ESS 223: Problem Set 1

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January 21, 2023

1 Problem 1

Aside from energy that leaves from Earth's surface (such as latent and sensible heat), energy from the sun is also reflected by clouds and particles in the atmosphere or can be absorbed and then re-emitted by the atmosphere.

Latent heat energy can return to space via the atmosphere, where energy from the liquid to water vapor conversion on land is released as water vapor re-condenses into clouds, and as this energy causes atmospheric circulation dynamics. The energy that is absorbed and re-emitted in the atmosphere will eventually be emitted to space.

2 Problem 2

The positive carbon-climate feedback in the ocean represents the land and ocean's reduced ability to take up carbon as the climate warms from increasing atmospheric CO_2, thereby leading to a continued increase in atmospheric CO_2 as even less anthropogenic emissions are taken up by the land and ocean sinks over time.

For the land sink, the carbon-climate feedback results from increased water limitation (hotter, drier climate) which can reduce evapotranspiration (and therefore carbon uptake), or even lead to vegetation mortality, as the climate progressively warms.

The ocean takes up CO_2 as it is dissolved into the ocean and transported via currents. The variable speeds of these deep currents and in ocean bathymetry results in a range of CO_2 residence times, with this "physical ocean pump" acting as a net carbon sink. Because temperature is the driving factor for both the density of ocean water and the solubility of CO_2 into the ocean, higher temperatures as a result of increased atmospheric CO_2 would be expected to lead to less dissolution and less deep mixing of CO_2 into the ocean.

I'm not totally sure how I'd think about the relative comparison of γ_O and γ_L (without looking it up). I am also thinking about the mention in class about how tropical ecosystems may actually *benefit* from increased aridity due to the decrease in cloud cover which increases PET without inducing water stress. Aside from these complications, I would expect γ_L to be larger than γ_O, or to perhaps have a "tipping point" where widespread vegetation mortality or ecosystem shift occurs and the land carbon sink is drastically reduced. However, I might expect that the overall impact on the global carbon budget of γ_O would be larger because the ocean is so huge (so even a small decrease in carbon dissolution per cubic meter could be a lot of carbon!) and because a drastic reduction in the deep circulation due to density changes, for example, might lead to a precipitous drop in ocean carbon sequestration (and a huge shift to global climate in general).

3 Problem 3

There is not a lot of overlap between the emission spectra of the sun and the atmosphere. The spectra of the sun peaks at smaller wavelengths (in the visible range) than that of the atmosphere (infrared) and has a much brighter maximum radiation value.

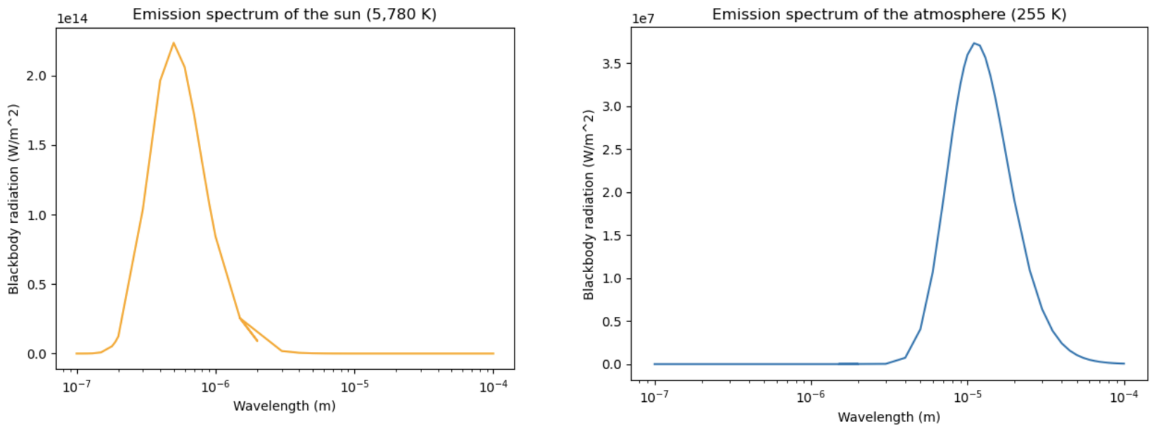

Figure 1: Blackbody emission spectrum for temperatures corresponding to the sun and atmosphere.

4 Problem 4

a) The linear fit between average CO_2 concentration and the terrestrial land use change carbon sinks can be modeled as:

$F_{land} = 0.0086x - 2.0419$
$F_{LUC} = -0.003x + 1.6912$

with R^2 values of 0.19 and 0.37, respectively (Figure 2). Based on these low R^2 values and the complex mechanisms which underlie terrestrial carbon uptake and land use change emissions, I would not expect them to have a perfect linear relationship with CO_2 concentration. In particular, because the land sink is influenced by inter-annual climate variability, I would not expect a linear relationship to be realistic.

b) Using the budget equation and the linear fits for F_{land} and F_{LUC}, the steady state value of C_a is 322 ppm (see Figure 3 for work).

c) This value is higher than the pre-industrial CO_2 concentrations. The ocean sink is not being represented.

d) Assuming the missing flux can be linearized as stated and that emissions leveled off at their 2015 value of 9.9 GTC/year, the new steady state CO_2 concentration would be 427 ppm. This is much larger than the steady state C_a in part b, indicating that even with the ocean sink taken into account and emissions capped at 2015 levels, anthropogenic emissions would still be responsible for a 32% increase in atmospheric CO_2 concentrations (see Figure 3 for work).

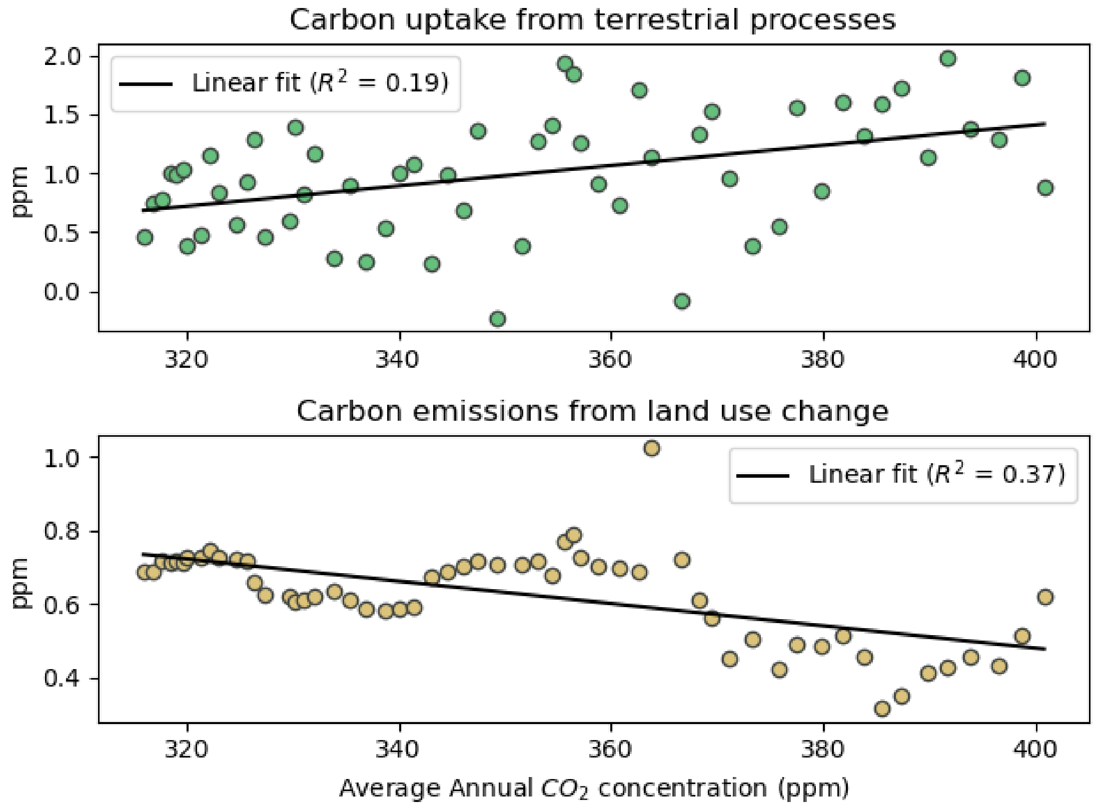

Figure 2: Carbon flux from the atmosphere due to the terrestrial carbon sink and to the atmosphere from land cover change for annual average CO_2 values.

b) F_land: F_LUC:

$$0.0086x - 2.0419 = -0.003x + 1.6912$$

$$0.0116x = 3.7331$$

$$\boxed{x = 321.82 \text{ ppm}}$$

d) 2015 E = 9.9 GT C/yr = 4.647 ppm

F_missing

$$0 = 4.647 + F_{LUC} - F_{LAND} + -0.02x + 5.10$$

$$0 = 4.647 + (-0.003x + 1.6912) - (0.0086x - 2.0419) +$$

$$0 = 4.647 - 0.003x + 1.6912 - 0.0086x + 2.0419 - 0.02x + 5.10$$

$$0.0316x = 13.4801$$

$$\boxed{x = 426.59 \text{ ppm}}$$

Figure 3: Work shown for Parts b and d.

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import math
from sklearn.linear_model import LinearRegression
def main():
    problem_3()
    problem_4()



def problem_4():
    # Import df
    gcp = pd.read_csv('GCP.csv')
    #print(gcp.head())

    # Scale to ppm
    gcp['F_land'] = gcp['F_land'] / 2.13
    gcp['F_LUC'] = gcp['F_LUC'] / 2.13
    gcp['E'] = gcp['E'] / 2.13

    # PART A: Calculate linear fit
    x = np.array(gcp['cCO2'].values).reshape((-1, 1))
    y_land = np.array(gcp['F_land'].values)
    y_luc =  np.array(gcp['F_LUC'].values)

    # fit linear model
    model_land = LinearRegression().fit(x, y_land)
    model_luc = LinearRegression().fit(x, y_luc)

    r_sq_land = model_land.score(x, y_land)
    print(f"R^2 land: {r_sq_land}")
    r_sq_luc = model_luc.score(x, y_luc)
    print(f"R^2 luc: {r_sq_luc}")

    plt.subplot(211)
    plt.plot(gcp['cCO2'], gcp['F_land'], 'o', c = '#66bf7d', mec =
'#404542')
    plt.plot(x, model_land.predict(x), c = 'black', label = f"Linear
fit ($R^2$ = {round(r_sq_land, 2)})") #type:ignore
    plt.ylabel('ppm')#'Gt C/yr')
    plt.title('Carbon uptake from terrestrial processes')
    plt.legend()
    plt.subplot(212)
    plt.plot(gcp['cCO2'], gcp['F_LUC'], 'o', color = '#dcc37c', mec =
'#404542')
    plt.plot(x, model_luc.predict(x), c = 'black', label = f"Linear
fit ($R^2$ = {round(r_sq_luc, 2)})") #type:ignore
    plt.xlabel('Average Annual $CO_2$ concentration (ppm)')
    plt.legend()
```

```
    plt.ylabel('ppm')#Gt C/yr')
    plt.title('Carbon emissions from land use change')
    plt.tight_layout()
    plt.savefig('flux.png')
    plt.close()

    # Print necessary stuff for answering questions
    print(f"F_land = {round(model_land.coef_[0],4)}x+
{round(model_land.intercept_,4)}")
    print(f"F_luc = {round(model_luc.coef_[0],4)}x+
{round(model_luc.intercept_,4)}")
    print(f"Emissions from 2015: {round(gcp[gcp['year']==2015]
['E'].values[0],4)} ppm") #type:ignore



def problem_3():
    # Problem 3

    def blackbody(wavelength, temp):
        h = 6.626e-34 # Planck constant (J s)
        k_b = 1.3806e-23 # Boltzmann constant (J/K)
        c = 3e8 # speed of light (m/s)

        numerator = 2 * math.pi * h * c * c
        denominator = pow(wavelength,5) * math.exp((h*c)/(wavelength *
k_b * temp) -1)
        return numerator / denominator

    # Wavelengths to calculate
    w = [0.1, 0.105, 0.11, 0.12, 0.13, 0.15, 0.18, 0.19, 0.2, 0.3,
0.4, 0.5, 0.6, 0.7, 0.8, 0.9,
         1, 1.5, 2, 1.5, 3, 4, 5, 6, 7, 8, 8.5, 9, 9.5, 10, 11, 12,
13, 14, 15, 16, 17, 18, 19, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65,
70, 75, 80, 85, 90, 95, 100]

    w = [i*1e-6 for i in w] # convert from micrometer to meter

    t_sun = 5780 # Kelvin
    t_atm = 255 # Kelvin

    rad_sun = []
    rad_atm = []
    for wavelength in w:
        rad_sun.append(blackbody(wavelength, t_sun))
        rad_atm.append(blackbody(wavelength, t_atm))

    #plt.figure(figsize = (10,3))
    plt.semilogx(w, rad_sun, '-', c = 'orange', label = 'Sun')
    plt.xlabel('Wavelength (m)')
```

```
    plt.ylabel('Blackbody radiation (W/m^2)')
    plt.title('Emission spectrum of the sun (5,780 K)')
    plt.savefig('rad_sun.png')
    plt.close()
    #plt.subplots(212)
    plt.semilogx(w, rad_atm)
    plt.xlabel('Wavelength (m)')
    plt.ylabel('Blackbody radiation (W/m^2)')
    plt.title('Emission spectrum of the atmosphere (255 K)')
    plt.tight_layout()
    plt.savefig('rad_atm.png')
    plt.close()



if __name__ == '__main__':
    main()
```