EARTHSYS 123A/223A/ESS 123/223: Biosphere-Atmosphere Interactions

Problem Set 1, due Thursday January 19^{th}, 2023 at 11:59 PM PDT

Please submit your problem set on Gradescope. Many of you are already enrolled in this course on Gradescope (using your Stanford email addresses for the account). Either handwritten or digital (e.g. LaTeX-generated pdfs) are welcome. If you handwrite solutions, please use the instructions for scanning here:

http://gradescope-static-assets.s3-us-west-2.amazonaws.com/help/submitting_hw_guide.pdf

Please include a copy of any code with your solutions (which can be written in any language)

Problem 1 (4 points)

To maintain energy balance, the earth must emit as much radiation as it absorbs. About half of the sunlight reaching Earth is absorbed at the land surface where it is used to heat the air directly, (sensible heat) and to evaporate water (latent heat). Some of this energy is also emitted as thermal radiation. However, only about 20% of the radiation leaving the planet comes directly from the surface. What is the origin of the remaining radiation needed to balance the energy budget? How does the energy carried by the latent heat exchanged at the surface ultimately return to space as thermal radiation?

Problem 2 (2 points)

Although it is a strong simplification of the processes at hand, the climate prediction community often uses a linear equation to try to quantify the magnitude of the carbon-climate and carbon-concentration feedbacks at hand:

$$\Delta C_L = \beta_L \Delta C_a + \gamma_L \Delta T$$

where ΔC_L is the amount of extra carbon stored in the land surface in a year (in soils and biomass), ΔC_a is the increase in atmospheric CO2 concentration and ΔT is the increase in air temperature. An analogous equation can be written that considers the feedbacks over the ocean, rather than over land:

$$\Delta C_O = \beta_O \delta C_a + \gamma_O \Delta T$$

In both cases, the β and γ are coefficients that denote the strength of the carbon-concentration and carbon-climate feedbacks specifically, for either land or the ocean depending on the subscript L vs O. For example, γ_O represents the strength of the ocean's carbon-climate feedbacks. These values can then be compared across time and across models (they are typically applied at global scales). For example, in a recent 2020 article in Biogeosciences, Arora et al. recently found that the β and γ values are similar between models of the Climate Model Intercomparison Project 5 (CMIP5), the previous generation of climate models, and the models of CMIP6, the current generation of climate models, despite other research showing model accuracy improvements in CMIP6 vs. CMIP5.

How do you expect the value of γ_L and γ_O to compare to each other? Why?

Problem 3 (2 points)

In class, we discussed that the amount of radiation emitted by a blackbody depends on its temperature, and varies by wavelength. The full spectrum of emitted radiation from a blackbody can be calculated using Planck's Law

$$B(\lambda,T)=\frac{2\pi hc^2}{\lambda^5\left(\exp(hc/\lambda k_B T)-1\right)}\ ,$$

where h is the Planck constant (6.626×10^{-34} J s), k_B is the Boltzmann constant (1.3806×10^{-23} J K^{-1}), c is the speed of light (3×10^8 m/s), λ is the wavelength of interest in meters, and T is the physical temperature of the body in degrees Kelvin. Plot the emission spectrum for the sun (T = 5780 K) and the atmosphere (T = 255 K) from 0.1 to 100 μm . How much overlap is there (note that this does not need an exact numerical answer!)?

Hint: you may want to use a semi-log plot.

Hint: The two curves do not have to be on the same plot

Problem 4 (4 points, for EARTHSYS223A/ESS223 students only)

We can write an (incomplete) budget equation for the concentration of CO_2-derived C [ppm] in the atmosphere, denoted as C_a

$$A\frac{dC_a}{dt} = E + F_{LUC} - F_{land},$$

where A = 2.13 Gt C/ppm converts between the concentration of CO_2 and the total mass of carbon in the atmosphere. The variable t denotes time. E [Gt C/yr] are anthropogenic emissions from burned fossil fuel and cement production. The F_{land} is the net uptake of C_a by terrestrial processes (e.g. the balance of photosynthesis and respiration), and F_{LUC} are the net emissions associated with land use change and disturbances.

The Global Carbon Project estimates annual values for these fluxes dating back to the 1959. If you are interested, the most recent version is described in:

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., ... & Zheng, B. (2022). Global carbon budget 2022. *Earth System Science Data*, *14*(11), 4811-4900.

Data from the Global Carbon Project with global mean estimates for E, F_{LUC} and F_{land}, as well as global mean CO_2 concentration - all covering the period 1959-2015 - from the Global Carbon Project are provided in the file GCP.csv

a) Plot F_{land} and F_{LUC} as a function of average CO_2 concentration. Calculate a linear fit between each of the net fluxes and CO_2. What processes cause and affect these relationships? Is a perfect linear regression realistic? For simplicity, we will assume this linear relationship for now.

b) Using this budget equation, what is the steady state value of C_a in the absence of fossil fuel emissions E?

c) Average pre-industrial CO_2 concentrations were no more than 280 ppm (depending on the exact period considered). How does this compare to your answer for part b? What term is missing in Eq. (1) to explain the difference?

d) Assume the missing flux can be linearized as

$$F_{missing} = -0.02C_a + 5.10$$

and

$$A\frac{dC_a}{dt} = E + F_{LUC} - F_{land} + F_{missing}$$

If emissions were to have leveled off at their 2015 values, what would have been the new steady state carbon dioxide concentration? How does this compare to your answer in part b?