Instructions for Lab #4

Lapse Rates, Clouds, and Water-Vapor Feedback

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Contents

Exercises with lapse rate, clouds, and water-vapor feedback.

In this lab, we will continue using MODTRAN and will introduce a new climate model, RRTM. RRTM, which stands for "Rapid Radiative Transfer Model," is a radiative-convective model that uses code from the radiative-transfer portion of a state-of-the-art globam climate model called the "Community Climate System Model," developed at the National Center for Atmospheric Research in Boulder CO.

The entire CCSM model runs on giant supercomputers, but this radiative transfer module can run efficiently on an ordinary computer. In order to speed up the calculations, RRTM does not calculate the entire longwave spectrum the way MODTRAN does, but uses a simplified approximation that is much faster when the big climate models need to run this radiative transfer calculation roughly 52 quadrillion (5.2×10^{15}) times in a simulation of 100 years of the earth's climate.

An advantage that RRTM has over MODTRAN, is that MODTRAN assumes that the atmosphere is static (none of the air moves), whereas RRTM allows for convective heat flow. This makes RRTM more realistic, even though it sacrifices detail in its treatment of longwave radiation.

We will use RRTM to explore the role of convection in the earth system and to examine the water-vapor feedback in the presence of convection.

You can run the RRTM model interactively on the web at http://climatemodels.uchicago.edu/rrtm/index.html and I have also written a script that allows you to run it from R.

To run the model interactively, you can adjust various parameters, such as the brightness of the sun, the albedo (it gives you a choice of many natural and human-made surfaces, such as asphalt, concrete, forest, grassland, snow, ocean, and the average for the earth) the concentrations of CO_2 and methane, the relative humidity, and the amount and type of high (cirrus) and low (stratus) clouds.

You can also introduce aerosols typical of different parts of the earth, such as cities (with soot, sulfates, and other pollution), deserts (with blowing dust), oceans (with sea spray and salt), and a Pinatubo-like volcanic eruption.

Like MODTRAN, the model does not automatically adjust the surface temperature. Instead, it calculates the upward and downward flux of longwave and shortwave radiation at 51 different levels of the atmosphere and reports whether the heat flow is balanced (heat in = heat out) at the top of the atmosphere.

If the earth is *gaining* heat, you can manually *raise* the surface temperature until you balance the heat flow, and if the earth is *losing* heat, you can manually *lower* the temperature.

R Interface to RRTM

I have written an R function `run_rrtm` that allows you to manually run RRTM from R. To use this function, you need to include the line `source("_scripts/rrtm.R")` or `source(file.path(script_dir, "rrtm.R"))` to load it.

- `run_rrtm()` allows you to automatically download a file with the data from a MODTRAN run. You call it with the following arguments:

  - `filename` is the name of the file to save the data to. The function returns the output data, so it's optional to specify a filename.

  - `co2_ppm` is the amount of CO_2 in parts per million. The default is 400.

  - `ch4_ppm` is the amount of methane in parts per million. The default is 1.7.

  - `relative_humidity` is the relative humidity, in percent. The default is 80%.

  - `T_surface` is the surface temperature, in Kelvin. The default (for 400 ppm CO_2, etc.) is 284.42. You adjust this to restore radiative equilibrium after you change the parameters (amount of CO_2, lapse rate, etc.).

  - `I_solar` is the brightness of the sun, in Watts per square meter. The default value is 1360.

  - `surface_type` is the type of surface (this is used to calcualte the albedo). The default is 'earth average. The options are:

* "earth average": The average albedo of the earth (0.30)
* "asphalt": Dark asphalt (0.08)
* "concrete": Concrete (0.55)
* "desert": Typical desert (0.40)
* "forest": Typical forest (0.15)
* "grass": Typical grassland (0.25)
* "ocean": Ocean (0.10)
* "snow": Typical snow (0.85)
* "ice": Large ice masses covering ocean or land (0.60)
* "soil": Bare soil (0.17)
* "custom": Custom albedo (if you choose this, you need to also supply a value for albedo)

- tropopause_km is the altitude of the tropopause, in kilometers above sea level. The default value is 15. On the earth, the tropopause varies from around 9 km at the poles to around 17 km near the equator.

- lapse_rate is the lapse rate, in Kelvin per kilometer. The default is 6. The dry adiabatic lapse rate is 10, so it's physically impossible to have a lapse rate greater than 10 and results with lapse_rate greater than 10 won't make sense.

- low_cloud_frac is the fraction (from 0–1) of the sky covered by low (stratus) clouds. The default is 0.

- high_cloud_frac is the fraction (from 0–1) of the sky covered by high (cirrus) clouds. The default is 0.

- cloud_drop_radius is the size of the water droplets in the clouds, in microns. The default is 10. (For reference, 10 microns is about the size of a red blood cell). You can reduce this to simulate the indirect aerosol effect.

- aerosols allows you to set up the atmosphere with the kinds and quantities of aerosols typical of a number of different environments. Options are:

  * "none": No aerosols
  * "ocean": Typical ocean aerosols (sea-spray, salt, etc.)
  * "desert": Typical desert aerosols (dust, sand)
  * "city": Typical city with soot (black carbon) and sulfate aerosols.
  * "city just sulfates": Just sulfate aerosols typical of a city.
  * "city just soot": Just soot (black carbon) aerosols typical of a city.
  * "land": Typical rural land (dust, etc.)
  * "polluted land": Typical rural land suffering from pollution (e.g., from farming)
  * "antarctic": Typical aerosols for Antarctica
  * "volcano": Similar sulfate and dust to the Mt. Pinatubo volcanic eruption.

Any arguments you don't specify explicitly take on their default value. Thus, run_rrtm(co2_ppm = 800, relative humidity = 10, T_surface = 300) would run with all the default values, except for 800 ppm CO_2, relative humidity of 10%, and a surface temperature of 300 Kelvin.

`run_rrtm` returns a list of data containing:

- Basic parameters of the model run:
    * `T_surface`
    * `co2_ppm`
    * `ch4_ppm`
    * `I_solar`
    * `albedo`
    * `lapse_rate`
    * `tropopause_km`
    * `relative_humidity`
    * `aerosols,`
    * `low_cloud_frac`
    * `high_cloud_frac`
    * `cloud_drop_radius`
- Results of the model calculations:
    * `Q`: The heat imbalance $I_{in} - I_{out}$
    * `i_in`: The net solar radiation absorbed by the earth $((1 - \alpha)I_{solar}/4)$
    * `i_out`: The net longwave radiation emitted to space from the top of the atmosphere
    * `profile`: A tibble containing a profile of the atmosphere (altitude in km, pressure in millibar, and temperature in Kelvin)
    * `fluxes`: A tibble containing the fluxes (in Watts per square meter) of longwave, shortwave, and total radiation going up and down at 52 levels from the surface to the top of the atmosphere. The columns are `altitude` (km), `T` (temperature in K), `P` (pressure in millibar), `sw_up` (upward shortwave), `sw_down` (downward shortwave), `lw_up` (upward longwave), `lw_down` (downward longwave), `total_up` (`sw_up` + `lw_up`), and `total_down` (`sw_down+lw_down`).

There are also functions for reading RRTM data files and plotting RRTM data:

- `read_rrtm(file)` reads an RRTM file saved by `run_rrtm` and returns a list of data just like the one returned by `run_rrtm`.

- `plot_heat_flows()`: plots the upward and downward fluxes of radiation from an RRTM file or data structure. You can call it either with `plot_rrtm(file = "filename")` or `plot_rrtm(data = rrtm_data)`, where "`filename`" and "`rrtm_data`" stand for your own filename or rrtm data structure returned by `run_rrtm` or `read_rrtm`.

  You can also specify which wavelengths to plot. By default, it plots shortwave (SW), longwave (LW), and total (SW + LW), but you can specify one or more of `sw = FALSE`, `lw = FALSE`, or `total = FALSE` to omit wavelengths.

Example of running RRTM

Here is an example of running RRTM:

```
default_rrtm = run_rrtm()

# Surface temperature:
default_rrtm$T_surface
```

```
## [1] 284.42
```

```
# Heat imbalance:
default_rrtm$Q
```
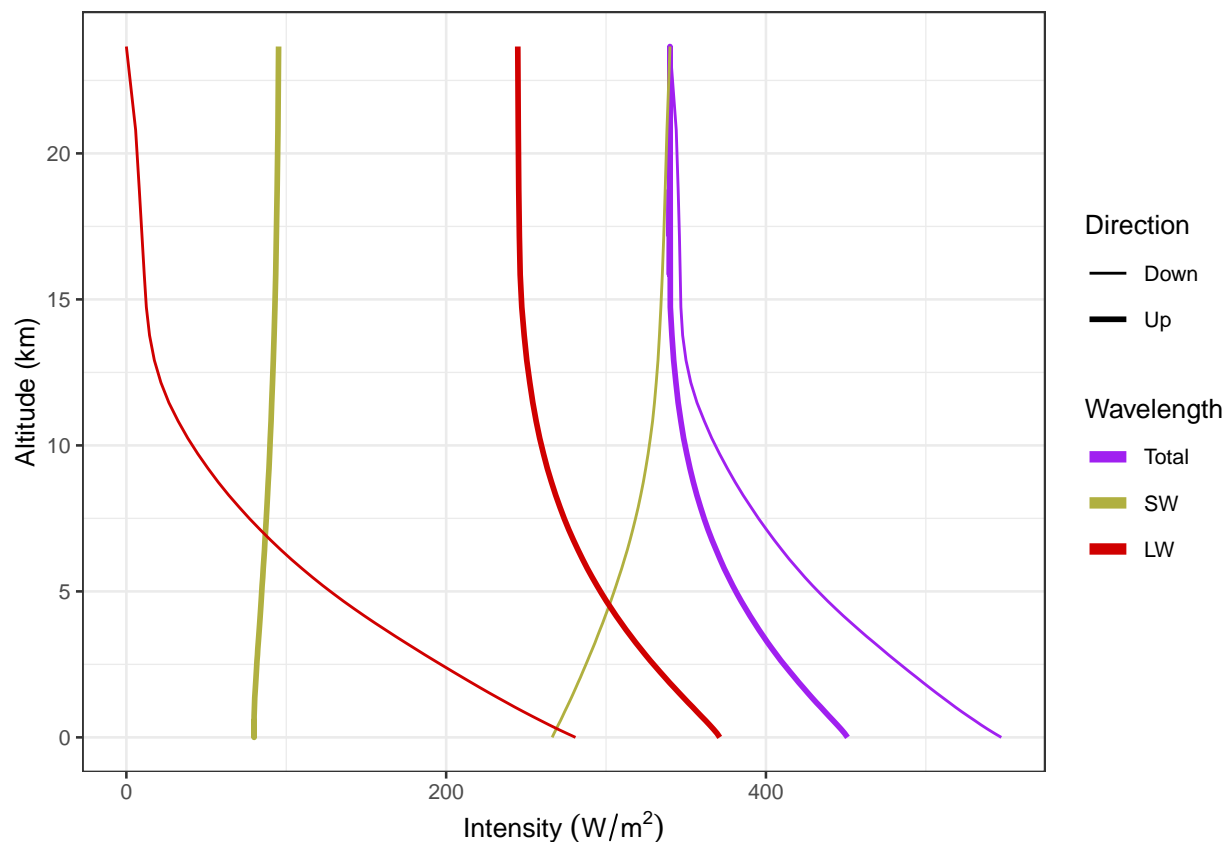
```
## [1] 0
```

This run has surface temperature 284. K and a heat imbalance of 0 Watts per square meter.

Interpreting RRTM Results

We can plot the heat flows as a function of altitude:

```
plot_heat_flows(default_rrtm)
```


What you see in this plot are thick lines representing downward heat flow and thin lines representing upward flow. The different colors represent shortwave, longwave, and total (shortwave + longwave).

A few things to notice: At the top of the atmospere, at 20. km, there is very little longwave going

5

down, but a lot of shortwave going down (around 300. W/m^2). Conversely, there is a modest amount of shortwave going up (around 100. W/m^2), but a lot of longwave going up (around 200. W/m^2).

The upward shortwave radiation is sunlight reflected from the atmosphere and the earth's surface.

The upward longwave radiation is emitted from the surface and the atmosphere. You can see that the longwave radiation, both up and down, is greater closer to the surface, where temperatures are warmer, and smaller at higher altitudes, where the atmosphere is cooler.

If we look at the total radiation, we see that there is a good balance near the top of the atmosphere (the upward and downward lines come together), but in the lower atmosphere, there is a serious imbalance with downward fluxes significantly larger than the upward ones.

This is a consequence of convection: The difference between the downward and upward radiative fluxes is taken up by convection, which moves heat upward when warm air rises and cool air sinks.

Determining Climate Sensitivity with RRTM

We can also use the RRTM model to study what happens when we double CO_2:

```
rrtm_double_co2 = run_rrtm(co2_ppm = 800)
```

When we double CO_2 without changing the surface temperature (T~surface = 284. K), this creates a heat imbalance of 4.2 W/m^2. We can use the online interactive version of RRTM to adjust surface temperature until the heat flows balance. The surface temperature where this happens is 287. K and we can paste it into our R code:

```
new_ts = 286.9 # Kelvin
rrtm_double_co2_balanced = run_rrtm(co2_ppm = 800, T_surface = new_ts)
```

When we set $T_{surface}$ to 287. K, the heat imbalance becomes 0 Watts/m^2. The climate sensitivity is the change in equilibrium $T_{surface}$ when you double CO_2: $\Delta T_{2\times CO_2} = 287.K - 284.K = 2.5$ K. You may remember that when we calculated the climate sensitivity with MODTRAN (using constant relative humidity to enable water-vapor feedback) we got $\Delta T_{2\times CO_2} = 1.21$ K for the tropical atmosphere (it's smaller for the other atmospheres), so this shows that including convection in our calculations roughly doubles the climate sensivity.

Enhancements to `read_modtran`
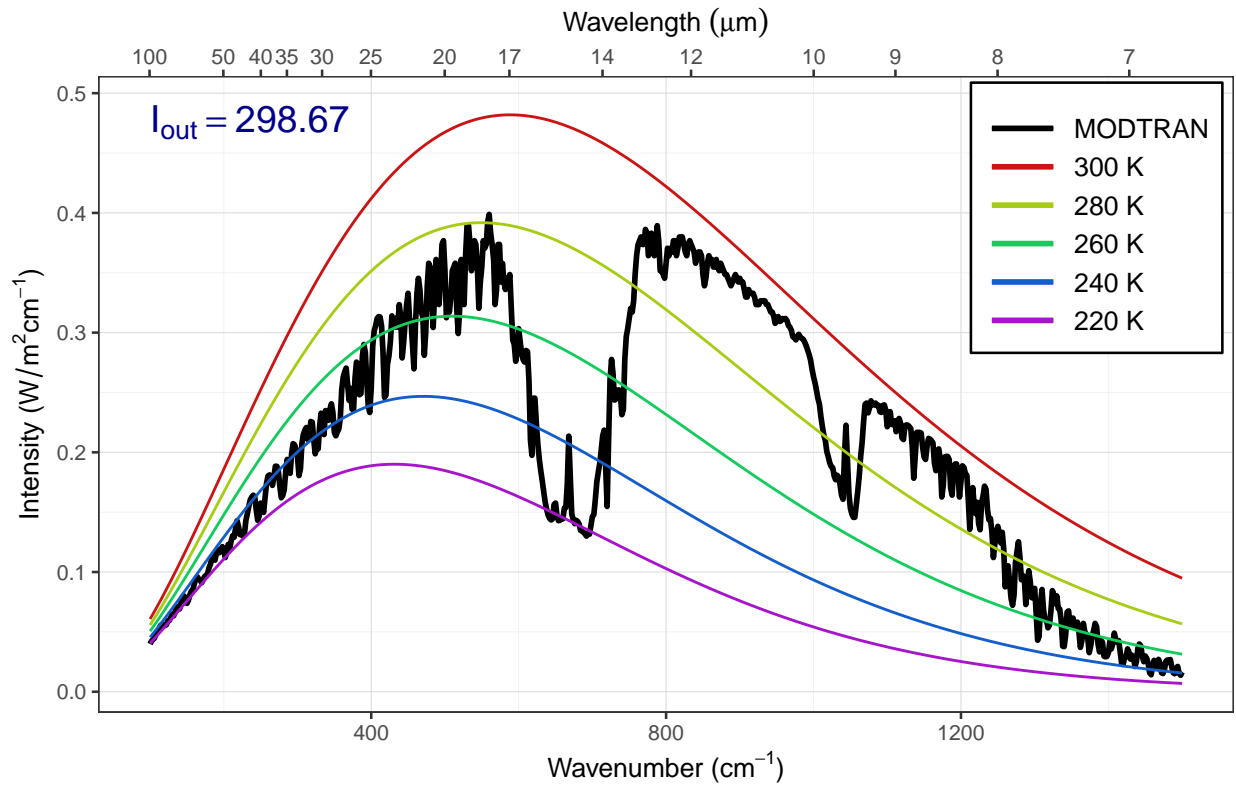
I have enhanced the MODTRAN functions:

- In addition to saving data to a file, `read_modtran` also returns data in a form that you can work with directly, without needing to use `read_modtran`:

```
modtran_baseline = run_modtran(file = "_data/modtran_baseline.txt")
modtran_baseline$i_out
```

```
## [1] 298.6712
```

```
plot_modtran(modtran_baseline)
```

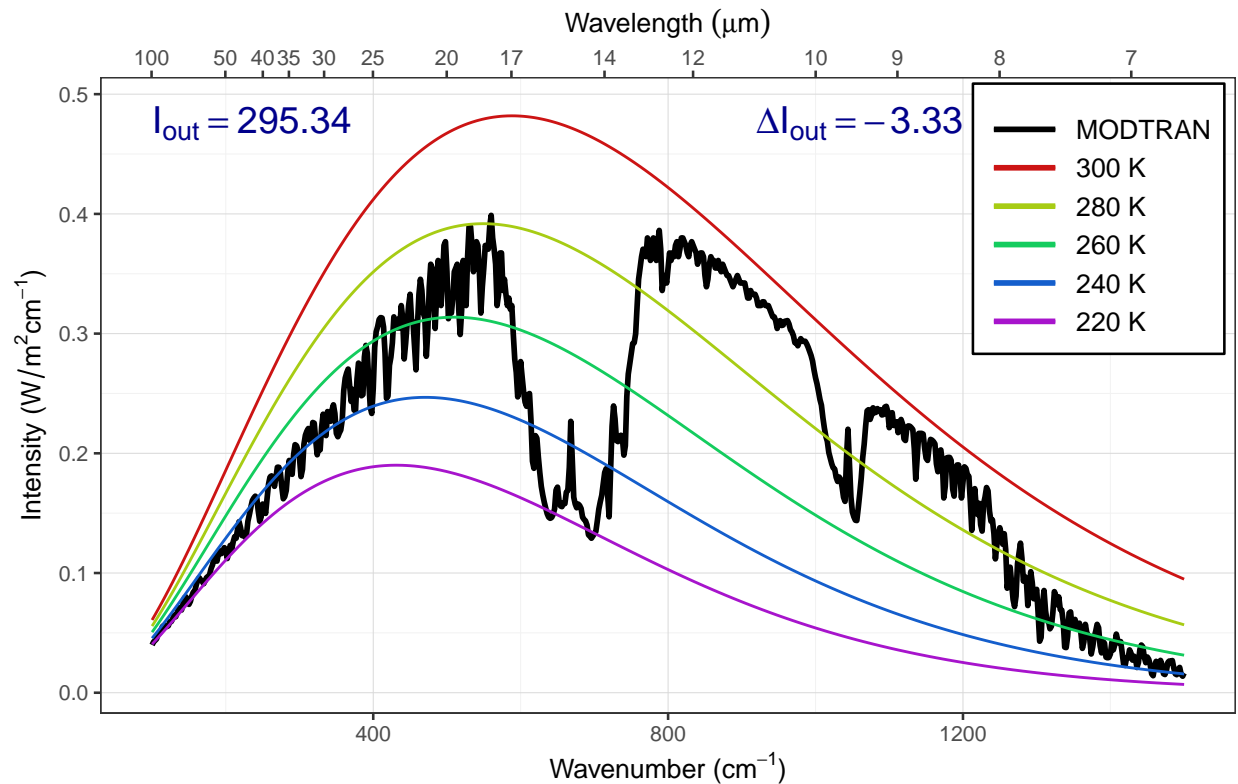## MODTRAN: 400 ppm CO_2, 70 km altitude

You can also leave out the `file` argument to `run_modtran` if you don't need to save the MODTRAN output to a file.

```
modtran_doubled_co2 = run_modtran(co2_ppm = 800)
modtran_doubled_co2$i_out
```

```
## [1] 295.3411
```

```
plot_modtran(modtran_doubled_co2, i_out_ref = modtran_baseline$i_out)
```

MODTRAN: 800 ppm CO_2, 70 km altitude

New R and RMarkdown tricks

Sometimes you may want to use different text into your document, depending on what the result of a calculation is.

For instance, I might define a function and call it by a random name, like `foo`. Suppose this function `foo` returns a number and I want my R code to behave differently if `foo(x) > x` than if `foo(x) < x`. Here, the function `ifelse` can come in handy.

```r
foo = function(x) {
  x^2
}
```

Now I can write `ifelse(foo(x) < x, "less than", "greater than")`:

```r
x = 0.5
print(str_c("foo(", x, ") is ", ifelse(foo(x) < x, "less than", "greater than"),
            " ", x))
```

```
## [1] "foo(0.5) is less than 0.5"
```

```r
x = 2.0
print(str_c("foo(", x, ") is ", ifelse(foo(x) < x, "less than", "greater than"),
```

```
        " ", x))
```

```
## [1] "foo(2) is greater than 2"
```

You may have spotted a problem with the code above: What if `foo(x) = x`? Then I need another ifelse: `ifelse(foo(x) < x, "less than", ifelse(foo(x) > x, "greater than", "equal to"))`. This is cumbersome to type into your text, so you might want to write a function, which I will call `compare_f`:

```
compare_f = function(f, x) {
  # f is a function
  # x is a number or a numeric variable
  result = f(x)
  ifelse(result < x, "less than",
         ifelse(result > x, "greater than",
                "equal to"))
}
```

Now I can just write `compare_f(foo, x)`:

```
x = 0.5
print(str_c("foo(", x, ") is ", compare_f(foo, x), " ", x))
```

```
## [1] "foo(0.5) is less than 0.5"
```

```
x = 1.0
print(str_c("foo(", x, ") is ", compare_f(foo, x), " ", x))
```

```
## [1] "foo(1) is equal to 1"
```

```
x = 2.0
print(str_c("foo(", x, ") is ", compare_f(foo, x), " ", x))
```

```
## [1] "foo(2) is greater than 2"
```

You can also incorporate this output into your RMarkdown text. The RMarkdown text

```
When x = 0.5 foo(x) is `r compare_f(foo, 0.5)` x,
and when x = 1.0 foo(x) is `r compare_f(foo, 1.0)` x,
and when x = 2.0 foo(x) is `r compare_f(foo, 2.0)` x.
```

Will produce the following:

> When x = 0.5 foo(x) is less than x, and when x = 1.0 foo(x) is equal to x, and when x = 2.0 foo(x) is greater than x.

This may seem kind of strange, but it can be helpful if you have a report that you prepare regularly with different data and want to be able to update by running RMarkdown with different data sets, and have the text adjust automatically to what the new numbers are.

This approach is used when businesses need to generate monthly reports (e.g., sales, finances, etc.)

and want to automate the process with an RMarkdown report template that can be used over and over with each new month's data.

It is also applicable to climate science, where many laboratories like to update their reports every month or every year with the latest climate data.

Exercises

These are the exercises you will work for the lab this week.

General Instructions

In the past three weeks, we focused on mastering many of the basics of using R and RMarkdown. For this week's lab, when you write up the answers, I would like you to think about integrating your R code chunks with your text.

For instance, you can describe what you're going to do to answer the question, and then for each step, after you describe what you're going to do in that step, you can include an R code chunk to do what you just described, and then the subsequent text can either discuss the results of what you just did or describe what the next step of the analysis will do.

This way, your answer can have several small chunks of R code that build on each other and follow the flow of your text.

Chapter 5 Exercise

For this model, you will use the RRTM model, which includes both radiation and convection.

Exercise 5.1: Lapse Rate

Run the RRTM model in its default configuration and then vary the lapse rate from 0 to 10 K/km. For each value of the lapse rate, adjust the surface temperature until the earth loses as much heat as it gains (i.e., the value of Q in the `run_rrtm` model output is zero.)

It will probably be easier to do this with the interactive version of the RRTM model at http://climatemodels.uchicago.edu/rrtm/ than with the R interface `run_rrtm`.

a) Make a tibble containing the values of the lapse rate and the corresponding equilibrium surface temperature, and **make a plot** with lapse rate on the horizontal axis and surface temperature on the vertical axis.

b) Describe how the equilibrium surface temperature varies as the lapse rate varies.

Chapter 7 Exercises

Exercise 7.2: Clouds and Infrared.

Note: this exercise only considers the effect of clouds on longwave radiation and ignores the effect of clouds on albedo, which is also important.

a) Run the MODTRAN model with present-day CO_2 (400 ppm) and a tropical atmosphere. Plot the outgoing infrared spectrum.

   Run MODTRAN four times: first with no clouds, and then with three different kinds of clouds: standard cirrus, altostratus, and stratus. These correspond to high, medium, and low-altitude clouds.

   Describe the important differences between the spectra for the four cases. Describe the differences in the intensity of outgoing infrared radiation I_{out} for the four cases.

   How do the four spectra compare for the 700 cm^{-1} band (where CO_2 absorbs strongly) and the 900 cm^{-1} band (in the atmospheric window)?

   Which kind of cloud has the greatest impact on outgoing infrared light? Why?

b) Now set `atmosphere` to `"midlatitude winter"`, set `clouds` to `"none"`, and set the sensor altitude to 0 km (`altitude_km = 0`) and make the sensor look up (`looking = "up"`). This means your sensor is on the ground looking up at the longwave radiation coming down from the atmosphere to the ground instead of looking down from the top of the atmosphere at the longwave radiation going out to space.

   Run MODTRAN first with `h2o_scale = 1` (the default), and then with `h2o_scale = 0` (no water vapor).

   Plot the two spectra and compare them. Discuss why you see what you see:

   - For the atmosphere with no water vapor, compare the parts of the spectrum corresponding to the strong CO_2 absorption (roughly 600–750 cm^{-1}) and the infrared window (roughly 800–1200 cm^{-1}).

     – Which corresponds to higher emission temperatures and which to lower temperatures?
     – Why do you think this is?

   - For the atmosphere with normal water vapor (`h2o_scale = 1`), how does water vapor change the spectrum you see from the ground?

     – Does it make the longwave radiation brighter (warmer) or dimmer (cooler)?
     – Why do you think this is?

c) Keeping the same settings for `atmosphere = "midlatitude winter"`, `altitude_km = 0`, and `looking="up"`, set `h2o_scale=1` and run MODTRAN first with no clouds, then with three kinds of clouds: standard cirrus, altostratus, and stratus (`clouds="none"`, `clouds="standard cirrus"`, `clouds="altostratus"`, and `clouds="stratus"`).

When we're looking up at the clouds, the base (bottom) of the clouds form a layer that is opaque to longwave radiation, with an emissivity of 1 (i.e., a perfect black body).

Cirrus clouds are very high (around 10 km above sea level), altostratus clouds are at a medium height (with a base around 2.4 km), and stratus clouds are very low (with a base around 0.33 km).

For each run examine
I_{down}. (Remember that the variable `i_out` in the MODTRAN output measures the intensity of longwave radiation reaching the sensor. In this exercise, the sensor is on the ground looking up, so `i_out` measures the downward radiation reaching the ground.)

Describe how I_{down} compares for the four conditions.

- Do the clouds have a heating or cooling effect?
- Which clouds have the greatest effect?
- What does this suggest about how clouds affect the ground temperature?

As you do this exercise, think about a winter night with clear skies versus a winter night with cloudy skies.

d) Plot the longwave radiation spectra for the four MODTRAN runs from part (c). Which parts of the spectrum do the different clouds affect the most? (Compare the infrared window to the parts of the spectra where CO_2 absorbs.)

- Look at two parts of the spectrum: the infrared window (roughly 800–1200 cm^{-1}) and the region where CO_2 absorbs strongly (roughly 600–750 cm^{-1}).

  Why do you suppose the high, medium, and low clouds affect the two different spectral regions the way they do?

- In which part of the spectrum do the clouds affect the downward longwave radiation the most?

Exercise 7.3: Clouds and Visible Light.

For this exercise, you will use the RRTM model to examine climate sensitivity and the water vapor feedback in a radiative-convective atmosphere.

a) First, run the RRTM model with its default parameters (400 ppm CO_2) and note the surface temperature (`T_surface`).

Then run it again with doubled CO_2 concentration (`co2 = 800`). Adjust the surface temperature to bring the heat imbalance `Q` to zero (it may be easier to do this with the interactive model at http://climatemodels.uchicago.edu/rrtm/ and then paste the new surface temperature into your R code).

The change in surface temperature between the 400 ppm CO_2 and 800 ppm CO_2 ($\Delta T_{2 \times CO_2}$) runs is the **climate sensitivity**. What is it?

b) Now run the RRTM model again, for 400 and 800 ppm CO_2, but this time setting `relative_humidity = 0` (this turns off the water vapor feedback). At each concentration of CO_2, adjust `T_surface` to bring the heat into balance (so the output has `Q` equal to zero). Now what is the climate sensitivity ($\Delta T_{2 \times CO_2}$)?

c) Compare the climate sensitivity ($\Delta T_{2 \times CO_2}$) in part (a) (with water-vapor feedback) and part (b) (without water-vapor feedback). The amplification factor for the water-vapor feedback is the ratio of the climate sensitivity with water-vapor feedback to the sensitivity without the feedback. What is it?