Instructions for EES 3310/5310 Lab #3

Exercises with the MODTRAN Model

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Instructions

For these exercises, I recommend that you work on them with the interactive web-based MODTRAN models to get a feel for how the models apply to the exercise.

Once you are clear what you are doing, you can use the R scripts and RMarkdown to turn those insights into reproducible research.

Using MODTRAN with RMarkdown.

This RMarkdown document includes the line `source("scripts/modtran.R")`, which loads a script with the following functions:

- `run_modtran()` 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. I recommend giving it a meaningful name: for instance, a run with 550 ppm CO2 and 3.4 ppm methane might be called "`modtran_440_34.txt`". Make up your own file names, but think about how you will tell which is which.
  - `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.
  - `trop_o3_ppb` is the amount of ozone in the troposphere, in parts per billion. The default is 28. You probably won't change this unless you're setting all greenhouse gases to zero.
  - `strat_o3_scale` is the amount of stratospheric ozone, relative to the naturally occurring levels in the ozone layer. You probably won't change this unless you're setting all greenhouse gases to zero.
  - `h2o_scale` is the amount of water vapor, relative to the naturally occurring levels in the atmosphere. You probably won't change this unless you're setting all greenhouse gases to zero.

- `freon_scale` is the amount of freon chemicals (used for refrigerators and air conditioners), relative to the current amounts. You probably won't change this unless you're setting all greenhouse gases to zero.
- `delta_t` is the temperature offset, in degrees C. You adjust this to restore radiative equilibrium after you change the amount of CO_2 or other greenhouse gases.
- `h2o_fixed` is what quantity to hold fixed for water vapor. Possible values are "vapor pressure" (the default), and "relative humidity"
- `atmosphere` is the locality in the MODTRAN model. Possible values are: "tropical" (the default), "midlatitude summer", "midlatitude winter", "subarctic summer", "subarctic winter", and "standard" for the 1976 U.S. standard atmosphere.
- `clouds` is the specification of clouds and rain. Possible values are "none" (the default), "cumulus", "altostratus", "stratus", "stratocumulus", "nimbostratus", "drizzle", "light rain", "medium rain", "heavy rain", "extreme rain", "standard cirrus", "subvisual cirrus", and "NOAA cirrus".

  Stratus clouds are flat, opaque, and low-altitude. **Altostratus clouds** are flat and medium altitude. **Cirrus clouds** are thin and high-altitude. They are hard to model, so there are three different varieties. **Cumulus clouds** are thick and stretch from low altitudes to medium altitudes. **Stratocumulus clouds** are like thunder clouds. They are very tall and reach from low altitudes to the top of the troposphere. **Nimbostratus clouds** are low and thick, like stratus, but produce rain.
- `altitude_km` is the altitude, in kilometers above sea level, that you put your virtual sensor in the model. The default is 70 km, which is above almost all of the atmosphere.

  For some exercises, you may experiment with putting the sensor somewhere around 8 to 12 km, which is the top of the troposphere, below the stratospheric ozone layer.

  For other exercises, you might want to put it at 0 km (ground level), and set it to look up instead of down, so you can see the IR radiation coming down to the ground from the atmosphere instead of looking at the IR radiation going out to space.
- `looking` is the direction the sensor is looking. The options are "down" (the default) or "up".

Any arguments you don't specify explicitly take on their default value. Thus, `run_modtran('data/modtran_experiment_1.txt', co2_ppm = 800, delta_t = 1.0, h2o_fixed = "relative humidity")` would run with all the default values, except for 800 ppm CO_2, a temperature offset of 1°C, and holding relative humidity fixed.

- `plot_modtran` reads a MODTRAN output file and generates a plot. There are many arguments, and I won't explain them all here, but the important ones are:
  - `filename` is the MODTRAN output file with the data to use for the plot.
  - `descr` is an optional string to use for the title of the plot. If you don't specify anything, the function will make a title that indicates the CO2 concentration and the altitude of

the virtual sensor.

- i_out_ref is a reference value for the outgoing infrared. If you don't specify it, it's ignored, but if you specify it, then the plotting function adds an annotation to indicate the difference in outgoing IR between the current run being plotted and the reference value. Typically, you'd run a baseline run of MODTRAN with default parameters and then use the upward IR flux from that run as i_out_ref when you change the CO_2 concentration or other model parameters.
- delta_t is the temperature offset for this model run. If you specify it, the plotting function adds an annotation to indicate it.
- text_size allows you to adjust the size of the text used for axis labels and the plot title.

- read_modtran(filename) allows you to read in a MODTRAN output file and examine the data. This function returns a list with 7 elements:
  - spectrum is a data tibble with the spectral information (wavelength lambda, wavenumber k, outgoing IR intensity tk, and a number of other variables.)
  - profile is the profile of the atmosphere: a tibble with three columns: Z is the altitude in km, P is the atmospheric pressure, in millibars, and T is the temperature in Kelvin.
  - co2 is the atmospheric CO_2 concentration
  - ch4 is the atmospheric methane concentration
  - i_out is the intensity of the outgoing IR radiation flux.
  - t_ground is the ground temperature (in Kelvin) used in the model run. (Remember that this is something you set when you run the model. MODTRAN cannot calculate the way ground temperature changes when you change greenhouse gases, clouds, or other characteristics of the atmosphere.)
  - t_tropo is the temperature at the tropopause (in Kelvin).
  - h_tropo is the height of the tropopause (in km).
  - alt is the altitude of the virtual sensor.
  - sensor_direction is the direction of the virtual sensor ("up" or "down").

- Some handy conversion functions are:
  - ktof(T) converts T from Kelvin to Fahrenheit.
  - ktoc(T) converts T from Kelvin to Celsius.
  - ftok(T) converts T from Fahrenheit to Kelvin.
  - ctok(T) converts T from Celsius to Kelvin.
  - ctof(T) converts T from Celsius to Fahrenheit.
  - ftoc(T) converts T from Fahrenheit to Celsius.

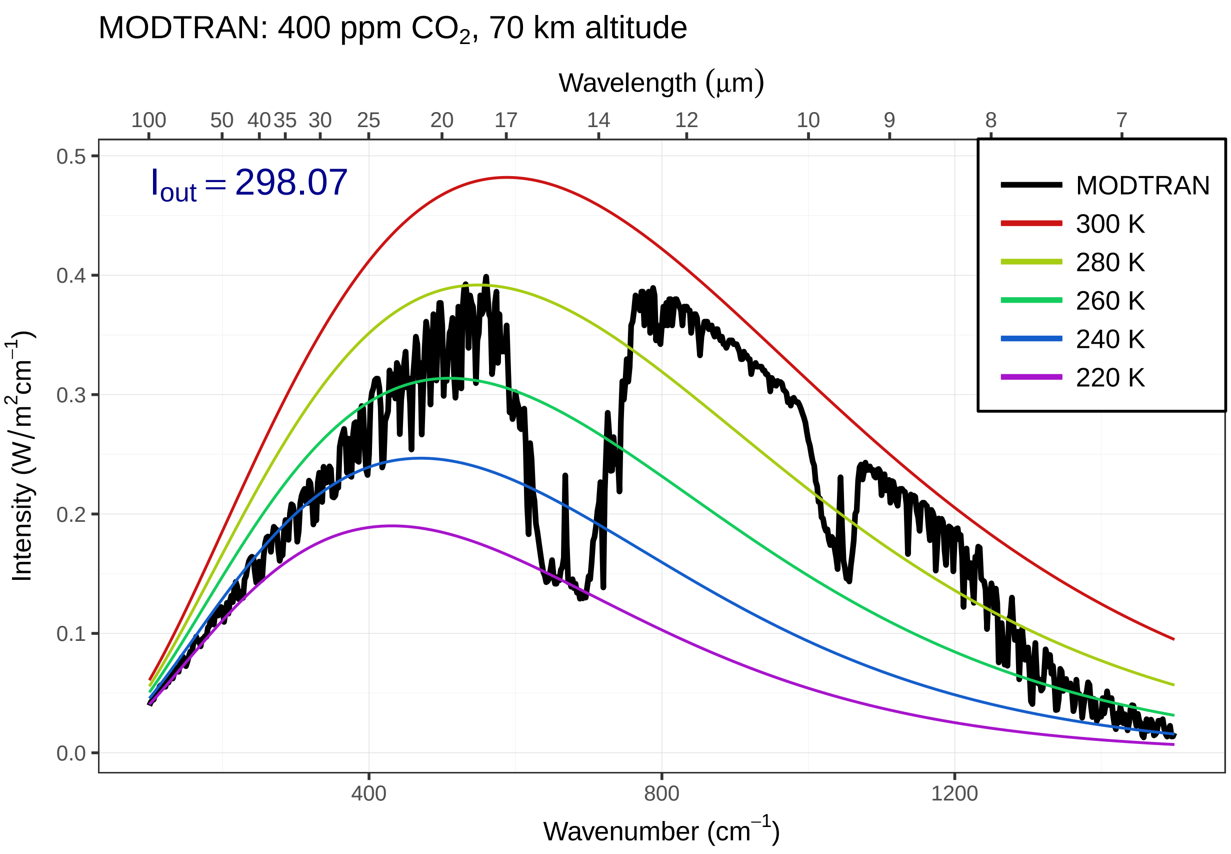
- Some variables that I have defined for you are:
  - `sigma_sb` is the Stefan-Boltzmann constant.
  - `solar_constant` is the Solar Constant (the intensity of sunlight at the top of the atmosphere).

Examples:

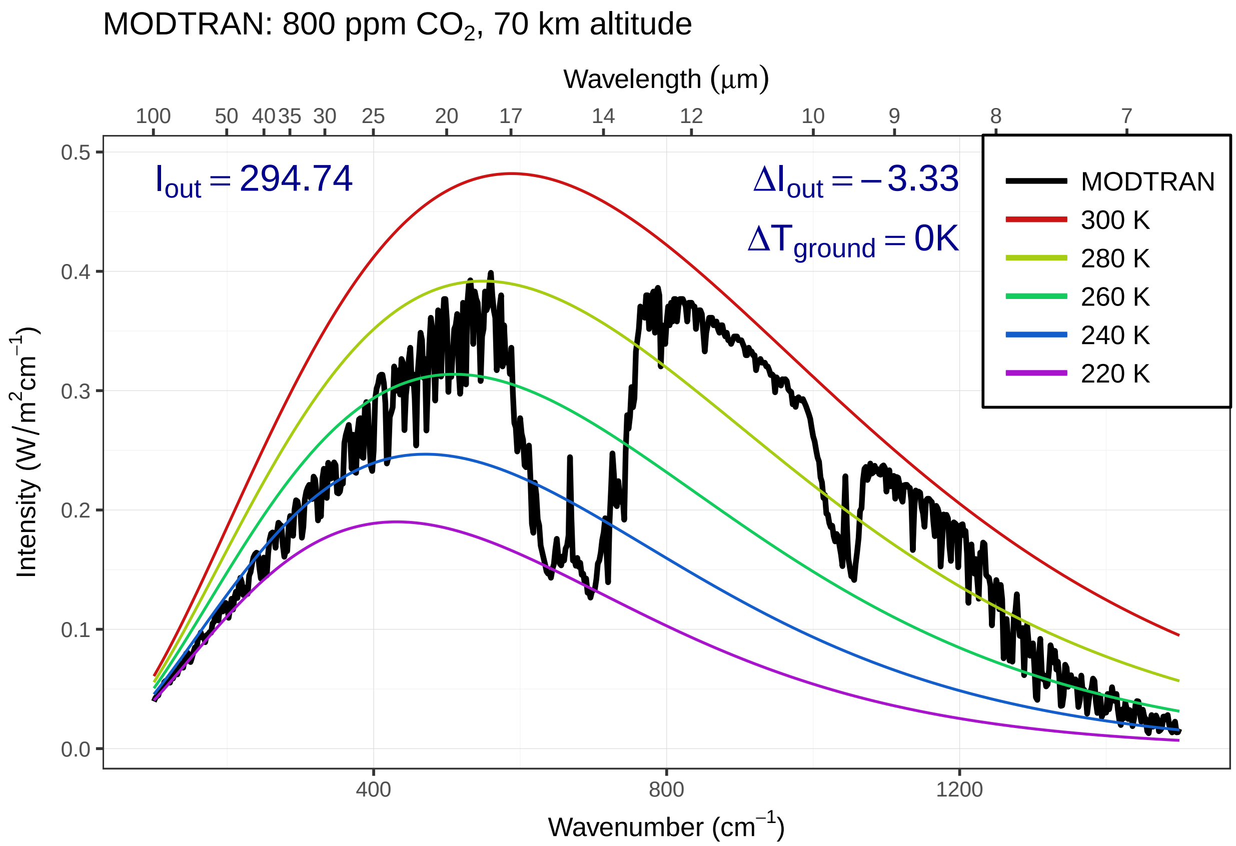
```
run_modtran(filename = "data/modtran_baseline.txt")

modtran_baseline = read_modtran('data/modtran_baseline.txt')

# Here is how you extract the various values from modtran_baseline:
baseline_i_out <- modtran_baseline$i_out
baseline_t_trop <- modtran_baseline$t_trop
```

The baseline MODTRAN run has $I_{\text{out}} = 298.07$ and $T_{\text{tropopause}} = 194.8$.

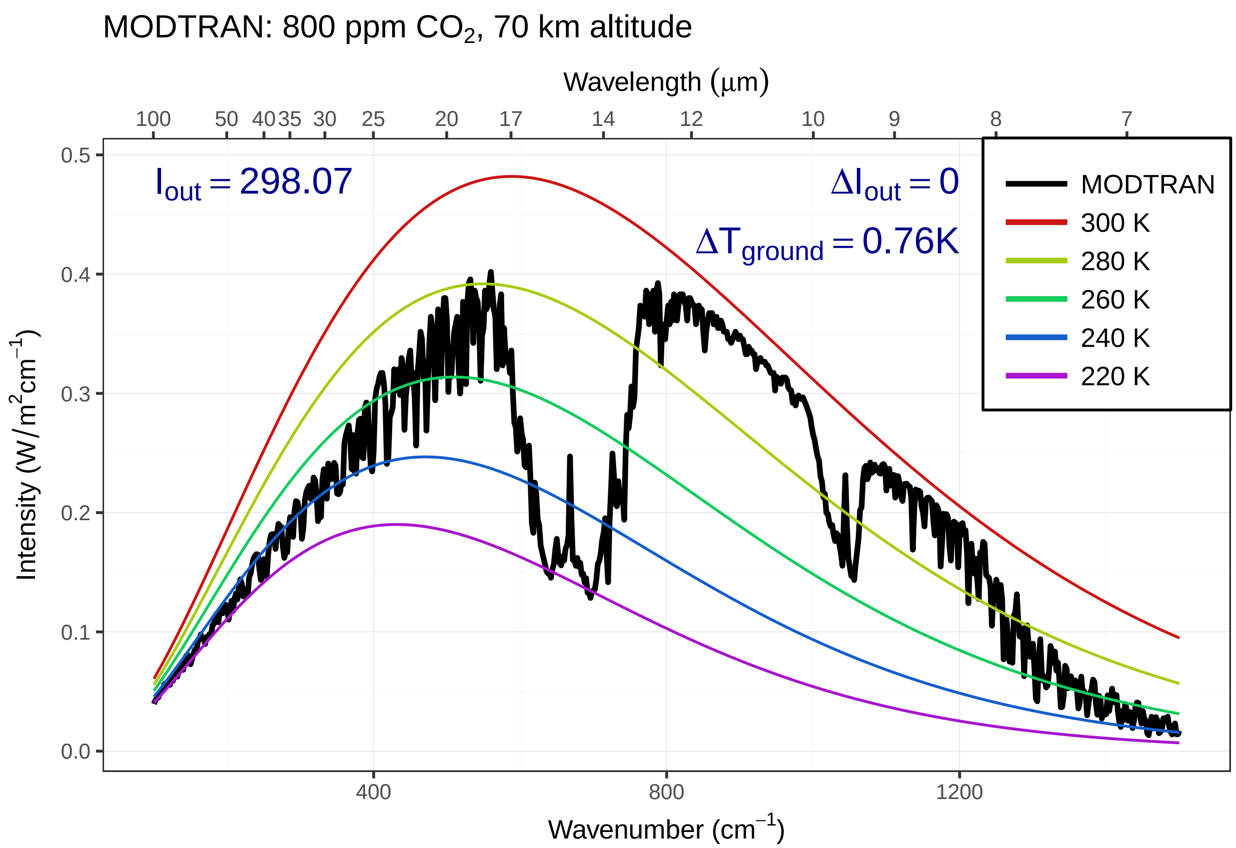
```
plot_modtran("data/modtran_baseline.txt")
```



```
run_modtran(filename = "data/modtran_double_co2.txt", co2_ppm = 800)
plot_modtran("data/modtran_double_co2.txt", i_out_ref = baseline_i_out, delta_t = 0)
```




```
run_modtran(filename = "data/modtran_double_co2_warming.txt", co2_ppm = 800, delta_t = 0
plot_modtran("data/modtran_double_co2_warming.txt", i_out_ref = baseline_i_out, delta_t
```



Chapter 4 Exercises

Exercise 4.1: Methane

Methane has a current concentration of 1.7 ppm in the atmosphere and is doubling at a faster rate than CO_2.

a) Would an additional 10 ppm of methane in the atmosphere have a larger or smaller impact on the outgoing IR flux than an additional 10 ppm of CO_2 at current concentrations?

b) Where in the spectrum does methane absorb? What concentration does it take to begin to saturate the absorption in this band? Explain what you are looking at to judge when the gas is saturated.

c) Would a doubling of methane have as great an impact on the heat balance as a doubling of CO_2?

d) What is the "equivalent CO_2" of doubling atmospheric methane? That is to say, how many ppm of CO_2 would lead to the same change in outgoing IR radiation energy flux as doubling methane? What is the ratio of ppm CO_2 change to ppm methane change?

Exercise 4.2: CO_2 (Graduate students only)

a) Is the direct effect of increasing CO_2 on the energy output at the top of the atmosphere larger in high latitudes or in the tropics?

b) Set pCO_2 to an absurdly high value of 10,000 ppm. You will see a spike in the CO_2 absorption band. What temperature is this light coming from? Where in the atmosphere do you think this comes from?

   Now turn on clouds and run the model again. Explain what you see. Why are night-time temperatures warmer when there are clouds?

Exercise 4.3: Water vapor

Our theory of climate presumes that an increase in the temperature at ground level will lead to an increase in the outgoing IR energy flux at the top of the atmosphere.

a) How much extra outgoing IR would you get by raising the temperature of the ground by 5°C? What effect does the ground temperature have on the shape of the outgoing IR spectrum and why?

b) More water can evaporate into warm air than into cool air. Change the model settings to hold the water vapor at constant relative humidity rather than constant vapor pressure (the default), calculate the change in outgoing IR energy flux for a 5°C temperature increase. Is it higher or lower? Does water vapor make the Earth more sensitive to CO_2 increases or less sensitive?

c) Now see this effect in another way.

   - Starting from the default base case, record the total outgoing IR flux.
   - Now double pCO2. The temperature in the model stays the same (that's how the model is written), but the outgoing IR flux goes down.
   - Using constant water vapor pressure, adjust the temperature offset until you get the original IR flux back again. Record the change in temperature
   - Now repeat the exercise, but holding the relative humidity fixed instead of the water vapor pressure.
   - The ratio of the warming when you hold relative humidity fixed to the warming when you hold water vapor pressure fixed is the feedback factor for water vapor. What is it?

Chapter 5 Exercise

Exercise 5.2: Skin Height

a) Run the MODTRAN model in using the "Tropical" atmosphere, without clouds, and with present-day pCO_2 (400 ppm). Use the ground temperature reported by the model to calculate $\varepsilon\sigma T^4_{\text{ground}}$, the heat flux emitted by the ground. Assume $\varepsilon = 1$, and I have already provided the value of the Stefan-Boltzmann constant σ, as the R variable `sigma_sb`, which equals 5.67×10^{-8}. (I defined it in the script "utils.R", which I loaded in the "setup" chunk in the RMarkdown document).

   Next, look at the outgoing heat flux at the top of the atmosphere (70 km) reported by the MODTRAN model. Is it greater or less than the heat flux that you calculated was emitted by the ground?

b) Use the outgoing heat flux at the top of the atmosphere to calcuate the skin temperature (use the equation $I_{\text{out}} = \varepsilon\sigma T^4_{\text{skin}}$)). What is the skin temperature, and how does it compare to the ground temperature and the temperature at the tropopause, as reported by the MODTRAN model?

   Assuming an environmental lapse rate of 6K/km, and using the skin temperature that you calculated above, and the ground temperature from the model, what altitude would you expect the skin height to be?

c) Double the CO_2 concentration and run MODTRAN again. Do not adjust the ground temperature. Repeat the calculations from (b) of the skin temperature and the estimated skin height.

   What is the new skin temperature? What is the new skin height?

d) Put the CO_2 back to today's value, but add cirrus clouds, using the "standard cirrus" value for the clouds. Repeat the calculations from (b) of the skin temperature and the skin height.

   What is the new skin temperature? What is the new skin height? Did the clouds or the doubled CO_2 have a greater effect on the skin height?

Chapter 7 Exercise

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.

Now run the model with altostratus clouds and plot the new spectrum.

Now run the model with stratus clouds and plot the new spectrum.

Describe the important differences between the spectra for the three cases. Describe the differences in the intensity of outgoing infrared radiation for the three cases.

How do the three 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 the sensor at an altitude of 0 km and make it look up. This means you are looking at the infrared coming down from the atmosphere to the ground instead of going out to space from the top of the atmosphere.

Run MODTRAN first with no clouds, then with three kinds of clouds: standard cirrus, altostratus, and stratus.

For each run, plot the downward infrared spectrum. Describe how the spectra compare. What does this suggest about how clouds affect the ground temperature?