., it emits a fraction of what a black body would emit at a given temperature. This emissivity is due to property of greenhouse gases within the atmosphere, and we will denote this atmospheric emissivity by ε (not to be confused with the epsilon of previous lessons which was associated with the emissivity of Earth's surface, which we are approximating here as unity!). According to *Kirchhoff's Law*, at thermal equilibrium, the emissivity of a body equals its absorptivity (i.e., the the fraction of incident radiation that is absorbed by the body). Therefore, ε is also a measure of the efficiency of the atmosphere's absorption of any infrared radiation (IR) incident upon it. IR radiation that is not absorbed by the atmosphere is transmitted through it; therefore, 1-ε is the fraction of incident IR radiation that is transmitted through the atmosphere without being absorbed.

An ε of zero corresponds to no greenhouse effect at all, while an ε of unity corresponds to a perfect IR absorber, i.e., a perfect greenhouse effect. The true greenhouse effect is, of course, somewhere in between, i.e., $0<\varepsilon<1$

We denote the effective *albedo of the Earth system* (i.e., the portion of incoming solar radiation immediately reflected back to space) as *A*, and we will now distinguish between the *atmospheric temperature* T_e (which we will envision as representing the mid-troposphere, somewhere around 5.5 km above the surface where roughly half the atmosphere by mass lies below) and the *surface temperature* T_S.

T_e is related to, but not equivalent to, another quantity known as the *effective radiating temperature*, which we will denote as T_o. T_o is the temperature the Earth would have if it were a black body, i.e., if there were no *greenhouse effect*. It can be thought of as the temperature at the effective height in the atmosphere from which Earth is radiating infrared radiation back to space. In the limit of a perfectly emissive atmosphere ($\varepsilon=1$), as you can verify from our mathematical treatment below, we would have the equality T_o = T_e.

You may recall from our earlier discussion (in Lesson 1 [3]) of the vertical structure of the atmosphere, that atmospheric temperatures cool on average roughly $\lambda=6.5^\circ\mathrm{C/km}$ in the troposphere — what is known as the *standard lapse rate*.

For the approximate current value of the solar constant *S* = 1370 W / m^2, we saw in Lesson 4 that the black body temperature, i.e., the effective radiating temperature T_o, is roughly 255 K [4].

Think About It!

*Come up with an answer to this question and then click the words **Reveal answer** below.*

Given that the Earth's average surface temperature is T_s = 288 K, the effective radiating temperature is T_o= 255 K, and the standard lapse rate is $\lambda=6.5^\circ\mathrm{C/km}$, can you determine the effective radiating level in the atmosphere?

Reveal answer.

We can now express the condition of energy balance at each level in our simplified model of the Earth:

1. the top of the atmosphere
2. the atmospheric layer, which we can think of as centered in the mid-troposphere
3. the surface

Balancing incoming and outgoing radiation at the *top of the atmosphere* gives:

$$\frac{S\left(1-A\right)}{4}=\sigma\varepsilon T_e^4+\left(1-\varepsilon\right)\sigma T_S^4$$

(1)

Balancing incoming and outgoing radiation from the *atmospheric layer* gives :

$$\sigma\varepsilon T_S^4=2\sigma\varepsilon T_e^4$$

(2)

(Note that short wave radiation is not included in this balance because the atmosphere does not absorb in short wave range.)

Finally, balancing incoming and outgoing radiation at the *surface* gives:

$$\frac{S\left(1-A\right)}{4}+\sigma\varepsilon T_e^4=\sigma T_S^4$$

(3)

Solving the system of equations for T_s and T_e gives:

$$T_S^4=\frac{S\left(1-A\right)}{\left[4\sigma\left(1-\varepsilon/2\right)\right]}$$

(4)

$$2T_e^4 = T_S^4$$

(5)

Or more simply

$$T_S = \left\{ \frac{(1-A)\,S}{[4\sigma\,(1-\varepsilon/2)]} \right\}^{1/4}$$

(6)

$$T_e = \frac{T_S}{2^{1/4}}$$

(7)

Let us use the standard values of *A* = 0.3 and S = 1370 *W* / *m*^{2}.

- If we take ε = 0 (which is equivalent to there being no greenhouse effect), we get our original blackbody result T_s = 255 K = -18°C. Too cold!
- If we take ε = 1 (which is equivalent to a perfectly IR absorbing atmosphere), we get the result T_s = 303 K = 30°C. Too warm!
- However, if we take ε = 0.77 (i.e., the atmosphere absorbs 77% of the IR radiation incident upon it), we get a result, T_s = 288 K = 15°C. Just right!

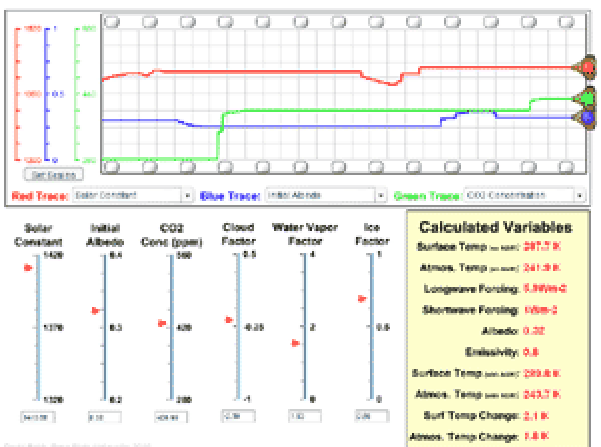
Using (7) and T_s = 288 K, we also get the result T_e = 242 K. This is modestly lower than the effective radiating temperature T_o = 255 K, indicating that it is found at about 5.5 km — a modestly higher level in the atmosphere than 5.1 km that you calculated earlier.

Of course, this model is still rather simplistic. For one thing, it only takes into account short wave and long wave radiation. We haven't accounted for important processes involved in the energy budget of the actual atmosphere and surface, which includes convection, latent heating, and the effect of large-scale motion.

We can nonetheless add *some* further realism to the model by incorporating some of the feedbacks we have discussed [5] previously. In Problem Set 4 you will investigate this slightly more sophisticated [6] version of the standard one-layer model. The model allows for the contribution of clouds to both the Earth's albedo and the longwave absorptive properties of the atmosphere in a very rough way. It also accounts for the positive ice albedo and water vapor feedbacks in a very rough manner.

Each of the feedbacks in the model will be expressed in the form of a *feedback factor* that you can vary. A *feedback factor* measures the relative magnitude of a feedback in terms of the amplitude of the response relative to the original forcing. If the response is equal in magnitude to the original forcing, there is no feedback, and the feedback factor is zero. If the response is double that of the original forcing, the feedback factor is one. For example, if a warming of 1°C due to $\mathrm{CO_2}$ doubling alone causes an increase in water vapor content that adds an additional equilibrium warming of 2°C, so that the net warming is 3°C, the water vapor feedback factor would be two. Feedback factors can be specified for a particular feedback (e.g., the water vapor feedback), or for the sum over all feedbacks under consideration (e.g., water vapor feedback, ice albedo feedback, and cloud feedback). For example, suppose that the initial 1°C warming, which led to 2°C warming due to water vapor feedback, also led to an increase primarily in low cloud cover, which added a relative cooling of -0.5°C, and a melting of ice, which added an additional relative warming of 1°C. Then the cloud feedback factor would be -0.5, the ice albedo feedback factor would be 1.0, and the net feedback factor would be 2 - 0.5 + 1 = 2.5! Alternatively, we could compute the overall feedback factor by taking the *total warming* (initial 1°C warming + 2°C - 0.5°C + 1°C = 3.5°C) divided by the *initial warming*, *minus one*, i.e., (3.5°C/1°C) - 1 = 2.5. The equilibrium climate sensitivity in this case would be 3.5.

While we have measured the feedback factors i*n terms of the temperature responses*, one could also compute these factors *in terms of the associated radiative forcing*. For example, we know from earlier in the course that the radiative forcing due to $\mathrm{CO_2}$ doubling is roughly 3.7W/m^2. Suppose that the increased greenhouse forcing associated with the water vapor feedback led to an additional downward long wave radiative flux of 7.4 W/m^2 (and let us assume for this example that the other feedbacks are zero). Then the water vapor feedback factor would be 7.4/3.7 which is, again, two. The total downward radiative forcing would be 3.7W/m^2 +7.4W/m^2 =11.1 W/m^2 total downward and the overall feedback factor would be 11.1/3.7 - 1 = 2!



Click on the link to see how our new One-Layer Energy Balance Model [7] works

One-Dimensional Energy Balance Model

There are many ways one can generalize upon the zero-dimensional EBM. As we saw in the previous section, we can try to resolve the additional, *vertical degree of freedom* in the climate system through a very simple idealization—the *one layer* generalization of the zero-dimensional EBM. If for no other reason than the fact that the incoming solar radiation is symmetric with respect to longitude, but varies quite dramatically with latitude, the *latitudinal degree of freedom* is the next most important property to resolve if we wish to obtain further insights into the climate system using a still relatively simple and tractable model.

That brings us to the concept of the *one-dimensional energy balance model*, where we now explicitly divide the Earth up into latitudinal bands, though we treat the Earth as uniform with respect to longitude. By introducing latitude, we can now more realistically represent processes like ice feedbacks which have a strong latitudinal component, since ice tends to be restricted to higher latitude regions.

Recall that we had, for the linearized zero-dimensional gray body EBM, a simple balance [4]:

$$C\frac{dT_S}{dt} = \frac{(1-\alpha)S}{4} - A - BT_S$$

(1)

where α is the Earth's albedo and A and B are coefficients for the linearized representation of the 4th degree term.

Generalizing the zero-dimensional EBM, we can write a similar radiation and energy balance equation for each latitude band i:

$$C_p\frac{dT_i}{dt} = (1-\alpha_i)\,S_i - A - BT_i$$

(2)

where i represents each latitude band.

We have now introduced some extremely important generalizations. The temperature T_i, albedo α_i , and incoming solar radiation T_S are now functions of latitude, allowing us to represent the disparity in incoming shortwave radiation between equator and pole, and the strong potential latitudinal dependence of albedo with latitude—in particular, when the temperature T_i for a particular latitude zone falls below freezing, we represent the increased accumulation of snow/ice in terms of a higher albedo. The global average temperature T_S is computed by an appropriate averaging of the temperatures for the different latitude bands T_i.

Recall that the disparity in received solar radiation between low and high latitudes leads to lateral heat transport [8] over the surface of the Earth by the atmospheric circulation and ocean currents. In the absence of lateral transport, the poles will become increasingly cold and the equator increasingly warm. Clearly, we must somehow represent this meridional heat transport in the model if we expect realistic results. This can be done through a very crude representation of the process of heat advection through a term that is proportional to the difference between the temperature, $F\left[T_i - T_s\right]$ where F is some appropriately chosen constant, and T_S is the global average temperature. This term represents processes associated with lateral heat advection that tends to warm regions that are colder than the global average and cool regions that are warmer than the global average.

This gives the final form of our one-dimensional EBM:

$$C_p \frac{dT_i}{dt} + F\left(T_i - T_s\right) = \left(1 - \alpha_i\right) S_i - A - BT_i$$

(3)

The model is complex enough now that there is no way to simply write down the solution anymore. But we can solve the model mathematically, through a very simple and primitive form of something we will encounter much more of in the future—a *numerical climate model*.

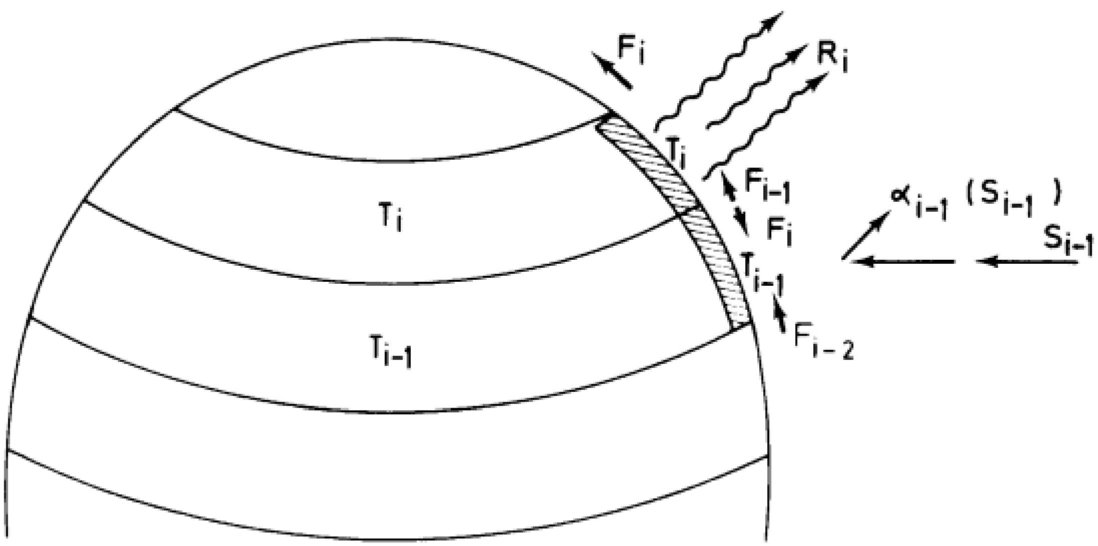


Figure 5.2: Schematic of a one-dimensional Energy Balance Model.
Credit: NYU, Courant Institute of Mathematical Sciences (CIMS) [9]
A Climate Modeling Primer, A. Henderson-Sellers and K. McGuffie, Wiley, pg. 58, (1987)

One of the most important problems that was first studied using this simple one-dimensional model was the problem of how the Earth goes into and comes out of *Ice Ages*. Use the links below to open the demonstration, which is in 3 parts.

- Part One [10]
- Part Two [11]
- Part Three [12]

General Circulation Models

Finally, we come to the so-called *General Circulation Models* or GCMs. GCMs attempt to describe the full three-dimensional geometry of the atmosphere and other components of Earth's climate system. Atmospheric GCMs numerically solve the equations of physics (e.g., dynamics, thermodynamics, radiative transfer, etc.) and chemistry applied to the atmosphere and its constituent components, including the greenhouse gases. In more primitive GCMs (the earlier generation models), the role of the ocean was treated in a very basic way, e.g., as a simple slab of water where only the thermodynamic role of the ocean was accounted for.

Current generation climate models typically include an ocean that plays a far more active role in the climate system. The major current systems are modeled, as is their direct role in transporting heat poleward. When the dynamics of the ocean and its interactions with the atmosphere are explicitly resolved by a climate model, the model is referred to as *Atmosphere-Ocean GCM*, or AOGCM, or sometimes simply a *coupled model*. Most state-of-the-art climate modeling centers today run AOGCMs. In addition, many state-of-the-art climate models today include a detailed description of the hydrological cycle (which couples atmospheric, terrestrial, and ocean reservoirs of water and the flows between these reservoirs) as well as the role of terrestrial biosphere, the continental ice sheets, and even the ocean's carbon cycle and its interactions with the ocean and the atmosphere.

Unlike simpler climate models like EBMs, GCMs and AOGCMS can be used to study a variety of climate attributes other than surface temperature, such as atmospheric temperature profiles, rainfall, atmospheric circulation, ocean circulation, wind patterns, snow and ice distributions, and many other variables that are part of the global climate system.

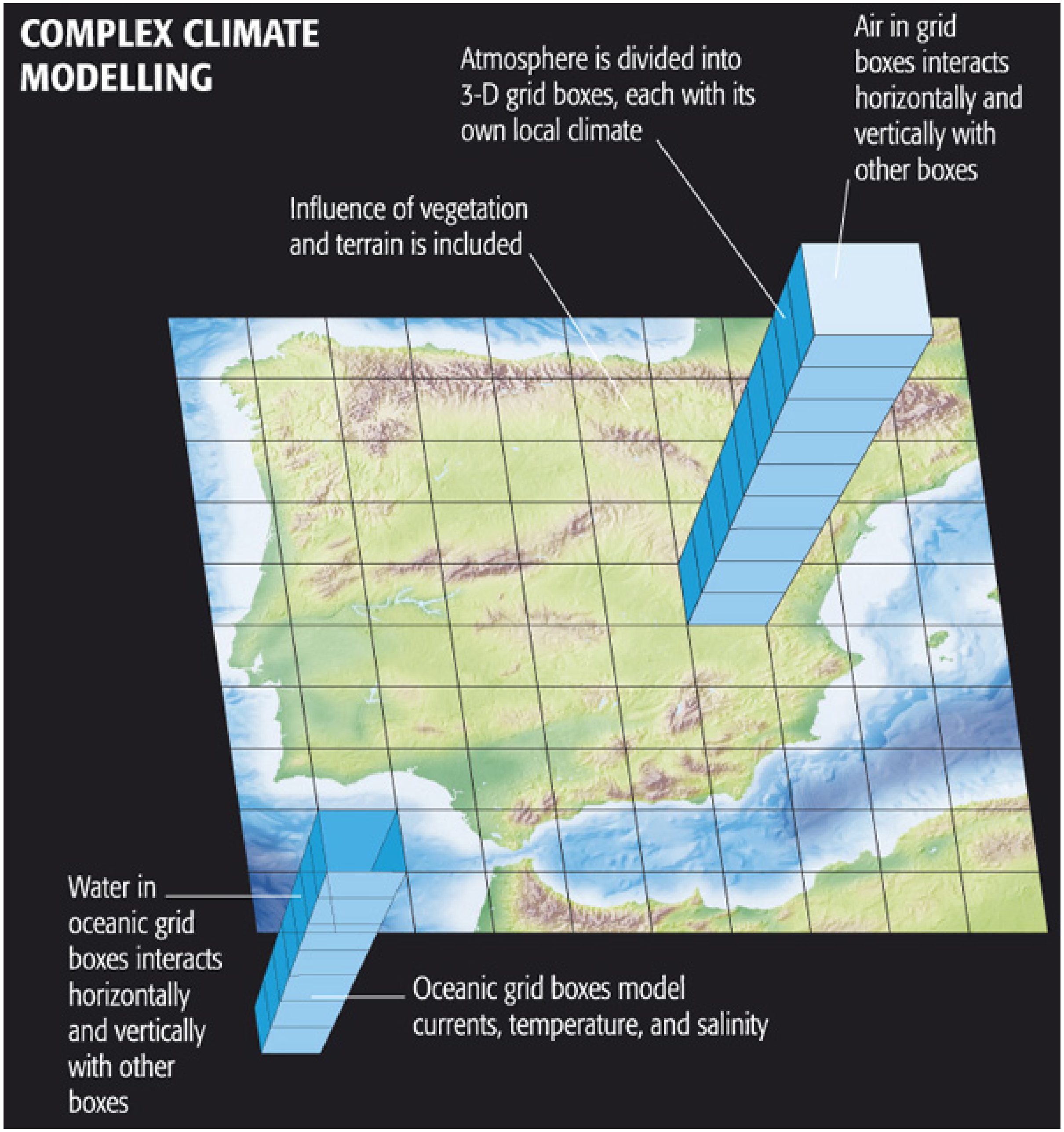


Figure 5.3: Schematic of a General Circulation Model.

Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition © 2015 Dorling Kindersley Limited.*

EdGCM

The EdGCM project [13], funded by the U.S. National Science Foundation and spearheaded by scientists associated with NASA Goddard Institute of Space Studies (GISS), uses the GCM originally used in a number of famous experiments (which we will review later in this lesson) by climate scientist James Hansen, Director of GISS.This model was developed in the 1980s and is primitive by modern standards, but it includes much of the important physics that is in current state-of-the-art climate models and it is far less computationally intensive. The scientists at EdGCM have ported the model into a format that can be run on a simple desktop or laptop computer (both PC and Mac). Originally it was free, but to cover expenses for the project, a minor fee is now required for download. Your course author has downloaded EdGCM onto his own laptop (Macbook Pro) and is now going to show you the results of several experiments he has run.

- Part One [14]
- Part Two [15]
- Part Three [16]
- Part Four [17]
- Part Five [18]
- Part Six [19]
- Part Seven [20]
- Part Eight [21]
- Part Nine [22]

Validating Climate Models

James Hansen
Photo Source: Wikipedia [23]

James Hansen [24] is a well known climate scientist who directs NASA's Goddard Institute for Space Studies. [25]

He was the first climate scientist to testify in the U.S. Congress that human-caused climate change had indeed arrived, back during the hot summer of 1988. Today, as far greater evidence has amassed, his early comments appear especially prescient.

During his 1988 congressional testimony, Hansen showed the results of simulations he had performed using the NASA GISS GCM—the very same climate model explored in the EdGCM experiments of the previous section. These simulations included not only historical simulation of past climate changes, but *three possible projections of future warming* that depended on different possible future fossil fuel utilization scenarios.

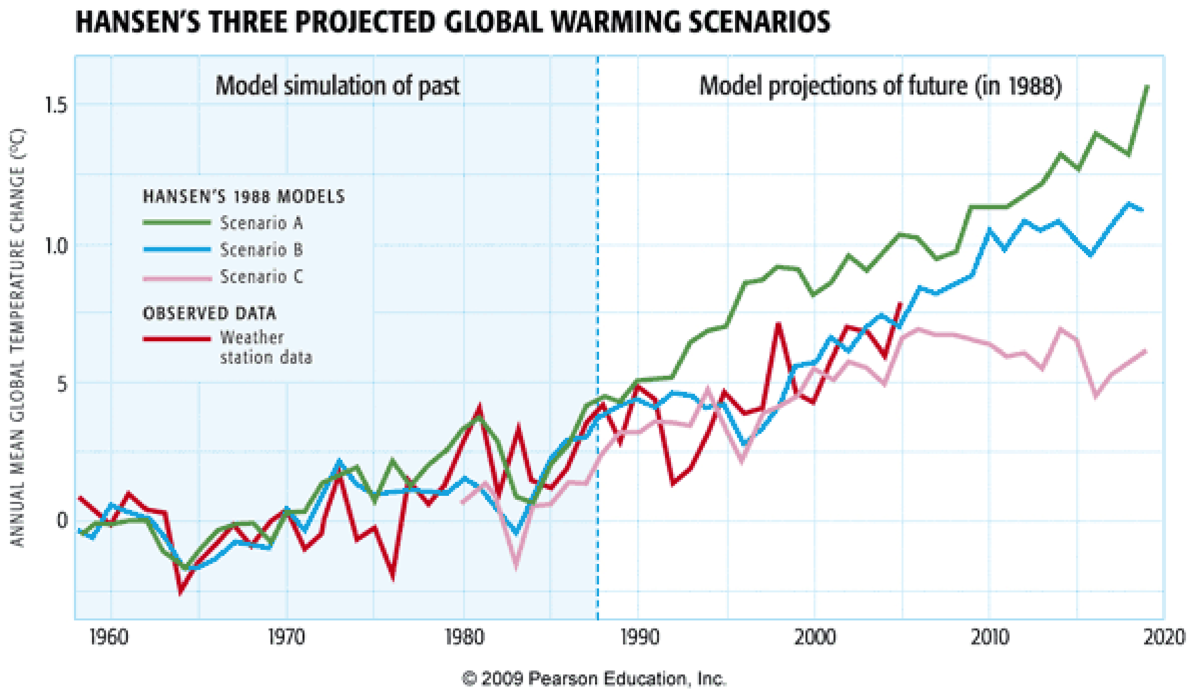


Figure 5.4: Model projections of global temperature by James Hansen in 1988 for three different fossil fuel emissions scenarios compared with the actual temperature observations.
Credit: Mann & Kump, *Dire Predictions, 2008 Dorling Kindersley Limited.*

Yogi Berra is quoted as having once said, "predictions are hard—especially about the future". Indeed, there is no better test than making a prediction about the future, and looking back and seeing how it panned out. This sort of post hoc validation is often done with numerical weather models. It's more difficult to do with climate models, however, because you have to wait not days or weeks, but years to see how the prediction actually measured up.

Hansen's 1988 simulations, in this regard, can be viewed as one of the great validation experiments in climate modeling history. In these experiments, Hansen included a high, medium, and low fossil fuel future emissions scenario, corresponding to the green, blue, and purple curves respectively. As it turns out, our actual fossil fuel emissions scenario during the two decades subsequent to Hansen's 1988 projections, has corresponded most closely to his middle scenario, the blue curve. And as you can see from the subsequent observations (the red curve), his prediction for that scenario quite closely matched the observed warming.

Now, you may have noticed, however, that this model simulation didn't capture the observed multi-year cooling in 1992. Is that a fault of the simulation?

No!—there is no way that James Hansen (or anyone for that matter) could have predicted the eruption of Mt. Pinatubo. And rather than proving a fault with the model, the Pinatubo eruption actually provided Hansen with another key test of the climate models. It takes about 6 months for the volcanic aerosol to spread out around the globe and begin to have a global cooling impact. This gave

Hansen about six months to run his model and make a prediction, at the instant Pinatubo erupted. As you can see, he was able to predict quite accurately the short-term cooling of the globe by a bit less than 1°C that would result from this eruption. His model simulation (the black curve below) actually predicted a bit too much cooling (observations shown by the blue curve below). But that, too, wasn't his fault. El Niño events occur randomly in time, and there was no way to know that an extended El Niño event would occur in 1991-1993, offsetting some of the volcanic cooling: As you found in your first problem set, El Niño events warm the globe by about 0.1-0.2°C.

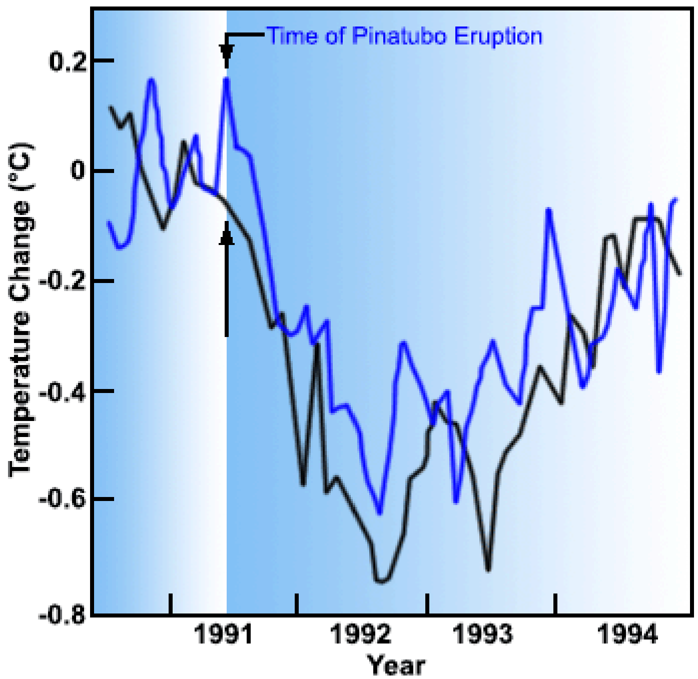


Figure 5.5: Observed cooling following 1991 eruption of Mt Pinatubo vs. cooling predicted in Hansen's climate modeling experiment. [Enlarge with original caption [26]]
Credit: Iowa State Global Change Course [27]

These examples may be the most striking examples of how the models have been validated, but they have been validated in many other more mundane ways. In fact, the various reports of the IPCC include hundreds of pages of 'model validation' (see e.g., chapter 9 on model evaluation [28] in the recent IPCC Fifth Assessment Report) showing the models do a good job capturing the main fluxes of energy and radiative balances, the general circulation of the atmosphere and the major ocean current systems, the amplitude and pattern of the seasonal response to changing patterns of solar insolation, etc.

Detecting Climate Change

So, we have seen in the previous section that climate models have been used to make some very successful predictions in the past, and there is reason to take them seriously. Can we use these models to go a step further than we already have? We have seen in previous lessons that modern-day climate change appears anomalous and without any obvious precedent in the historical past. That alone does not establish that the changes that we are seeing—warming of the Earth's surface, and many other changes—are due to human impacts. Using climate models, we can, however, address this issue of causality. We can use the models to investigate the hypothesis that the observed changes can be explained by *nature alone*, and the alternative hypothesis that they can only be explained by a combination of *human and natural factors*. Investigations employing more than 20 state-of-the-art climate models (see below) show that natural factors alone cannot explain the global temperature record of the past century—including the long-term warming trend—while human factors, combined with the natural factors, can.

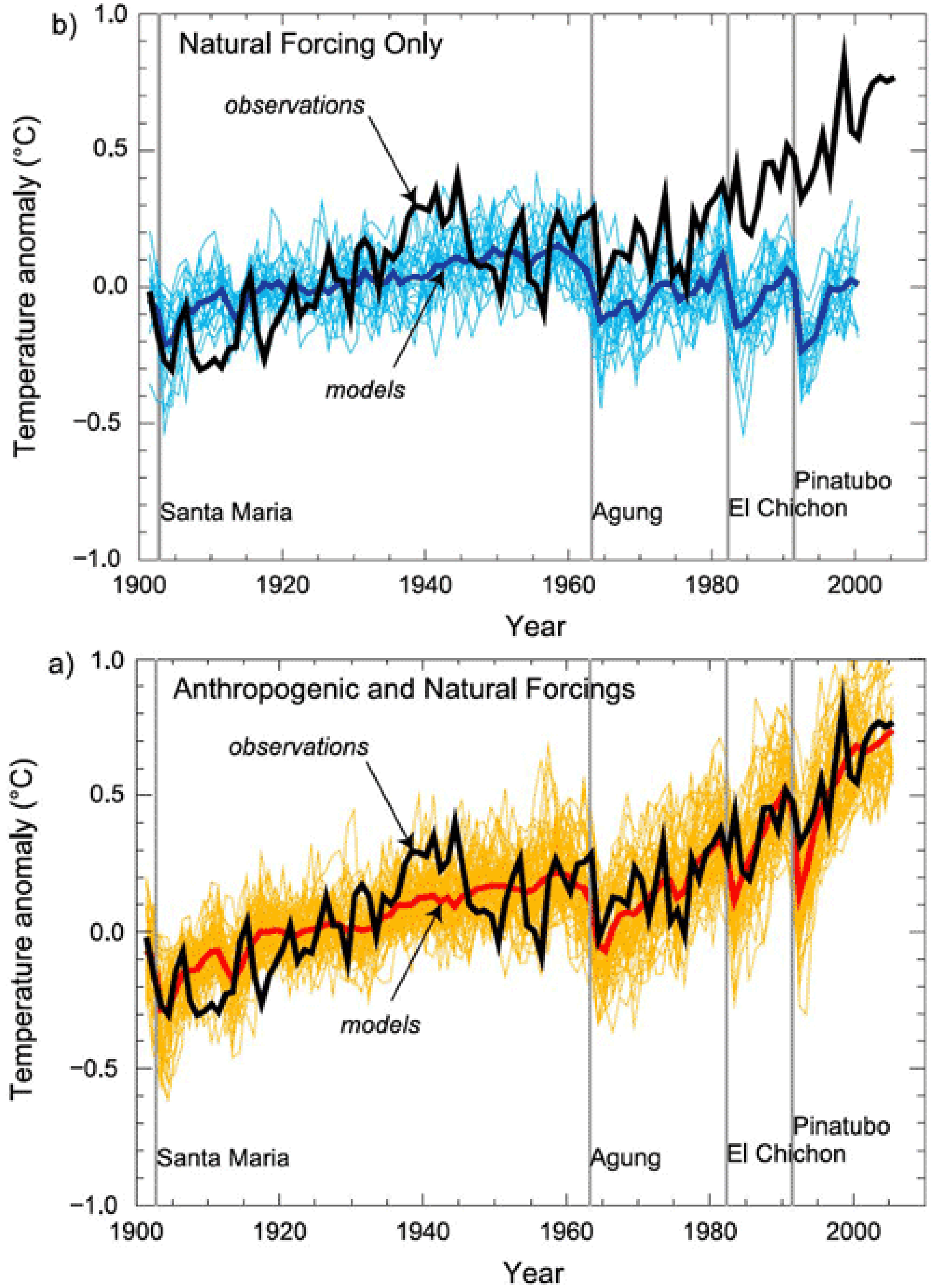


Figure 5.6: Model Simulations of Surface Warming over Past Century Compared with Observations for (top) natural forcing only and (bottom) natural+anthropogenic forcing.

Credit: IPCC, 2007

Some might argue that this alone is not convincing evidence. Perhaps, for example, we simply have the trend in solar output *wrong* and the *true* trend in solar output closely resembles the trend in human impacts (i.e., greenhouse forcing + anthropogenic aerosols). Then we might be misinterpreting the goodness of the fit shown above.

Let us, for argument's sake, accept that criticism. Is there some other type of comparison of observations and model predictions that might be more robust in this situation? Well, we can try to take advantage of the fact that the patterns of response to different forcings might look different. It turns out that the surface expressions are not that different—the surface expression of warming due to solar output increases actually looks a fair amount like the pattern of surface warming due to greenhouse gas increases. The *vertical* patterns of temperature change, however, as we alluded to previously in the course [29], are expected to be quite different. They provide a true *fingerprint* to search for—and indeed, the process of using the expected patterns of response of different forcings to determine which forcings best explain the observed changes is known as *fingerprint detection*.

The vertical pattern of response to increasing greenhouse gas concentrations is one in which the troposphere warms (as we have seen in previous exercises), *but* the stratosphere cools at the expense of this tropospheric warming; greenhouse forcing is a zero sum game and there is no increase in radiation at the top of the atmosphere, but merely a redistribution of energy and radiation within the atmosphere. The vertical pattern of temperature change we would expect for an increase in *solar output*, however, is one in which the *entire atmosphere warms*, from top-to-bottom, as there is an increase in the received radiation at the top of the atmosphere which warms the entire atmospheric column. The pattern of temperature response to an explosive volcanic eruption is yet different from either of these patterns. From comparing the observed patterns of vertical temperature change to model simulations of the responses to each of these different factors, we find that only greenhouse surface warming exhibits the vertical pattern consistent with the model's predicted fingerprint (in fact, there is also impact of ozone depletion on the cooling of the stratosphere, but even after accounting for that effect, the remaining trend can clearly only be accounted for by greenhouse forcing).

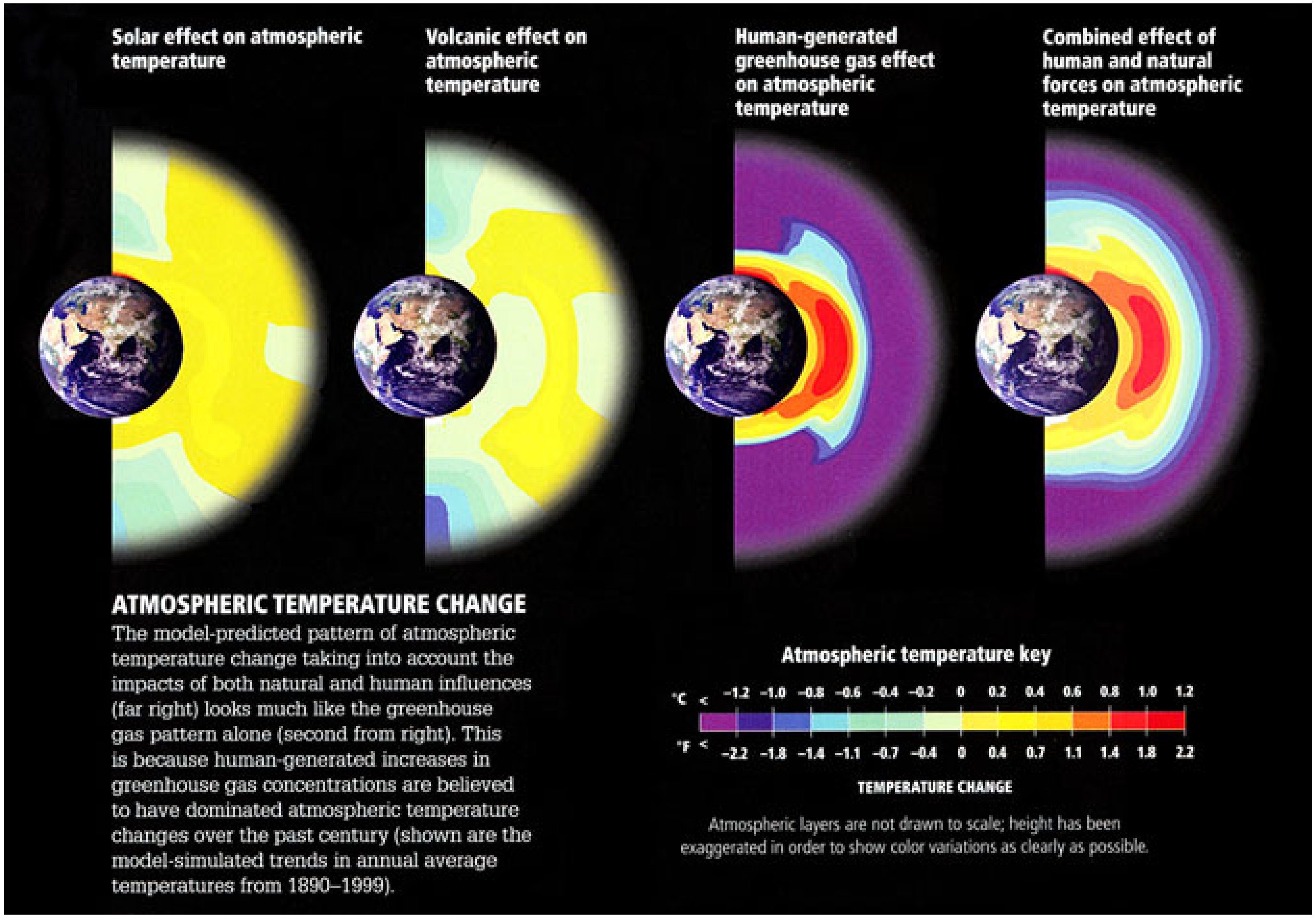


Figure 5.7: Atmospheric Temperature Change Pattern.
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition © 2015 Dorling Kindersley Limited.*

Estimating Climate Sensitivity

One of the key unknowns in the behavior of the climate, as we have seen, is the sensitivity—how much warming we can expect in response to a doubling of atmospheric CO_2 concentrations. Current evidence suggests a most likely value of around 3.0°C warming, but there is—as we have seen—a wide range, anywhere from roughly 1.5°C to 4.5°C. Scientists attempt to try to constrain estimates of this key quantity by comparing model simulations with observations.

For example, scientists use models similar to the zero-dimensional EBMs we discussed in Lesson 4, driving them with the estimated changes in both natural factors (volcanoes and solar output) and human factors (greenhouse gas increases and sulphate aerosol emissions). Since the climate sensitivity is simply a parameter that can be changed in the model, scientists can do many simulations using different values of the climate sensitivity, and observe which values yield the best fit with the observations.

Such experiments can be done over the modern period back to the mid 19th century during which observations of global mean temperature are available.

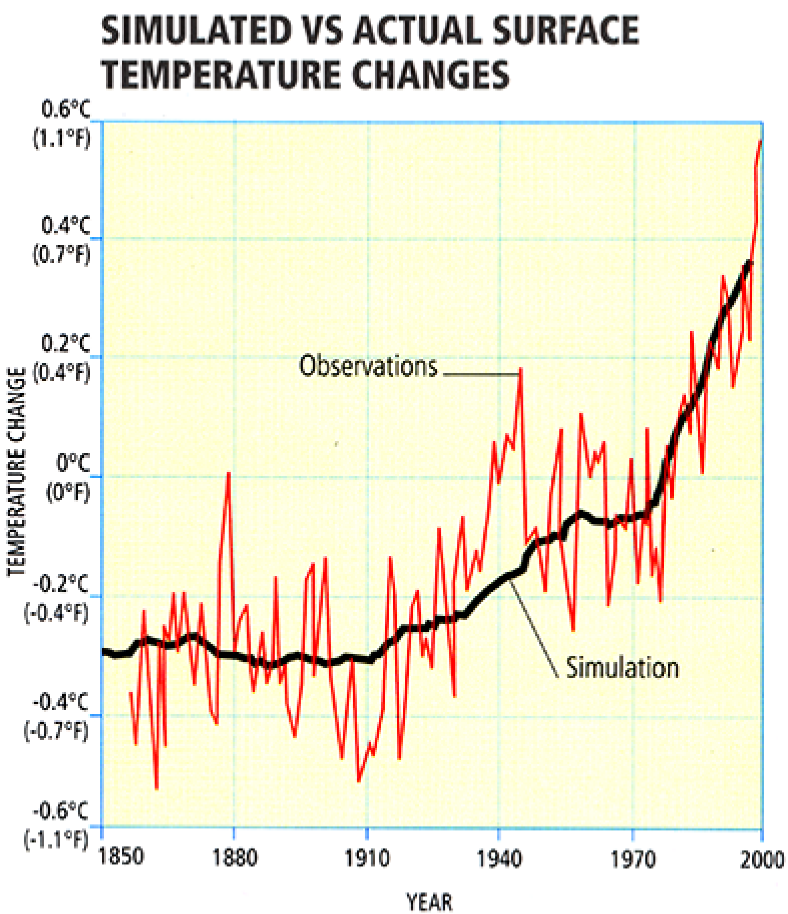


Figure 5.8: Global Temperature vs. Model Simulations During the Modern Instrumental era.
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*

During the shorter period of the past half century when deep ocean temperature observations are available, experiments can be done to compare the model-simulated changes in ocean heat content with those that have been observed.

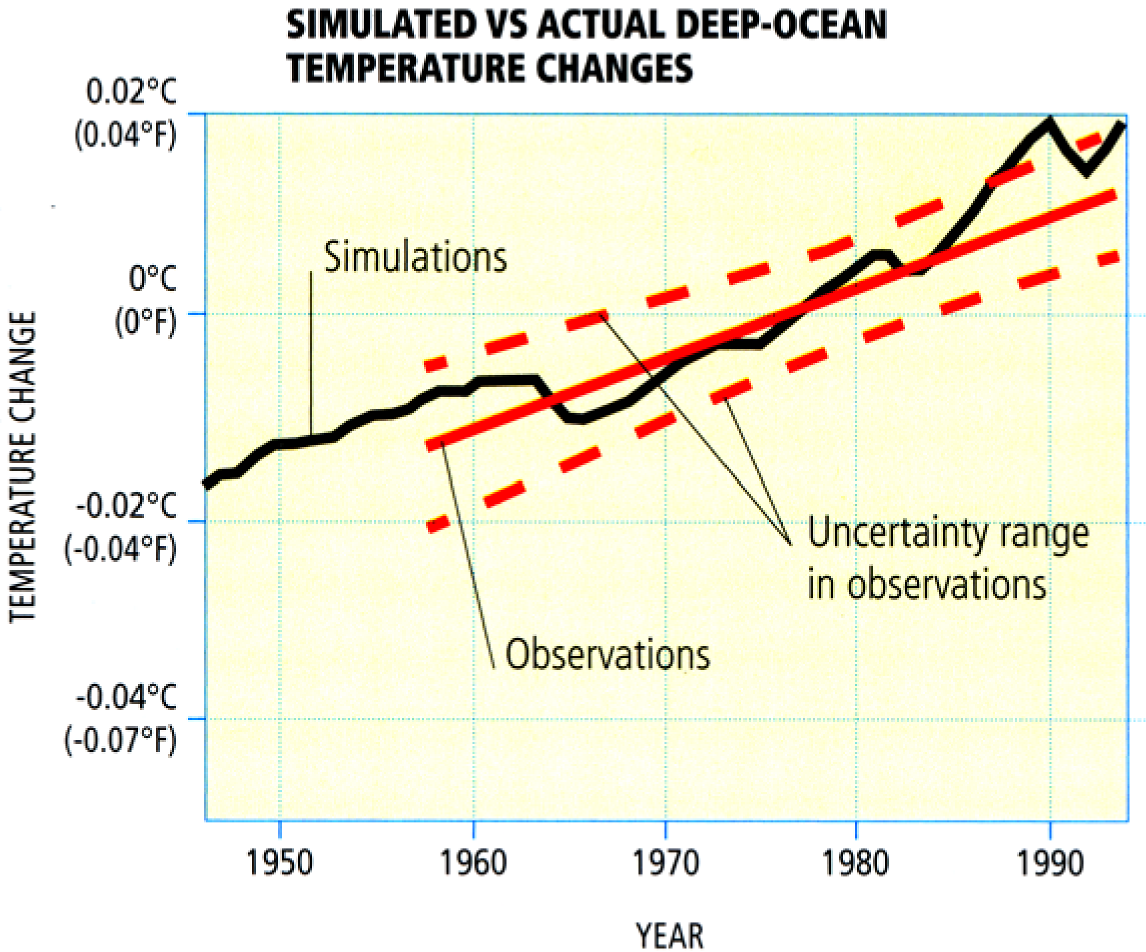


Figure 5.9: Deep Ocean Temperatures vs. Model Simulations During the Past Half Century.
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*

For the longer period of the past millennium during which temperature changes, as we have seen in Lesson 3 [30], have been documented based on climate *proxy* data—it is possible to compare simulated and observed changes over a longer time period, providing potentially tighter constraints on climate sensitivity. The computer model simulations in this case are driven by longer-term estimates (e.g., from ice core evidence) of natural (volcanic and solar) forcings as well as modern anthropogenic forcing:

ESTIMATES OF NATURAL AND HUMAN IMPACTS ON CLIMATE OVER THE PAST 1000 YEARS

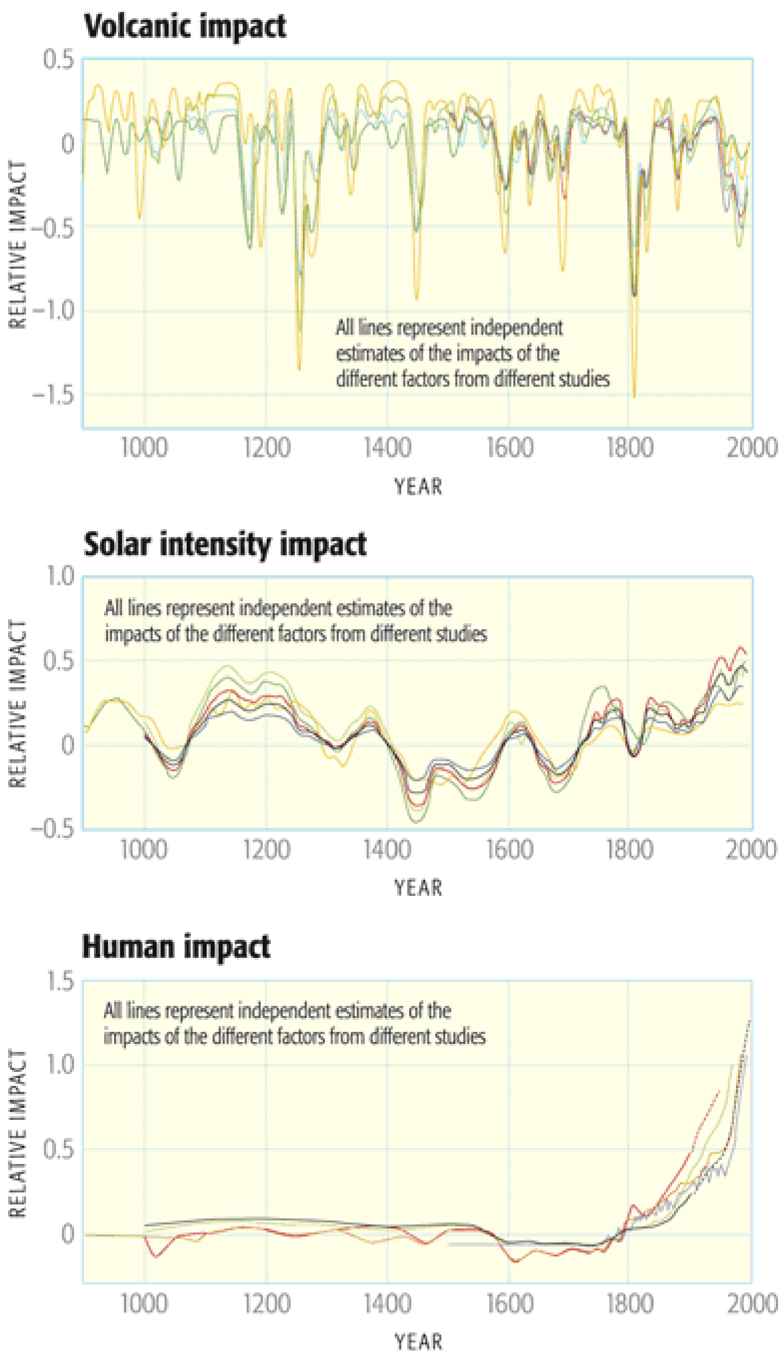


Figure 5.10: Radiative Forcing Estimates Used to Drive Climate Model Simulations of Past Millennium.

Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*
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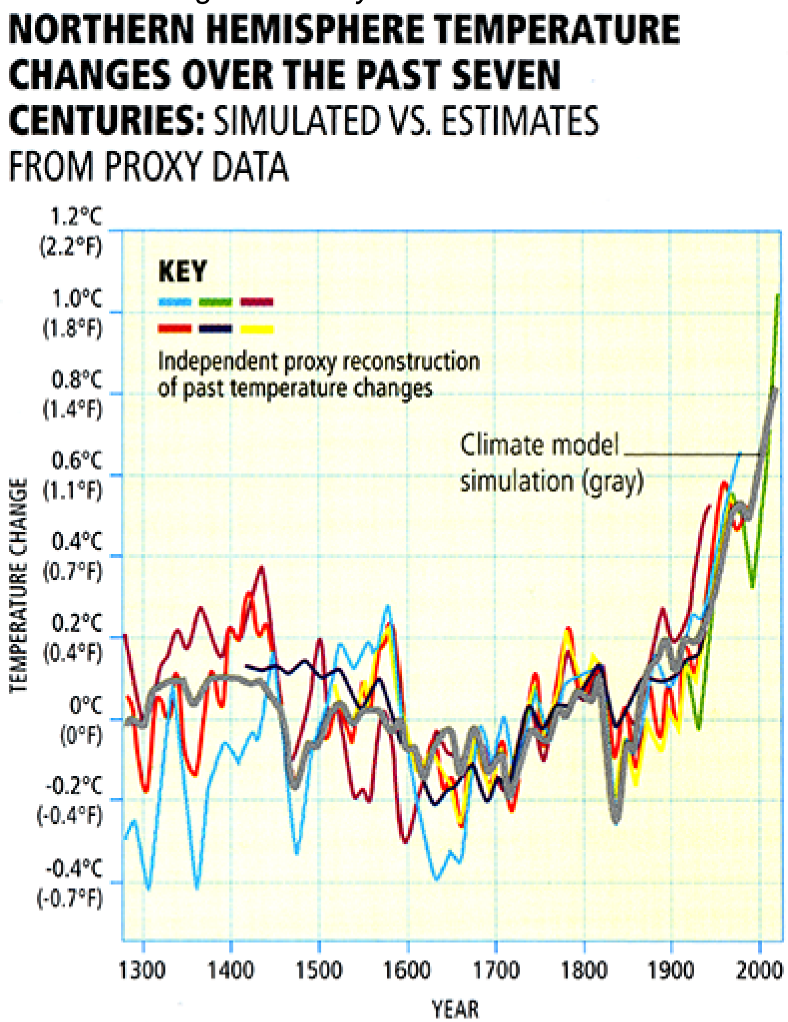

Figure 5.11: Proxy Reconstructions of Northern Hemisphere Temperatures Over Past Millennium Compared Against Model Simulations.

Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*
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Going further back in time, scientists compare climate model simulations of the cooling during the height of the Last Glacial Maximum (LGM) roughly 21,000 years ago resulting from lowered atmospheric CO_2, increased continental ice cover, and altered patterns of solar insolation, and proxy evidence of ocean surface cooling derived from climate-sensitive surface dwelling organisms trapped in ocean sediment cores.

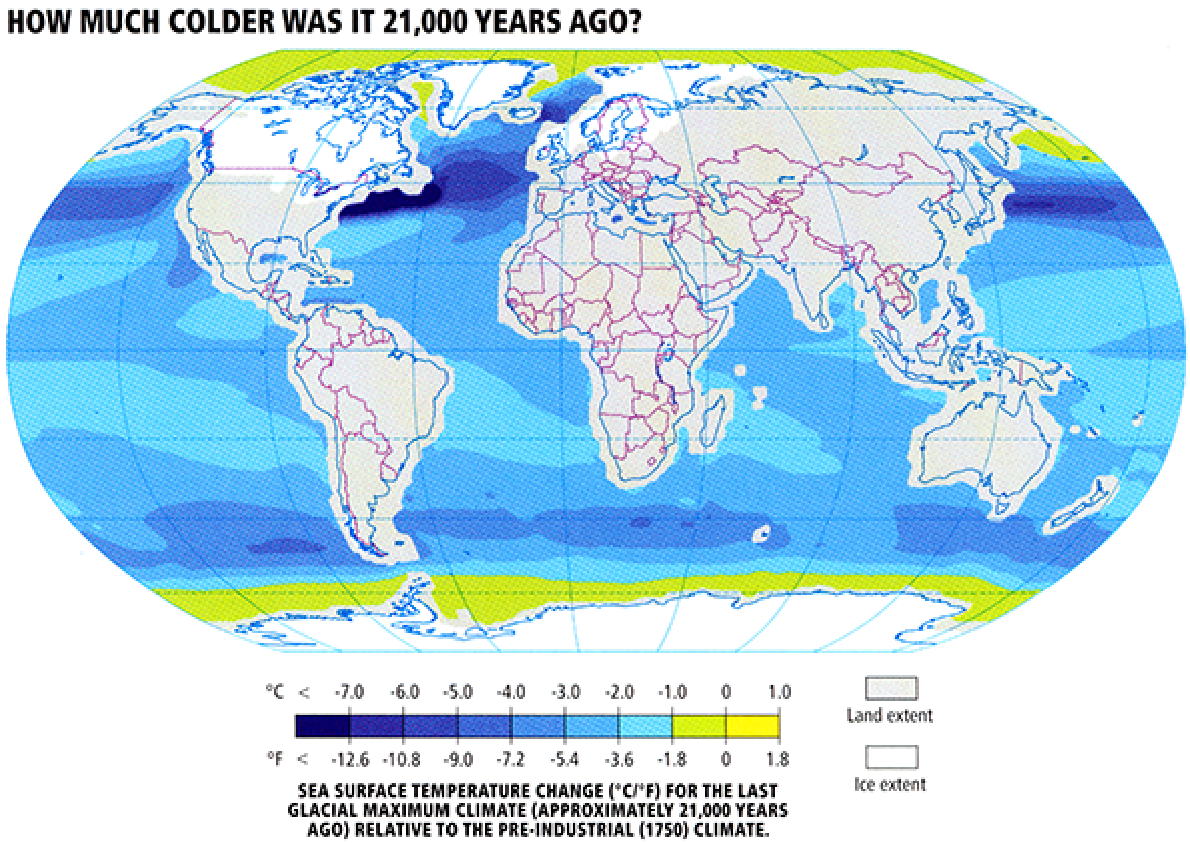

Figure 5.12: Proxy Evidence of Ocean Surface Temperatures During the LGM.
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*
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Finally, going even *further* back in time, into the deep geological past, scientists compare model results with geological evidence of past warm and cold periods.

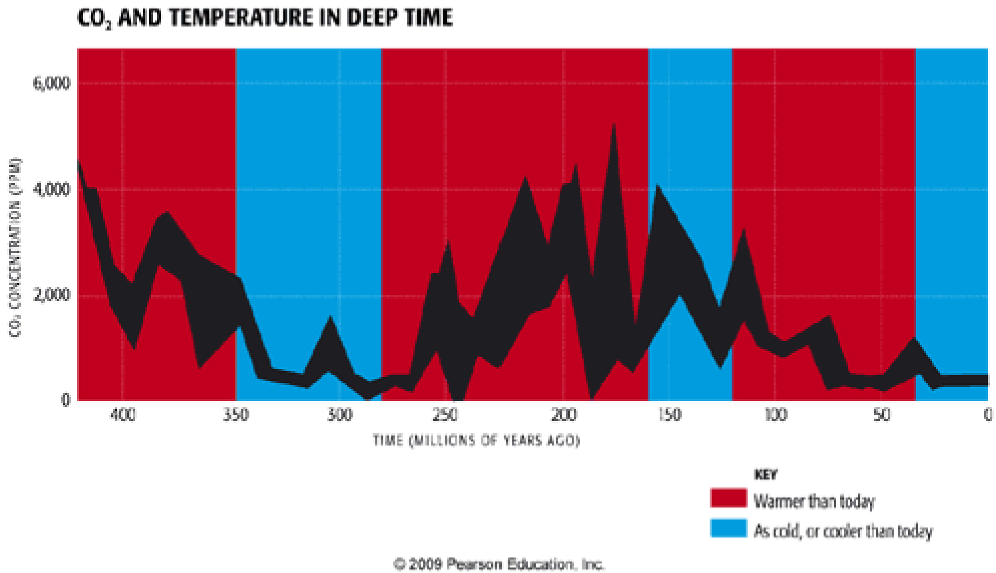

Figure 5.13: Deep Ocean Temperatures vs. Model Simulations During the Past Half Century.
Credit: Mann and Kump, *Dire Predictions: Understanding Global Warming* (DK, 2008)

The overall evidence from all of these different lines of evidence regarding both human-caused and natural climate changes over a broad range of time scales, is that the equilibrium climate sensitivity likely falls within the range of 1.5°C to 4.5°C for CO_2 doubling, with a most likely value of roughly 3°C warming.

Given the full array of available evidence from instrumental and paleoclimate proxy data, and the comparisons of this evidence with theoretical estimates, there is a very low likelihood of either a *trivially small* (e.g., 1.5°C or less) or *extremely high* (greater than 7°C) equilibrium climate sensitivity.

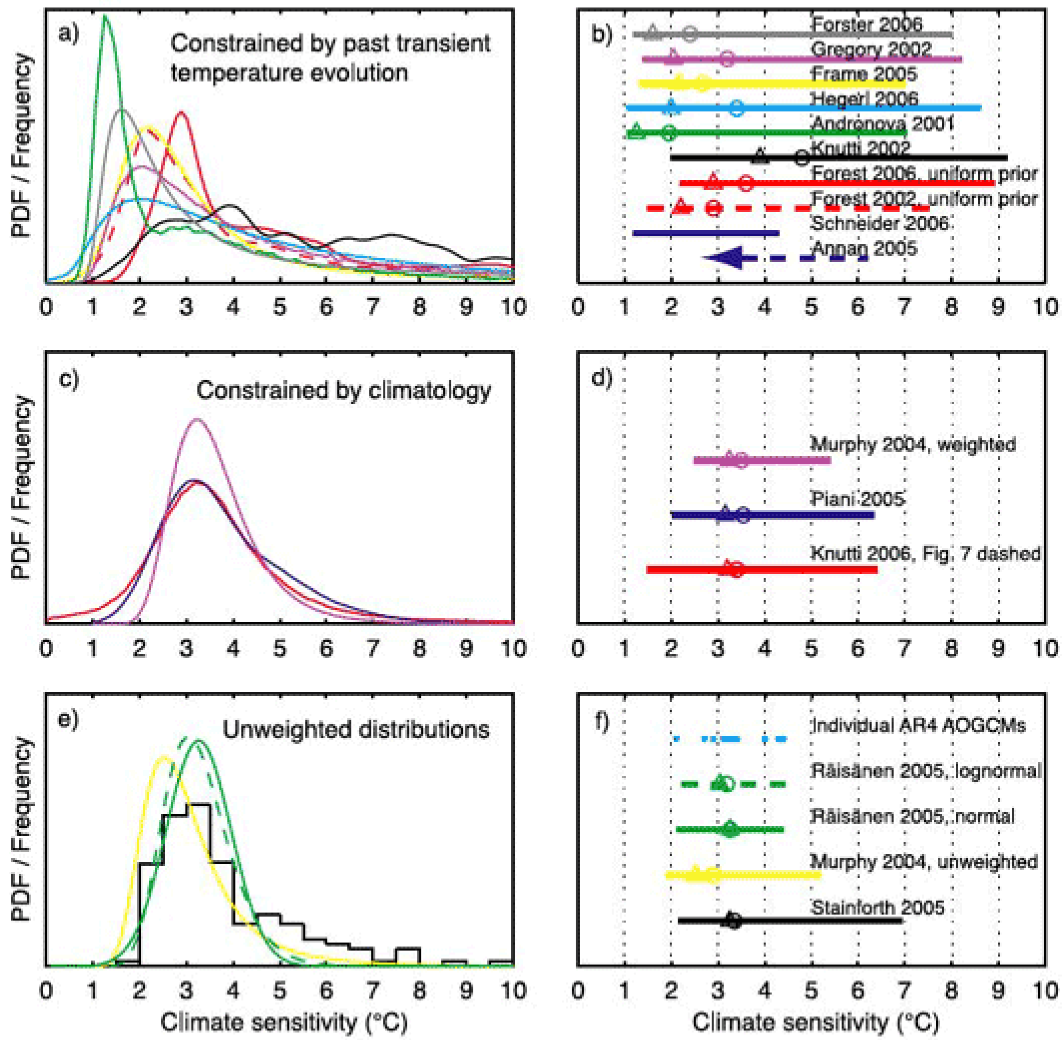

Figure 5.14: Range of Estimates of Equilibrium Climate Sensitivity Based on Studies of (top row) Past Climate Variablity, (middle row) current-day climatological data and (bottom row) Fitting Parameters of Climate Model to Available Climate Observations.
Credit: IPCC 2007

Problem Set #4

Modeling the Earth's Climate Using One-Layer Energy Balance Model

Activity

Note:

For this assignment, you will need to record your work on a word processing document. Your work must be submitted in Word (.doc or .docx) or PDF (.pdf) format so the instructor can open it.

For this activity, you will explore the warming of the surface and the atmosphere due to increases in CO_2 using a one-layer EBM climate model. You will consider/investigate the role of various feedbacks in the climate system (water vapor, ice, and clouds), the influence they have on climate sensitivity, and the impact of the uncertainties in the precise magnitudes of the feedbacks.

Link to The One Layer EBM Application [6]

Directions

1. First, save the Problem Set #4 Worksheet [31] to your computer. You will use this word processing document to electronically record your work in the remaining steps.
   - Save the worksheet to your computer by right-clicking on the link above and selecting "Save link as..."
   - The worksheet is in Microsoft Word format. You can use either Word or Google Docs (free) to work on this assignment. You will submit your worksheet at the end of the activity, so it must be in Word (.doc or .docx) or PDF (.pdf) format so the instructor can open it.
   - Please show your work! When you are explicitly asked to create plots in a question, please cut-and-paste graphics and the output from the screen (e.g., by first printing the output to a pdf file and then directly inserting into the worksheet) to submit along with your discussion and conclusions.
2. Using the online one layer EBM application, double the CO_2 concentrations relative to the pre-industrial level and calculate the climate sensitivity and warming of the mid-troposphere for the following three cases: (A) no feedbacks (i.e., cloud feedback, water vapor feedback, and ice feedback factors all set to zero); (B) mid-range feedback factors (i.e., the default settings of -0.83 for cloud feedback, 2 for water vapor feedback, and 0.5 for ice feedback); (C) high-end estimates of the feedback factors (i.e., the highest settings allowed by the sliders). How does your calculated climate sensitivity range compare with the prevailing range of climate sensitivity estimates? In each case, does the mid-troposphere warm more, the same, or less than the surface? Is this pattern of warming consistent with the predictions by the state-of-the-art climate models? If not, what physics do you think might be missing in our one-layer model?
3. For the doubling of CO_2 for the same three cases (A), (B), and (C) explored in Question 2, please answer the following questions. What are the long wave and short wave forcing, and the total surface forcing (i.e., the sum of the two)? Calculate the overall feedback factor. To do that, first take the ratio of the total surface forcing to the forcing due to the direct radiative impact of CO_2 doubling alone, which simply equals the total forcing in the "no-feedback" case (A); then subtract one from this ratio. What are the Earth's albedo and the atmospheric emissivity? For cases (B) and (C) is there a change in the Earth's albedo and

atmospheric emissivity compared to the "no feedback" case (A)? Which feedbacks could be responsible for the observed changes in each case?

4. Save your word processing document as either a Microsoft Word or PDF file in the following format:

    PS4_AccessAccountID_LastName.doc (or .pdf).
    For example, student Elvis Aaron Presley's file would be named "PS4_eap1_presley.doc" This naming convention is important, as it will help me make sure I match each submission up with the right student!

Submitting your work

- Upload your file to the "Problem Set #4" assignment in Canvas by the due date indicated on our Canvas calendar.

Grading rubric

The instructor will use the general grading rubric for problem sets [32] to grade this activity.

Lesson 5 Summary

In this lesson, we further explored the use of theoretical models of the climate system. We found that:

- a generalization of the *zero-dimensional EBM* known as *the one-layer EBM* can be used to provide a more realistic description of the greenhouse effect. This model can be used to estimate both surface temperatures and temperatures of the mid troposphere. It is also possible to study the effect of *feedbacks* using a simple model of this sort;
- a further generalization known as the *one-dimensional EBM* can be used to study the latitudinal dependence of energy balance and temperature distributions. The one-dimensional EBM can be used, among other applications, to try to understand the processes that drive climate into and out of Ice Ages;
- full three-dimensional general circulation models (GCMs) and coupled Atmosphere-Ocean (AOGCM) versions of the the GCM can be used to model the more detailed patterns of climate variability and climate change, and the study not just of temperature changes but other key fields such as precipitation, wind patterns, etc.;
- theoretical climate models have been validated in numerous ways. Predictions of warming made back in the late 1980s have been borne out, and experiments simulating the response to natural events, such as volcanic eruptions, have demonstrated that climate models have the ability to make accurate predictions of the responses of the climate to both natural and human forcings;
- comparisons of model simulations and observations, including so called "fingerprint detection" studies, indicate that natural factors alone cannot explain the observed trends of the past century; only a combination of natural and human factors can explain these trends;
- by comparing model simulations and observations on a variety of timescales, scientists have constrained climate sensitivity—the equilibrium warming expected in response to a doubling of CO_2 concentrations—to lie somewhere within the range of 1.5 to 4.5°C, with a most likely estimate of around 3°C warming.

Reminder - Complete all of the lesson tasks!

You have finished Lesson 5. Double-check the list of requirements on the first page of this lesson [33] to make sure you have completed all of the activities listed there before beginning the next lesson.

Source URL: https://www.e-education.psu.edu/meteo469/node/139

Links
[1] https://www.ipcc.ch/report/ar5/wg1/
[2] https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf
[3] https://www.e-education.psu.edu/meteo469/node/115
[4] https://www.e-education.psu.edu/meteo469/node/137
[5] https://www.e-education.psu.edu/meteo469/node/116
[6] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/one_layer.html
[7] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/one_layer_model.html
[8] https://www.e-education.psu.edu/meteo469/node/203
[9] http://www.cims.nyu.edu/~mostovyi/Course/EBM/one_dim_ebm_files/one_dim_cartoon.gif
[10] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/demo_part_one.html
[11] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/demo_part_two.html
[12] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/demo_part_three.html
[13] http://edgcm.columbia.edu/spotlight-o/the-project/
[14] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_one.html
[15] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_two.html
[16] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_three.html
[17] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_four.html
[18] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_five.html
[19] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_six.html
[20] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_seven.html
[21] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_eight.html
[22] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/edgcm_part_nine.html
[23] https://es.wikipedia.org/wiki/James_Hansen
[24] http://en.wikipedia.org/wiki/James_Hansen
[25] http://data.giss.nasa.gov/gistemp/
[26] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/pinatubo.gif
[27] http://www.meteor.iastate.edu/gccourse/
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[29] https://www.e-education.psu.edu/meteo469/node/121
[30] https://www.e-education.psu.edu/meteo469/node/134
[31] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson05/PS4_worksheet_SP17.docx
[32] https://www.e-education.psu.edu/meteo469/sites/dev.e-education.psu.edu.meteo469/filesGradingRubricforProblemSets.pdf
[33] https://www.e-education.psu.edu/meteo469/node/139