Published on *METEO 469: From Meteorology to Mitigation: Understanding Global Warming D7* (https://www.e-education.psu.edu/meteo469)

Lesson 4 - Modeling of the Climate System, part 1

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 4

We have now seen evidence indicating that the globe is warming, and that there is an array of other internally-consistent changes in the climate system that are associated with that warming. While these changes are suggestive of human-caused climate change, the existence of trends cannot alone be used to draw causal inferences.

That is where theoretical climate models come in. Climate models allow us to test particular hypotheses about climate change. For example, we can interrogate the models with respect to how much warming of the globe we might expect for a given change in greenhouse gas concentrations. In this lesson, we will consider the simpler classes of climate models, and we will engage in hands-on climate modeling activities.

What will we learn in Lesson 4?

By the end of Lesson 4, you should be able to:

- describe the factors that govern Earth's climate system;
- perform basic energy balance computations to estimate the surface temperature of the Earth;
- perform basic energy balance computations to estimate the response of Earth's surface temperature to hypothetical changes in natural and anthropogenic forcing; and
- explain what "equilibrium climate sensitivity" is.

What will be due for Lesson 4?

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

The following is an overview of the *required activities* for Lesson 4. Detailed directions and submission instructions are located within this lesson.

- Problem Set #3: Estimate the warming due to an increase in CO_2
- Read: Dire Predictions, v.2: p. 68-69

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.

Energy and Radiation Balance

We actually covered this topic back in the introductory lecture (lecture #1), so I'm going to ask you to simply review the Overview of the Climate System (part 2) [1] before continuing on to our initial discussion of climate models...

Simple Climate Models

We will start out our discussion of climate models with the simplest possible conceptual models for modeling Earth's climate. These models include different variants on the so-called *Energy Balance Model*. An Energy Balance Model or 'EBM' does not attempt to resolve the dynamics of the climate system, i.e., large-scale wind and atmospheric circulation systems, ocean currents, convective motions in the atmosphere and ocean, or any number of other basic features of the climate system. Instead, it simply focuses on the energetics and thermodynamics of the climate system.

We will start out discussion of EBMs with the so-called *Zero Dimensional* EBM—the simplest model that can be invoked to explain, for example, the average surface temperature of the Earth. In this very simple model, the Earth is treated as a mathematical point in space—that is to say, there is no explicit accounting for latitude, longitude, or altitude, hence we refer to such a model as 'zero dimensional'. In the zero-dimensional EBM, we solve only for the balance between incoming and outgoing sources of energy and radiation at the surface. We will then build up a little bit more complexity, taking into account the effect of the Earth's atmosphere—in particular, the impact of the atmospheric greenhouse effect—through use of the so-called "gray body" variant of the EBM.

Zero Dimensional EBM

The zero dimensional ('0d') EBM simply models the balance between incoming and outgoing radiation at the Earth's surface. As you'll recall from your review of radiation balance in the previous section, this balance is in reality quite complicated, and we have to make a number of simplifying assumptions if we are to obtain a simple conceptual model that encapsulates the key features.

For those who are looking for more technical background material, see this "Zero-dimensional Energy Balance Model" online primer [2] (NYU Math Department). We will treat the topic at a slightly less technical level than this, but we still have to do a bit of math and physics to be able to understand the underlying assumptions and appreciate this very important tool that is used in climate studies.

We will assume that the amount of short wave radiation absorbed by the Earth is simply $(1-\alpha)\,S/4$, where *S* is the Solar Constant (roughly 1370 W/m^2 but potentially variable over time) and α is the average reflectivity of Earth's surface looking down from space, i.e., the 'planetary albedo', accounting for reflection by clouds and the atmosphere as well as reflective surface of Earth including ice (value of roughly 0.32 but also somewhat variable over time).

We will assume that the outgoing longwave radiation is given simply by treating the Earth as a 'black body' (this is a body that absorbs all radiation incident upon it). The *Stefan-Boltzman law* for black body radiation holds that an object emits radiation in proportion to the 4th power of its temperature, i.e., the flux of heat from the surface is given by

$$F_{bb} = \varepsilon \cdot \sigma \cdot {T_S}^4$$

(1)

where σ is known as the *Stefan-Boltzmann constant*, and has the value $\sigma = 5.67 \text{ x } 10^{-8} (Wm^{-2}K^{-4})$; ε is the *emissivity* of the object (unitless fraction) — a measure of how 'good' a black body the object is over the range of wavelengths in which it is emitting radiation; and T_s (K) is the surface temperature. For the relatively cold Earth, the radiation is primarily emitted in the infrared regime of the electromagnetic spectrum, and the emissivity is very close to one.

We will approximate the surface temperature, T_S, as representing the average 'skin temperature' of an Earth covered with 70% ocean (furthermore, we will treat the ocean as a mixed layer of average 70m depth—this ignores the impacts of heat exchange with the deep ocean, but is not a bad first approximation). We can then approximate the thermodynamic effect of the mixed layer ocean in terms of an *effective heat capacity* of the Earth's (land+ocean) surface, $C = 2.08 \text{ x } 10^8 \; JK^{-1}m^{-2}$. The condition of energy balance can then be described in terms of the thermodynamics, which states that any change in the internal energy per unit area per unit time (<$\Delta F = CdT_s/dt$) must balance the rate of net heating, which is the difference between the incoming shortwave and outgoing longwave radiation. Mathematically, that gives:

$$C\frac{dT_s}{dt} = \frac{(1-\alpha)\,S}{4} - \varepsilon \cdot \sigma \cdot {T_s}^4$$

(2)

Let's suppose that the incoming radiation (the first term on the right hand side) were larger than the outgoing radiation (the second term on the right hand side). Then the entire right-hand side would be positive, which means that the left-hand side, the rate of change of T_s over time, must also be positive. In other words, T_s must be increasing. This, in turn, means that the outgoing radiation must increase, which will eventually bring the two terms on the right hand side into balance. At this point, there is no longer any change of T_s with time, i.e., we achieve an equilibrium.

In equilibrium, the time derivative term is, by definition, zero, and we thus must have equality between the outgoing and incoming radiation, i.e., between the two terms on the right-hand side of equation 1. This yields the purely algebraic expression

$$\varepsilon \cdot \sigma \cdot {T_s}^4 = \frac{S\,(1-\alpha)}{4}$$

(3)

The factor of 1/4 comes from the fact (see Figure 4.1, below) that the Earth is *emitting* radiation over the entirety of its surface area ($4\pi R^2$ where R is the radius of the earth), but at any given time only *receiving* incoming (solar) radiation over its cross-sectional area, πR^2.

It turns out that since the Earth's surface temperature varies over a relatively small range (less than 30° K) about its mean long-term temperature (in the range of O° C, or 273° K), i.e., it varies only by at most 10% or so, it is valid to approximate the 4th degree term in equation (1) by a linear relationship, i.e.,

$$\varepsilon \cdot \sigma \cdot {T_s}^4 = A + BT_S$$

(4)

A and *B*, thus defined, have the approximate values: $A\ = 315\ \ Wm^{-2}$; $B\ = 4.6\ \ Wm^{-2}K^{-1}$

Such an approximation is often used in atmospheric science and other areas of physics when appropriate, and is called *linearization*.

Using this approximation, we can readily solve for T_S as

$$T_S = \left[\frac{S\,(1-\alpha)}{4} A\right] / B$$

(5)

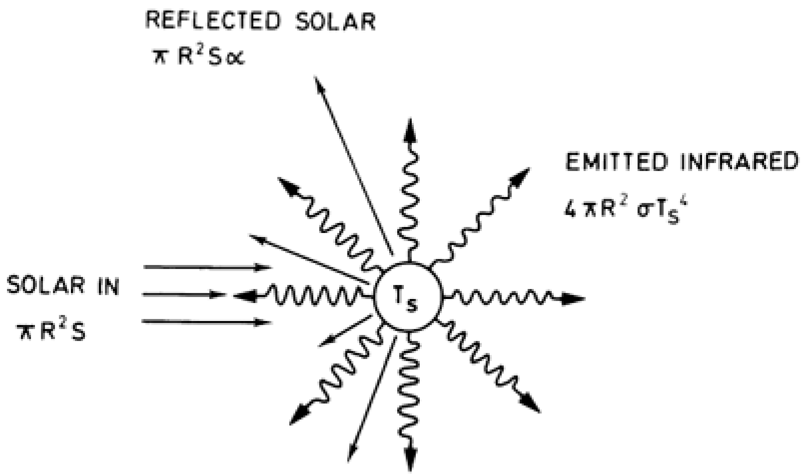
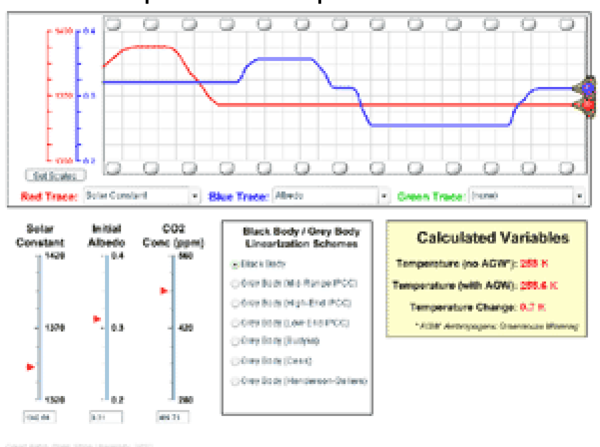


Figure 4.1: Simple Planetary Energy Balance (assume T_e = T_S for our present purposes).
Credit: Reprinted with permission from: *A Climate Modeling Primer*, A. Henderson-Sellers and K. McGuffie, Wiley, pg. 58, (1987).



[3]

We'll now play around a bit with our own customized 0d EBM [3] you'll be using for your problem set. First, we will solve for Earth's mean surface temperature in the *black body approximation*, given reasonable values of the key governing physical parameters (i.e., α and *S*).

Black Body Approximation - Demonstration [4]

You might find it rather disappointing that, after all the work we did above to develop a realistic Energy Balance Model for Earth's climate, we were way off. Our EBM indicates that, given appropriate parameter values (i.e., $S = 1370 \ \ W/m^2, \ \alpha = 0.32$), the Earth should be a frozen planet with T_S = 255° K, rather than the far more hospitable T_S= 288° K we actually observe. Our model gave a result that was a whopping 33° C (roughly 60° F) too cold!

Think About It!

What do you think we forgot?

Click for answer.

So, how do we include the effect of the atmospheric greenhouse effect in a simple way? That is the topic of our next section.

Simple Climate Models, cont'd

Gray Body Variant of the Zero Dimensional EBM

Even in the presence of the greenhouse effect, the net longwave radiation emitted out to space must balance the incoming absorbed solar radiation. So, we can think of the Earth system as still possessing an *effective radiating temperature* (T_e), which is the *black body* temperature we calculated earlier with the zero-dimensional EBM and the black body parameter values for A and B, i.e., T = 255^o K. It is the temperature Earth's surface has in the absence of any greenhouse effect. The outgoing longwave radiation to space is still given by $\varepsilon \cdot \sigma \cdot {T_e}^4$. The atmosphere will have a temperature T_e somewhere aloft in the cooler region of the mid-troposphere. If we like, we can think of the Earth as, on average, emitting temperature to space from this level; hence, we refer to the temperature as the effective radiating temperature.

When a greenhouse effect is present, the temperature at the surface, T_S, will be substantially higher, however, due to the additional *downward* longwave radiation emitted by the atmosphere back down towards the Earth's surface.

We can attempt to account for this effect by by simply changing the way we model the longwave radiation in the zero-dimensional EBM to account for the additional downward longwave radiation component.

Returning to the linearized form of the energy balance equation (i.e., equation 3 above), we will, therefore, now relax the assumption that A and B are given by their *black body* values. Instead, we will allow A and B to take on arbitrary values. This is a crude way of taking into account the fact that the Earth does not behave as a black body because the atmosphere has non-zero emissivity due to the presence of atmospheric greenhouse gases.

Simply put, we can tweak the values of A and B until they provide a good approximation. We refer to this generalized version of the black body approximation as the *gray body* approximation. The gray body model is a very crude way of accounting for the greenhouse effect in the context of a simple zero-dimensional model. In Lesson 5, we will build our way up to more realistic representations of the atmospheric greenhouse effect.

Various gray body parameter choices for A and B have been used by different researchers, in different situations. Since the gray body approximation is a linear approximation to a non-linear (Planck radiation) relationship, it is only valid over a limited range of temperatures about a given reference temperature. This means that a different set of parameters might be used for studying, e.g., the ice ages than would be used for studying, e.g., the early Cretaceous super greenhouse.

It turns out that the choices $A = 214.4\ W/m^2$ and $B = 1.25\ W/m^2\ K^{\ -1}$ yield realistic values for both the current average temperature of the earth T_S, and gives a value for the *climate sensitivity* — a concept we will define in the next section — that is consistent with mid-range IPCC estimates. We will, therefore, adopt these as our standard *gray body* parameter values, but we will also explore the impact of using alternative values a bit later.

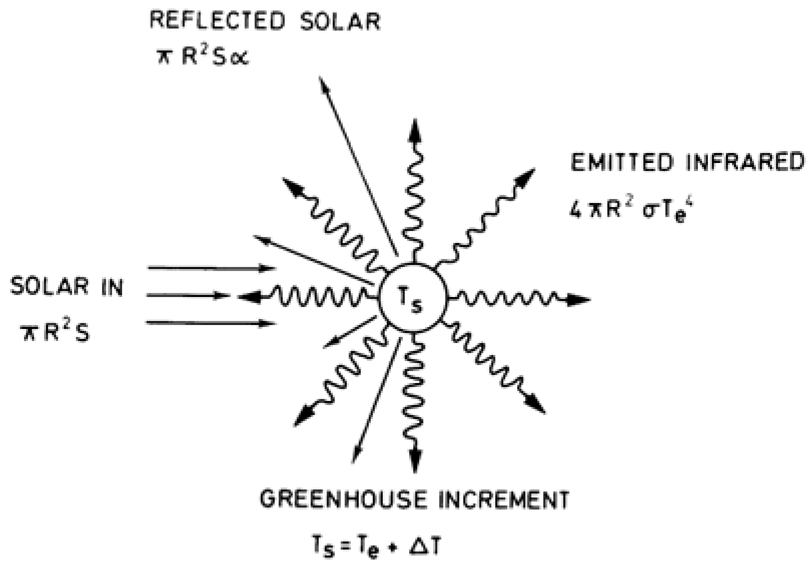


Figure 4.2: Simple Planetary Energy Balance - Greenhouse Effect Included.
Credit: Reprinted with permission from: *A Climate Modeling Primer*, A. Henderson-Sellers and K. McGuffie, Wiley, pg. 58, (1987).

Think About It!

Use the Online 0d EBM Application [3] to estimate the average temperature of the Earth for the "mid-range IPCC" gray body parameter values. What surface temperature do you find, and how does it compare with the previous black body estimate of Earth's surface temperature?

Click for answer.

The Concept of *Equilibrium Climate Sensitivity*

Let us rewrite the equation energy balance equation (3) above in a slightly different form,

$$T_S = \left[F_{in} - A\right] / B$$

(4)

$$T_S = \left({}^{1}\!\big/_{B}\right) F_{in} - {}^{A}\!\big/_{B}$$

(5)

where F_{in} represents the total incoming radiative energy flux at the surface, which includes incoming short wave radiation, but also any potential changes in the downward longwave radiation towards the surface.

Let us now consider the response of T_s to an incremental change in F_{in}. Since the 2nd term in (5) is a constant, we simply have

$$\Delta T_s = \frac{\Delta F_{in}}{B}$$

(6)

We can also rewrite (6) as

$$\frac{\Delta T_s}{\Delta F_{in}} = \frac{1}{B}$$

(7)

The change in downward longwave radiation forcing associated with a change in CO_2 concentration from a reference concentration, $[CO_2]_0$ to some new value, $[CO_2]$, can be approximated by the following relationship from a paper by Myhre et al. (1998) [5]

$$\Delta F_{CO_2} = 5.35 \ln\left(\frac{[CO_2]}{[CO_2]_0}\right)$$

(8)

Now, let us further specify that we are interested in the change in radiative forcing resulting from a *doubling of atmospheric CO_2 concentrations*. For a CO_2 doubling, e.g., an increase from pre-industrial levels of 280 ppm to twice that value, 560 ppm,

$$\Delta F_{2xCO_2} = 5.35 \ln\left(\frac{560ppm}{280ppm}\right) = 3.7 \frac{W}{m^2}$$

(9)

We can define *equilibrium climate sensitivity*, *s*, as the change in temperature resulting from a doubling of pre-industrial CO_2 concentrations; *s* has units of K (or equivalently degrees C, since differences in C and K are equal). To estimate s, we combine equations (6) and (9)

$$S = \Delta T_{2xCO_2} = \frac{\Delta F_{2xCO_2}}{B} = \frac{3.7}{B}$$

(10)

The equilibrium climate sensitivity is the equilibrium warming we expect in response to CO_2 doubling. In the simple case of the 0d EBM, it is readily calculated through equation (10).

Think About It!

Using the formula above (10), estimate the equilibrium climate sensitivity *s* for both the *black body* model and our standard version of the *gray body* model. Record your answers.

Click for answer.

Think About It!

Let's now use the Online 0d EBM Application [3] again to estimate the climate sensitivity for these two cases, by explicitly varying the CO_2 level until you achieve a CO_2 doubling, and recording the warming that you observed. Compare to the

results you calculated above directly from the formula for climate sensitivity for the 0d EBM.

Click for answer.

Problem Set #3

Estimating Future Warming

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 I can open it.

For this activity, you will explore the warming due to increases in CO_2 using a simple (0d EBM) climate model. You will consider applications to:

- defining CO_2 thresholds for avoiding dangerous human impacts on climate;
- the controversial notion of 'geo-engineering' as a means of mitigating human-caused climate change.

Online 0d EBM Application [3]

Directions

1. First, save the Problem Set #3 Worksheet [6] 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. Use the online 0d EBM application to calculate the Earth's mean temperature (pre-industrial, that is, without anthropogenic greenhouse warming) and climate sensitivity (the net warming due to CO_2 doubling from pre-industrial) for the (i) low-end, (ii) mid-range, and (iii) high-end IPCC gray body parameter settings. To do that, please use the default settings for the solar constant ($S = 1370\ Wm^{-2}$) and the Earth's albedo ($\alpha = 0.32$), and double the pre-industrial CO_2 concentrations. Discuss how the mean temperature and climate sensitivity change depending on the choice of IPCC gray body parameter.
3. The European Union has defined 2 °C degrees warming relative to the pre-industrial temperatures as the threshold for dangerous anthropogenic interference (DAI) with the climate system. Use the online 0d EBM application to estimate the level of CO_2 at which would we expect to breach the DAI amount of warming for the (i) low-end, (ii) mid-range, and (iii) high-end IPCC gray body parameter settings. Once again, use the default settings for the solar constant and the Earth's albedo. NOTE: that the adjustable slider for CO_2 only goes up to 560 ppm, so to use higher values you need to enter them by hand into the box below the slider. [See here for a commentary on the notion of DAI by your course author [7].]
4. Atmospheric CO_2 is currently at about 400 ppm and is increasing by about 2 ppm per year. If we continue to increase CO_2 at this rate, how many years will it take until we commit ourselves to DAI, based on the three climate sensitivities (i.e., gray body IPCC parameterizations) considered above? To answer this question, use your results from Question 3. If you were advising policy makers, how many years would you tell them we have to stabilize CO_2 emissions and why?
5. Later in this course, we will encounter the concept of geo-engineering — an approach to climate change mitigation which involves the attempt to offset greenhouse warming through various means of intervention with the climate system. One much-discussed geo-engineering scheme involves shooting sulfate aerosols into the stratosphere, mimicking the natural cooling impact of explosive volcanic eruptions. The eruption of Mount Pinatubo in 1991, for example, caused approximately 2.5 W m^{-2} reduction in the amount solar radiation incident at the Earth's surface, which is equivalent to about a 14 W m^{-2} reduction in the solar constant, and the effect lasted over about a 3 year period. (Recall from Lesson 4 that the amount of solar radiation incident at the Earth surface, Fi_n, relates to the solar constant, S, as $\mathrm{F_{in}} = (1 - \alpha) * S/4$, where α is the Earth's albedo.) Therefore, over a 3 year period, Mt. Pinatubo caused about a 1% reduction in the solar forcing. Use the online 0d EBM application to consider a scenario where we stabilize CO_2 concentrations at double their pre-industrial levels. Assuming the mid-range gray body IPCC parameterization, with what frequency would we have to simulate Mt. Pinatubo-like eruptions to keep global mean temperatures from exceeding the 2 °C DAI threshold? HINT: Start by recording temperature (with AGW) for the default values of the solar constant and the Earth's albedo, and double pre-industrial CO_2 for the mid-range gray body IPCC parameterization. This setup produces a 3 °C increase in temperature over the pre-industrial CO_2 levels. Then, decrease the solar constant until you find that the temperature (with AGW) decreased by 1°C, which results in total 2 °C increase in temperature that we need for DAI (ignore Temperature Change field, as it does not change). Based on the change you applied to the solar constant, approximate the required frequency of Mt. Pinatubo eruptions: one way to think of it is that one Pinatubo every 3 years gives you an average 1% reduction in *S*, so one Pinatubo every 6 years gives an average 0.5% reduction in *S*, one Pinatubo every 9 years gives an average 0.33% reduction in *S*, etc.
6. An alternative geo-engineering approach involves changing the Earth's surface properties by altering the albedo through various schemes, e.g., painting rooftops white, [8] or artificially seeding low clouds [9] over the ocean. By what percent would we need to increase Earth's albedo to avoid exceeding 2 °C warming relative to the pre-industrial level, under a CO_2 doubling scenario and using the mid-range IPCC gray body parameterization? In your opinion, is this is a realistic approach? [HINT: Start by recording temperature (with AGW) for the default values of the solar constant and the Earth's albedo, and double pre-industrial CO_2 using

the mid-range gray body IPCC parameterization. This setup produces a 3 °C increase in temperature over the pre-industrial CO_2 levels. Then, increase the Earth's albedo until you find that the temperature (with AGW) decreased by 1°C (ignore *Temperature Change* field, as it does not change). Note that the increase will be very small, so it might be easier to enter values by hand into the box below the slider.]

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

   PS3_AccessAccountID_LastName.doc (or .pdf).

   For example, student Elvis Aaron Presley's file would be named "PS3_eap1_presley.doc". This naming convention is important, as it will help the instructor match each submission up with the right student!

Submitting your work

- Upload your file to the "Problem Set #3" assignment in Canvas by the due date indicated in the syllabus.

Grading rubric

The instructor will use the general grading rubric for problem sets [10] to grade this activity.

Lesson 4 Summary

In this lesson, we began to explore the use of theoretical models of the climate system. We saw that:

- a simple *zero-dimensional energy balance model* can be used to estimate the surface temperature of the Earth, as well as the response of surface temperatures to changes external (including human-induced perturbations). The model balances the incoming solar radiation absorbed at Earth's surface and the outgoing longwave radiation emitted from Earth's surface;
- a simple linear approximation can be used in the zero dimensional EBM to represent the outgoing longwave radiation, leading to a mathematical simplification and a simple formula for global surface temperature;
- using the simplest, *black body* approximation for the outgoing longwave radiation gives a global surface temperature of about 255K, i.e., 18C below freezing—obviously way too cold;
- the *gray body approximation* provides a simple fix to the zero-dimensional EBM that incorporates, at least crudely, the atmospheric greenhouse effect;
- using appropriate values of the *gray body* model coefficients, we can accurately predict both the Earth's surface temperature (roughly 288K, i.e., approximately 15°C), and the response of surface temperatures to perturbations such as increasing greenhouse gas concentrations (roughly 3°C for a doubling of atmospheric CO_2).

This lesson also introduced us to the important concept of equilibrium climate sensitivity—a concept we will encounter again and again throughout this course.

Reminder - Complete all of the lesson tasks!

You have finished Lesson 4. Double-check the list of requirements on the first page of this lesson 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/135

Links
[1] https://www.e-education.psu.edu/meteo469/202
[2] http://www.cims.nyu.edu/~mostovyi/Course/EBM/zero_dim_ebm.html
[3] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson03/0d_EBM.html
[4] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson04/black_body_approx.html
[5] http://88.167.97.19/albums/files/TMTisFree/Documents/Climate/New_estimate_of_radiative_forcing_of_well_mixed_greenhouse_gases_myhre_grl98.pdf
[6] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson04/PS3_worksheet_Sp2017.doc
[7] http://www.meteo.psu.edu/%7Emann/shared/articles/MannCommentaryPNAS09.pdf
[8] http://money.cnn.com/2009/07/13/news/economy/white_roofs/index.htm
[9] http://ecocentric.blogs.time.com/2010/06/28/a-quick-fix-for-climate-change-falls-flat/
[10] https://www.e-education.psu.edu/meteo469/243