Homework Assignment Sheet #1

EES 2110/5110 Global Climate Change

Homework for Aug. 24–Dec. 7, 2016

Disclaimer

This is a schedule of homework assignments through the entire term. I have worked hard to plan the semester, but I may need to deviate from this schedule, either because I decide that it's important to spend more time on some subjects, or because new developments in either climate science or climate policy require us to depart from my plans to discuss current events and breaking news.

Ground Rules

- Homework is due at the beginning of class on the due date. Late homework will be accepted for half-credit until I post the answers on Blackboard (usually a week after the due date).
- At the end of the chapters of *Understanding the Forecast*, there are study questions and exercises. Don't get confused between the two: Study questions are for your own use in reviewing whether you understand the chapter. My homework assignments ask you to do the Exercises, which are more challenging and ask you to apply the concepts from the chapter.
- Homework problems may be confusing. I expect you to start working on the problems well before they are due. You should read over the homework problems a week before they are due and start thinking about them, even if you don't start working on them right away. This will give you a chance to check whether you understand the ideas, and what the questions are asking. If you don't understand, you can ask questions in class, at my office hours, or by email (remember to put "EES 2110" or "EES 5110" in the subject line!).
- You should start working seriously on the homework problems at least three days before they are due. That will give you at least one class period before they are due, when you can ask questions. It also gives you a chance to see whether you are having problems with the online computer models that we use for many of these exercises.
- I encourage you to discuss homework assignments with your classmates. It is fine to work together on homework assignments, but you must actually do the work yourself. This means that you can ask a classmate to explain how they solved a problem but you have to go through the steps independently and put the answer in your own words, not simply copy someone else's work. **It is a violation of the honor code to turn in homework that someone else has done for you or which you copied from someone else.**
- When you turn in homework, be sure to put your name, the course ("EES 2110" or "EES 5110"), and the date at the top of the first page. Separate sheets must be stapled together. I do not bring a stapler to class, so you are responsible for this. It is a good idea to put your name on top of every sheet in case the sheets tear apart.

Fri., Sep. 2: Homework #1: Energy-Balance and Layer Models

Homework

A the beginning of class today, turn in the following homework:

- **Undergraduate Students:** *Forecast*, Ch. 2, Exercises 1, 2, 4, 5, & 7 and Ch. 3, Exercises 2 & 3.
- **Graduate Students:** *Forecast*, Ch. 2, Exercises 1–5, & 7 and Ch. 3, Exercises 1–3.

Notes on Homework

There is a typo in the book. In Ch. 2, Ex. 2, a dietary Calorie is 4200 J, not 4.2 J.

Fri., Sep. 9: Homework #2: The Greenhouse Effect

Homework

A the beginning of class today, turn in the following homework:

- **Undergraduate Students:** *Forecast*, Ch. 4, Ex. 1 & 3.
- **Graduate Students:** *Forecast*, Ch. 4, Ex. 1–3.

Notes on Homework

For these exercises, you will use the on-line computer model **MODTRAN**, which you can find at `climatemodels.uchicago.edu`. The URL given in the textbook is outdated, so use this link instead.

A helpful feature of the model is that when you start it out, before changing methane or CO_2 you can press the button "Save this run to background," and then when you change something, the model will report how the upward infrared heat flux changed. By default, the model starts up with settings for the tropical atmosphere. For these exercises I want you to set the Locality to "1976 U.S. Standard Atmosphere." Then you can save the run to background and change the concentrations of greenhouse gases as the exercises direct you to.

Mon., Sep. 12: Homework #3: Vertical Structure of the Atmosphere

Homework

A the beginning of class today, turn in the following homework:

- **Everyone:** *Forecast*, Ch. 5, Ex. 1–2

Notes on Homework

- These two exercises use two different models. In both models, you adjust parameters to achieve radiative balance (where the heat going out equals the heat coming in), but you adjust different parameters in each model, and each model has a different way for you to tell whether the earth is at radiative equilibrium.
  - The **RRTM** full-spectrum model is a radiative-convective model that considers the impact of lapse rate on the radiative balance. You can adjust the amount of sunlight hitting the earth, the albedo, the surface temperature, the lapse rate, and other parameters including the amount of cloud cover at different altitudes. The model then divides the atmosphere into many layers and at each layer, it calculates the amount of heat going up and down in

the form of shortwave radiation (sunlight) and longwave radiation emitted by the earth and the atmosphere. The model also reports about the balance of heat going up and down at the top of the atmosphere. Your goal is to adjust parameters until the model reports that "If the earth has these properties ... then it loses as much energy as it gains." You can also move your mouse over the yellow and purple arrows, which represent shortwave and longwave radiation, respectively, and the computer will show you the amount of heat flowing up or down (in watts per square meter) for that kind of radiation.

- The **MODTRAN** model ignores shortwave light and only considers longwave (infrared) light emitted by the earth's surface and atmosphere. When you start it up, you pick a locality (for this exercise, use "1976 U.S. Standard Atmosphere" just as you did for the exercises in Chapter 4) and the model will initialize to conditions of radiative balance at that locality (for the 1976 U.S. standard atmosphere, this is $260.18\,\mathrm{W/m^2}$). You can then adjust all sorts of parameters (the concentrations of different gases, the conditions of clouds or rain, and the temperature of the ground), and the model will calculate the new upward longwave heat flux at the altitude you specify. You want to make a note of the upward IR heat flux for the default conditions before you start changing things, and then when you change parameters, such as the amount of CO_2 in the atmosphere, you can adjust the ground temperature until the upward IR heat flux returns to its initial value.

- For Exercise 1, use the **RRTM** full-spectrum model, at `climatemodels.uchicago.edu/rrtm/`. For this model, you set the lapse rate, CO_2 concentration, etc., and the model automatically calculates the imbalance between I_{in} and I_{out}. You can then adjust the surface temperature until the model reports, "... then it loses as much energy as it gains."

- There's a typo in exercise 2(a): The Stefan-Boltzmann constant should be

$$\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2K^4} \quad (10^{-8}, \text{not } 10^{8}).$$

- For exercise 2, use the **MODTRAN** model. Choose "1976 U.S. Standard Atmosphere" for Location and keep the altitude at its default value of 70 km. How would you calculate the skin altitude from this model?

- When exercise 2(d) asks you to add cirrus clouds, use the "NOAA Cirrus model."

Fri., Sep. 16: Homework #4: Climate Feedback Exercises

Homework

A the beginning of class today, turn in the following homework:

- **Undergraduate Students:** Exercises 1–3 from the exercises below.

- **Graduate Students:** Exercises 1–4 from the exercises below.

Notes on Homework

These exercises are based on the exercises in *Understanding the Forecast* Ch. 7, but the web interfaces for the models have changed a lot since the book was written and you can't do the exercises the way they're written in the book. I have written these exercises instead to give you a chance to apply the same concepts.

Exercise #1: Use the **MODTRAN** model with the "1976 U.S. Standard Atmosphere" and vary the clouds. Note that this model does not consider incoming shortwave light, and therefore it ignores the albedo effect of clouds. It only calculates the effect of the clouds on outgoing longwave light for a given surface temperature. One way to think about this is that it looks at the effect the clouds have at night.

a) Run the model three times: First with clear skies, then with "Altostratus: Cloud Base 2.4 km Top 3.0 km," and finally with "Stratus: Cloud Base 0.33 km Top 1.0 km." Describe the change in I_{out} for each type of clouds:

- Is the effect warming or cooling?
- Which type of cloud has the bigger effect on I_{out}?
- Why do you see the difference between the two types of clouds?

b) Starting set the altitude to zero and select "Looking up." When you are looking up, the model reports the longwave radiation coming down to the surface from the atmosphere and hitting the earth's surface. This heat is in addition to whatever heat the earth gets from shortwave solar radiation.

For simplicity, think of this as the conditions at night, when the sun is not shining: without sunlight, the temperature of the ground will be determined by balancing the outgoing heat with the heat radiated downward by the warm atmosphere and clouds.

First, note the downward longwave heat flux (I_{down}) with clear sky (no clouds or rain). Then turn on altostratus clouds and note the change in I_{down}. Next, turn on stratus clouds and note the change in I_{down}.

Answer the following questions:

- How does I_{down} change when you add clouds?
- Do the clouds have a heating or cooling effect? Why?
- Which clouds have a greater heating or cooling effect? Why?

Exercise #2: Use the **RRTM** model.

a) First set the model to its default parameters. It should report, "If the earth has these properties ... then it loses as much energy as it gains." Move your mouse over the arrows at the top and bottom of the graph. The orange arrows are shortwave (mostly visible) light, and the purple arrows are longwave (far-infrared) radiation. How much shortwave and longwave light is absorbed by the ground (the downward arrows at the bottom) and how much of each is emitted to space (the upward arrows at the top)?

b) Next, add 100% high clouds (set "High cloud (fraction)" to 1.0). Record the total gain or loss of of heat, and the amount of shortwave and longwave radiation absorbed by the surface and emitted to space. Clouds affect both longwave and shortwave heat fluxes. Which kind of radiation changed more?

c) Now do the same thing for low clouds: set "High cloud (fraction)" to zero and "Low cloud (fraction)" to 1.0. Which kind of radiation changed more, compared to the no-cloud condition?

d) With the low cloud fraction still set to 1.0 (100%), change the drop radius from 10 μm to 8 μm. How does this change the heat flux?

e) Now set the cloud fraction to zero and double the CO_2. How does this change the heat flux? How does the effect of doubling CO_2 compare to the effect of changing the droplet size for the low clouds? You can see how important it is to get the cloud droplet size right in climate models!

Exercise #3: The "climate sensitivity" (ΔT_{2x}) refers to the change in temperature when you double the amount of CO_2 in the atmosphere. Here, we will examine how the water vapor feedback affects climate sensitivity.

a) Run the **RRTM** model with the default parameters. Write down the ground temperature.

Next, double CO_2 and note the change in energy balance. At the beginning of the exercise, the earth was in radiative equilibrium. Changing CO_2 disturbed this equilibrium and produced a radiative imbalance where $I_{out} \neq I_{in}$. Adjust the surface temperature to bring the earth back into balance.

- What is the new temperature?
- How much did the earth warm or cool? This temperature change for doubling CO_2 is what we call the **climate sensitivity**, or $\Delta T_{2\times CO_2}$.

b) Set CO_2 back to the default value (400 ppm) and set relative humidity to zero. This turns off the water vapor feedback. Adjust the surface temperature offset until the earth loses as much energy as it gains. Write down this temperature.

Now double the CO_2 and adjust the surface temperature to bring the heat back into balance.

- How much did the temperature change?

c) Compare the climate sensitivity with zero relative humidity to the sensitivity with the default value of 80% relative humidity. The difference is the effect of water vapor feedback.

- What was the amplification factor of the water vapor feedback (the ratio of the climate sensitivity $\Delta T_{2\times CO_2}$ with water vapor feedback to $\Delta T_{2\times CO_2}$ without it)?

Exercise #4 (Graduate students only): Repeat exercise 3, but using the **MODTRAN** model instead of **RRTM**.

a) Set the model to the 1976 U.S. Standard atmosphere, CO_2 to 400 ppm, and the water vapor scale to 1. Click on "Save This Run to Background."

- Note the upward IR heat flux.
- Double the CO_2 concentration.
- Adjust the ground temperature offset and set "Holding Fixed" to "Relative Humidity." (the "Holding Fixed" option will not appear until you change the ground temperature offset) Adjust the ground temperature offset until the upward IR heat flux returns to its original value. The change in temperature is the climate sensitivity including water-vapor feedback.

b) Now return CO_2 to 400 ppm and set the water vapor scale to 0. This takes all the water out of the atmosphere so there is no water vapor feedback. Check that your locality is still "1976 U.S. Standard Atmosphere.

- Adjust the ground temperature offset until the upward IR heat flux returns to the value it had at the beginning of part (a).
- Double the CO_2 concentration.
- Adjust the ground temperature offset until you restore the upward IR heat flux to its original value.

The difference in ground temperature offset from 400 to 800 ppm is the climate sensitivity with no water vapor feedback.

c) What is the amplifying factor of water vapor feedback? How does the amplifying factor you calculated with **MODTRAN** compare to the value you calcuated with **RRTM**?

Fri., Sep. 23: Homework #5: Carbon-Cycle

Homework

A the beginning of class today, turn in the following homework:

- **Undergraduate Students:** *Forecast*, Ch. 8, Ex. 1–2, Ch. 10, Ex. 1, and the **SLUGULATOR** exercise below.

- **Graduate Students:** *Forecast*, Ch. 8, Ex. 1–3, Ch. 10, Ex. 1, and the **SLUGULATOR** exercise below.
- **Everyone:** Do the following exercise (call it 10.4): Using the **SLUGULATOR** model at `climatemodels.uchicago.edu/slugulator/`, compare the impact of methane and CO_2 on timescales of 1, 10, 25, 50, 100, 500, and 1000 years.

  The **SLUGULATOR** model simulates releasing a large amount of CO_2 and methane and then calculates what happens over time. At time zero, the concentration of each gas is the natural level from shortly before the industrial revolution: 280 ppm of CO_2 and 1.6 ppm of methane. At one year, a large amount of each gas is released instantly (after this, there are no further emissions of either gas).

  a) Run the model using the default model input parameters, setting the left graph to "Concentrations" and the right graph to "Surface T Anomaly". Set the time scale on the bottom to show 10 years.

     Move your mouse over the graphs to measure the exact values (a "tooltip" will pop up next to the cursor telling the time in years and the value of the line on the graph: concentration of CO_2 or methane, or the warming due to that gas). Be aware that on the concentration graph, the concentration of CO_2 is plotted against the left axis while methane is plotted against the right axis.

     What happens to the concentrations of methane and carbon dioxide? Why does the concentration of CO_2 continue to rise after the first year, when methane is falling?

  b) What is the warming due to methane at 1 year and at 10 years? What is the warming due to CO_2 at 1 and 10 years? (Use the mouse to examine the time-dependent temperature plotted on the graphs, not the "Time-integrated temperature" in the table at the top of the page). Calculate the ratio of methane-warming to CO_2-warming at each time.

  c) Change the time scale to show 25, 50, 100, 500, and 1000 years. Make a table showing the warming due to each gas and the ratio of methane-warming to CO_2-warming at 1, 10, 25, 50, 100, 500, and 1000 years.

  d) Plot the ratio of methane-warming to CO_2-warming over time.

  e) Why does the ratio change with time?

  f) Generating electricity by burning natural gas (methane) releases much less CO_2 than generating the same amount of electricity by burning coal. "Fracking" has dramatically lowered the cost of natural gas, so many people think this will let us reduce CO_2 emissions significantly by shutting down coal-fired generating plants and replacing them with natural-gas generation. However, gas wells that use fracking may also leak a lot of methane. Comment on what the significance of this homework exercise is to the debate over whether fracking will help or hurt the problem of global warming.

Notes on Homework

The **GEOCARB** model has two time periods: First, it runs for 5 million years with the "Spinup" settings in order to bring the carbon cycle and climate into a steady state. Then, at time zero, it abruptly changes the parameters to the "Simulation" settings and also dumps a "spike" of CO_2 into the atmosphere and runs for another 2 million years with the new parameters to see how the climate and carbon cycle adjust to the new parameters and the CO_2 spike.

Notice that some of the graphs show short-time behavior (the first 100,000 years after the transition) and some show the long-time behavior (two million years after the transition).

The quantities that are graphed include:

pCO2 is the concentration of CO_2 in the atmosphere, in parts per million.

WeatC is the amount of CO_2 weathered from carbonate rocks and moved to the oceans.

BurC is the amount of carbonate converted into limestone and buried on the ocean floor.

WeatS is the amount of SiO_2 weathered from silicate rocks and moved to the oceans.

Degas is the amount of CO_2 released to the atmosphere by volcanic activity.

tco2 is the total CO_2 dissolved in the ocean, adding all its forms:

$$\text{tco2} = [CO_2] + [H_2CO_3] + [HCO3-] + [CO_3{}^{2-}].$$

alk is the ocean alkalinity: the total amount of acid (H^+) necessary to neutralize the carbonate and bicarbonate in the ocean. The detailed definition is complicated, but to a good approximation, alk = $[HCO_3{}^-] + 2[CO_3{}^{2-}]$. This is not crucial for this homework assignment.

CO3 is the concentration of dissolved carbonate ions ($CO_3{}^{2-}$) in the ocean, in moles per cubic meter.

d13Cocn is the change in the fraction of the carbon-13 (^{13}C) isotope relative to the more common carbon-12 (^{12}C) isotope in the various forms of carbon dissolved in the ocean water.

d13Catm is the change in the fraction of ^{13}C relative to ^{12}C in atmospheric CO_2.

Tatm is the average air temperature.

Tocn is the average water temperature of the oceans.

In this homework, you mostly just look at pCO_2, but in exercise 2 in chapter 8, you also have to look at the weathering.

DETAILS ABOUT THE ASSIGNMENT:

Chapter 8, #1: Run the model with "Transition CO_2 spike" set to zero and change the CO_2 degassing rate in the "Simulation" box. Examine how changing in the degassing rate affects the atmospheric concentration of CO_2 the time it takes to equilibrate (how can you tell when the atmospheric CO_2 has reached equilibrium?), and how weathering changes to produce this new equilibrium.

Chapter 8, #2:
- First, run the simulation with the transition spike set to zero, the degassing rate set to 7.5 in both the spin-up and the simulation and the "Geologic setting" set to 0 (meaning the present).
- Then press "Save model run to background," which lets you compare this run to a different run.
- Next, run the model with the geologic setting at 500 million years ago. The sun was substantially dimmer then. How did this affect pCO_2? The original run that you saved (present-day conditions) is labeled as "Alt" in the graphs and the current model run is shown without the "Alt" label. The simulation is supposed to reflect a steady state, so if you see pCO_2 changing, take a careful look at how much it changes during the two million years the graphs cover (it should not change very much, if at all). How does the average value of pCO_2 compare to today? Why is there such a difference?

Chapter 10, #1: Run the model with year = 0, degassing set to 7.5 for both the spin-up and the simulation, and a spike of 1000. If you want, feel free to run it more times with different values for the spike. You're looking for how long it takes pCO_2 to level out and how long it takes pCO_2 to return to its original value (before time zero).

Fri., Nov. 4: Homework #6: Decarbonization Homework Part 1: Top-Down

Homework

A the beginning of class today, turn in the following homework:

- **Everyone:** The first part of the decarbonization homework (posted on Blackboard).

Fri., Nov. 11: Homework #7: Decarbonization Homework Part 2: Bottom-Up

Homework

A the beginning of class today, turn in the following homework:

- **Everyone:** The second part of the decarbonization homework (posted on Blackboard).

Wed., Nov. 16: Homework #8: Emissions Trading Exercises

Homework

A the beginning of class today, turn in the following homework:

- **Everyone:** The worksheet on market-based solutions to reducing greenhouse gas emissions (posted on Blackboard together with the reading handout on market-based solutions).