Chapter 7 Homework Answers

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Exercise #1: Cloud Effects

Use the MODTRAN model with the "Tropical 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 .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?

Answer 1(a)

With clear skies, $I_{\text{out}} = 299.\ \mathrm{W/m^2}$. With altostratus clouds, $I_{\text{out}} = 269.\ \mathrm{W/m^2}$, which is $ 30.~~W/mˆ2$ less, so altostratus clouds have a warming effect.

With stratus clouds, which are closer to the ground, $I_{\text{out}} = 289.\ \mathrm{W/m^2}$, which is $10.\ \mathrm{W/m^2}$ less, so stratus clouds have a warming effect.

Altostratus clouds have a bigger effect on I_{out}. This is because altostratus clouds are higher in the atmosphere (the tops are at 3 km, compared to 1 km for stratus), so the tops of altostratus clouds are cooler than the tops of stratus clouds, and thus emits less longwave radiation.

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?

Answer 1(b)

With clear skies, $I_{\text{down}} = 447.\ \text{W/m}^2$. With altostratus clouds, $I_{\text{down}} = 447.\ \text{W/m}^2$, which is $0\ \ \text{W/m}^2$ greater, so altostratus clouds have a warming effect.

With stratus clouds, which are closer to the ground, $I_{\text{down}} = 447.\ \text{W/m}^2$, which is $0\ \ \text{W/m}^2$ greater, so stratus clouds have a warming effect.

Stratus clouds have a bigger effect on I_{down}. This is because altostratus clouds are higher in the atmosphere (the bottoms are at 2.4 km, compared to 0.33 km for stratus), so the bottoms of altostratus clouds are cooler than the bottoms of stratus clouds, and thus emits less longwave radiation.

Exercise #2: Cloud Effects with RRTM

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)?

Answer for 2(a)

At the bottom, the intensity of longwave radiation is 280.9 W/m^2 and the intensity of shortwave radiation is 266.3 W/m^2.

At the top of the atmosphere, the intensity of longwave radiation is 244.8 W/m^2 and the intensity of shortwave radiation is 95.2 W/m^2.

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?

Answer for 2(b)

Altitude	Wavelength	Direction	Clear Sky	High Clouds	Difference
Ground	Shortwave	Down	266.3	222.3	-44.0
Ground	Longwave	Down	280.9	288.3	7.4
Top of atmosphere	Shortwave	Up	95.2	131.5	36.3
Top of atmosphere	Longwave	Up	244.8	130.2	-114.6

The biggest change was in outgoing longwave radiation from the top of the atmosphere, which dropped by 114.6 W/m^2.

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?

Answer for 2(c)

Altitude	Wavelength	Direction	Clear Sky	Low Clouds	Difference
Ground	Shortwave	Down	266.3	223.1	-43.2
Ground	Longwave	Down	280.9	336.0	55.1
Top of atmosphere	Shortwave	Up	95.2	121.2	26.0
Top of atmosphere	Longwave	Up	244.8	238.4	-6.4

The biggest change was in the longwave coming down to the ground, which increased by 55.1 W/m^2.

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

Answer for 2(d)

Altitude	Wavelength	Direction	Large drops	Small drops	Difference
Ground	Shortwave	Down	223.1	219.9	-3.2
Ground	Longwave	Down	336.0	337.4	1.4
Top of atmosphere	Shortwave	Up	121.2	123.3	2.1
Top of atmosphere	Longwave	Up	238.4	238.3	-0.1

There is very little change in the longwave, but big reduction in shortwave reaching the ground and a big increase in shortwave reflected back to space.

In terms of total heat fluxes, with the 10 μm drops, we had $I_{\text{in}} = 218.8$ and $I_{\text{out}} = 238.4$.

For the 8 μm drops, we had $I_{\text{in}} = 216.7$ and $I_{\text{out}} = 238.3$.

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!

Answer for 2(e)

Altitude	Wavelength	Direction	Normal CO2	Double CO2	Difference
Ground	Shortwave	Down	266.3	265.9	-0.4
Ground	Longwave	Down	280.9	283.5	2.6
Top of atmosphere	Shortwave	Up	95.2	95.1	-0.1
Top of atmosphere	Longwave	Up	244.8	240.7	-4.1

In terms of total heat fluxes, with 400 ppm CO_2, we had $I_{\text{in}} = 244.8$ and $I_{\text{out}} = 244.8$.

For the 800 ppm CO_2, we had $I_{\text{in}} = 244.9$ and $I_{\text{out}} = 240.7$.

Changing the size of cloud drops affects the heat balance about half as much as doubling CO_2, but CO_2 mostly affects I_{out} and droplet size mostly affect I_{in}

Exercise #3: Water-Vapor Feedback

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 $I_{\text{out}} \neq I_{\text{in}}$. 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 $\Delta T_{2\times CO_2}$.

Answer for 3(a)

When I run the RRTM model with the default parameters, the ground temperature is 284.42 K.

When I double CO_2, initially, this reduces I_{out} so the Earth gains energy at a rate of 4.2 W/m^2. I adjust the surface temperature by trial and error, raising it when the Earth gains energy and reducing it when Earth loses energy, until I find that at 286.9 K, the Earth loses as much energy as it gains.

The earth warmed up by 2.48 K when we doubled CO_2, so this is the *climate sensitivity*.

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?

Answer for 3(b)

When I return RRTM to its default conditions and turn off the water vapor feedback by setting relative humidity to zero, this increases I_{out} so the Earth loses energy at a rate of 91.1 W/m^2. I adjust the surface temperature by trial and error until I find that at 261.55 K, the Earth loses as much energy as it gains.

Then I double CO_2 to 800 ppm and the Earth gains energy at a rate of 3.8 W/m^2. Again, I adjust the surface temperature by trial and error until I find that at 262.65, the Earth loses as much energy as it gains.

The climate sensitivity for 0% relative humidity is 1.1 K.

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)?

Answer for 3(c)

With relative humidity set to zero (no water-vapor feedback), the climate sensitivity is 1.1. With relative humidity set to 80% (normal water-vapor feedback) the climate sensitivity is 2.48. The amplification factor for water-vapor feedback is the ratio of these numbers

$$\text{amplification factor} = \frac{2.48K}{1.1K} = 2.2$$

Water vapor feedback more than doubles the climate sensitivity!