13 Feb: Modification to Q3, part b (bold-faced text)

AOSC 433/633 & CHEM 433 Atmospheric Chemistry and Climate

Problem Set #1 Due: Tuesday, 14 February 2017 (start of class)

Late penalty: 10 points per day late, unless there is a legitimate medical or extra-curricular circumstance (i.e., band, athletics, GREs, etc) brought to our attention ***prior to the due date!***

The information needed to complete this assignment is contained in the lecture notes and reading assignments. However, it is fine to use any resource (i.e., any book, website, etc) to complete this assignment, provided that your answers reflect *your own understanding of the solution*. While we encourage students to share notes and discuss course material, we also expect that problem set solutions will reflect individual efforts (i.e., verbatim solutions may attract our attention ☺). Also, please "show your work", "carry units" while plugging numbers into equations, and express answers using a reasonable estimate of the appropriate number of significant digits.

Finally … both Pam and Ross will be around during the office hour on Monday, 13 February (2:00 to 3:00 pm) and throughout this day, if the time of our office hour is not convenient. Much better to approach us on Monday (or sooner!) than wait for the day the problem set is due.

1. Global Warming Potential (40 points total)

Note: you should be able to complete this question after Lecture 2

In **Lecture 2** the formula for estimating **global warming potential (GWP)** was given as:

$$\text{GWP (Species)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\text{Species}} \times [\text{Species (t)}]\ \text{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2\text{(t) dt]}} \approx \frac{a_{\text{Species}} \int_{\text{time initial}}^{\text{time final}} [\text{Species (t)}]\ \text{dt}}{a_{\text{CO2}} \int_{\text{time initial}}^{\text{time final}} [\text{CO}_2\text{(t) dt]}}$$

where:

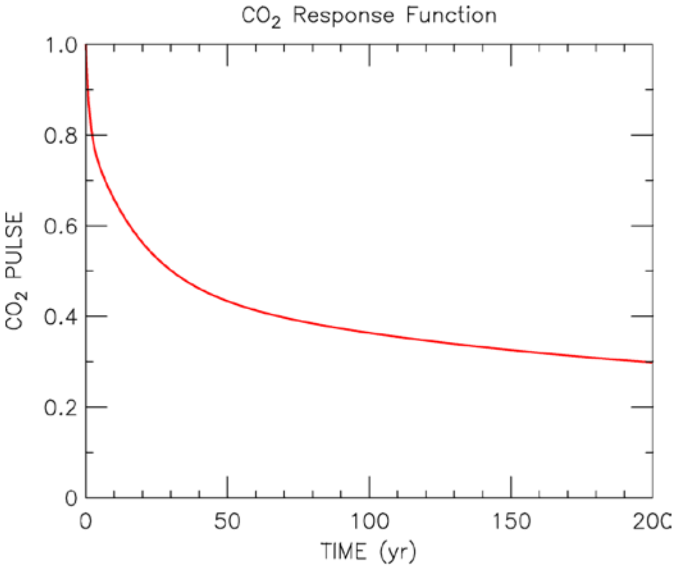
a_{Species} = Radiative Efficiency (W m^{-2} kg^{-1}) due to an increase in Species
a_{CO2} = Radiative Efficiency (W m^{-2} kg^{-1}) due to an increase in CO_2
Species (t) = time-dependent response to an instantaneous release of a pulse of Species
CO_2 (t) = time-dependent response to an instantaneous release of a pulse of CO_2

Here we will examine the GWP of the compounds listed in the table below.

Species	Chemical Formula	Lifetime (yrs)	Radiative Efficiency (10^{-15} W m^{-2} kg^{-1})
Carbon Dioxide	CO_2	---	1.74
HFC-152a	$C_2H_4F_2$	1.5	8278
HFC-125	C_2HF_5	28.2	10474
HFC-23	CHF_3	222	14062

13 Feb: Modification to Q3, part b (bold-faced text)

The formula for the response function of atmospheric CO_2 to an instantaneous release of a pulse of CO_2 was given in **Lecture 2.** Graphically, this response looks like:



a) (20 points) Estimate the GWP for HFC-152a, HFC-125, and HFC-23 over a 100 year time horizon.

> Note: to complete this calculation, you will have to evaluate an integral to find the numerical value of the ***numerator*** of the GWP formula. Assume that the integrand of this integral is:
>
> > $[\text{Species}\,(t)] = e^{-t\,/\,\text{lifetime}}$
> >
> > that the limits of integration are 0 to 100 years, and that the initial abundance of each species is unity: i.e., [Species (*0*)] = 1.0 for all gases.
>
> The numerical value of the integral that appears in the ***denominator*** of the GWP expression can be found *either* by coding up the CO_2 response function (given in lecture) within a numerical package *or* making an estimate from the graph given above (either method is perfectly fine).

b) (10 points) If you had to guess-estimate which of the three HFC compounds would have a vastly different global warming potential over a 20 year time horizon, compared to your estimates for the 100 year time horizon given in part a):

> i) which compound do you suppose would display the largest sensitivity to choice of time horizon?
>
> ii) briefly, why would this compound exhibit such strong sensitivity?
>
> iii) would the GWP of this compound for the 20 year time horizon be larger, or smaller, than found over the 100 year time horizon?

c) (10 points) If you had to choose one of these HFCs as the eventual, long-term replacement for CFCs and if your driving premise is mitigating global warming over the next century:

> i) which HFC compound should industry favor?
>
> ii) what characteristic about the chosen compound (i.e., lifetime, molecular weight, radiative efficiency, etc) is the ultimate driver of this decision?

13 Feb: Modification to Q3, part b (bold-faced text)

2. Effective Temperature (25 points total).

Note: you should be able to complete this question after Lecture 4

In class we presented the formula for calculating the effective temperature of the Earth, as well as nearby planets. We have given Earth's effective temperature, for an albedo of 0.300.

One consequence of a warmer Earth is the melting of the sea ice and ice sheets. Ice is highly reflective; therefore, a melting of Earth's ice would expose the underlying darker surface, decreasing the planetary albedo.

a) (10 points) Suppose Earth's average albedo were to decrease to 0.289 due to widespread melting of the sea ice and ice sheets. What would the effective temperature be for this new, lower planetary albedo?

b) (10 points) Assume that the change in Earth's globally averaged temperature due to the lower albedo is exactly the same as the change in Earth's effective temperature found in part a). Also, assume that Earth's atmosphere has a climate sensitivity factor (λ) of 0.63 K / W m^{-2} and that the present day, global average atmospheric abundance of CO_2 is 400 ppm.

What would the abundance of CO_2 have to be for the increase in surface radiative forcing due to the greenhouse effect to impart the same change in globally averaged temperature that was found by the albedo forcing considered in part a)?

c) (5 points) Based on your answers to parts a) and b), do you think the coverage that polar ice receives in the media, such as this recent article:

http://www.vox.com/2017/1/17/14299768/global-sea-ice-record-lows

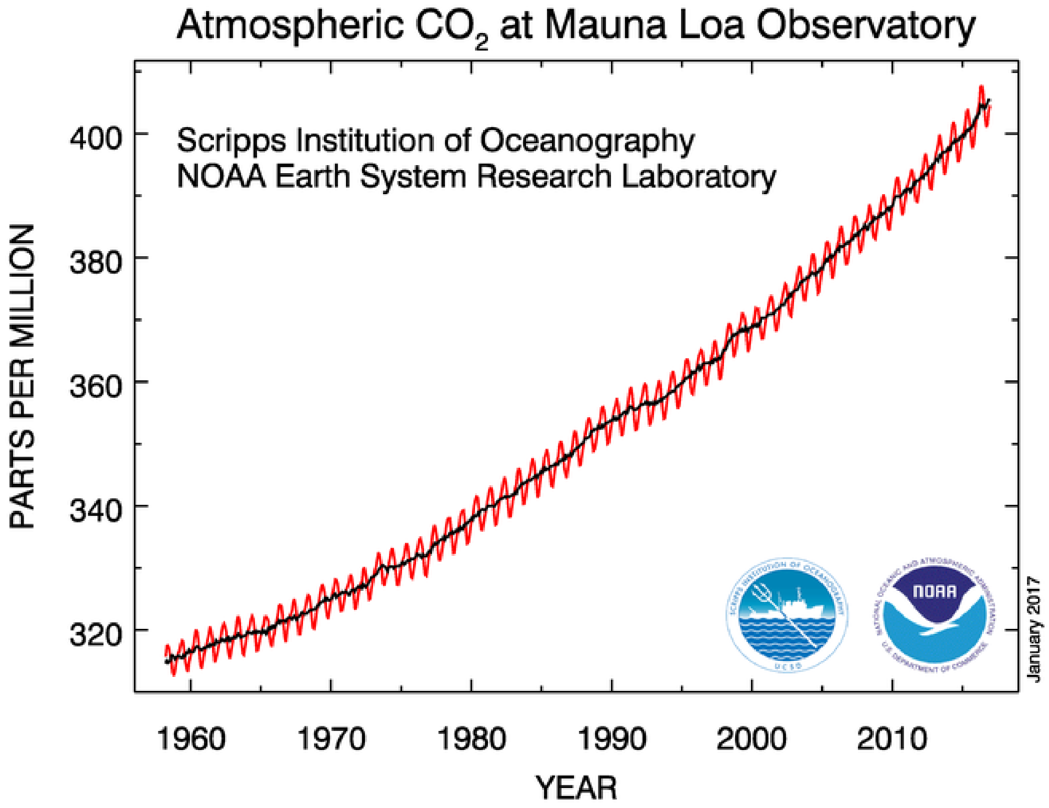
is warranted?

13 Feb: Modification to Q3, part b (bold-faced text)

3. Global Carbon Cycle (25 points total).

Note: you should be able to complete this question after Lecture 5

The figure below shows a time series of CO_2 volume mixing ratio at Mauna Loa Research Station;



Here we will calculate the magnitude of the seasonal cycle of CO_2 in the northern hemisphere (NH) and compare to the mass of carbon that accumulates, on an annual basis, in the global atmosphere.

a) (5 points) Approximately how much CO_2 in units of gigatons (Gt of CO_2) ***accumulates*** in the northern hemisphere each year?

> Note: there are a variety of ways to estimate this quantity; one manner involves a straight forward multiplication using numbers presented in **Lecture 5**. Also, 1 gigaton = 10^9 tons, which also happens to equal 10^{15} grams.

b) (15 points) Assuming the figure above is representative of the entire NH, how much CO_2, again in units of Gt of CO_2, is taken up and released by photosynthesis and respiration each growing season?

> Hint:
>
> First estimate the amplitude of the CO_2 annual cycle from the Mauna Loa figure, in units of ppm.
>
> Then, convert this quantity to mass of CO_2, in grams.
>
> Finally, convert to Gt CO_2 (gigatons of CO_2) by using an appropriate scaling factor.

13 Feb: Modification to Q3, part b (bold-faced text)

> Please note we are asking for Gt of CO_2, rather than units of Gt of C.
>
> To complete this exercise, you will need to know the mass of the atmosphere, which has been given in lecture and can also be obtained from a variety of other sources. Also, **the mean molecular weight of air, 28.8 grams/mole, should appear in your solution, as well as the molecular weight of CO_2.**

c) (5 points) Compare numerical values found in part a) (carbon accumulation rate) and part b) (carbon annual cycle) and answer the following question:

> *If society could figure out how to capture all of the leaves that hit the ground at the start of each winter, and then bury these leaves "forever", would this have the potential to be an effective means to reduce the annual rise of atmospheric CO_2 ?*

13 Feb: Modification to Q3, part b (bold-faced text)

4. 633 Students Only (45 points total)

> This question is assigned ***only to the students*** enrolled in AOSC 633. If undergraduate students would like to work through the problem, they are welcome to do so. *But no extra credit will be given to undergraduates for solving this problem**!*** Sorry but if we were to give extra credit, then the problem would no longer be exclusively assigned to graduate students. We do not expect students enrolled in AOSC 433 or CHEM 433 to work this problem. But should anyone decide to do so, we will gladly note whether your solution is correct ☺.

a) (15 points) Calculate the mass of Earth's atmosphere, in grams, by assuming:

> Surface Pressure = 1013 mbar

and noting that:

> Pressure = Force per unit area
>
> Force = Mass × Acceleration
>
> Note: you will need to look up and use the definition of millibar in order to complete this exercise.

b) (15 points) In **Lecture 2** a Table from IPCC (2007) was presented that gives the Radiative Efficiency of CO_2 as 1.4×10^{-5} W m^{-2} ppb^{-1} , where ppb refers to ppb of CO_2

The text book definition of Global Warming Potential requires Radiative Efficiency to be expressed in units of W m^{-2} kg^{-1} (here, kg refers to kg of CO_2).

Derive the Radiative Efficiency for CO_2 in units of per "kg of CO_2" from the value of the Radiative Efficiency for CO_2 given in units of per "ppb of CO_2".

c) (10 points). Calculate the mass of ***carbon*** in Earth's *entire atmosphere* in units of Giga tons (Gt C), using only the C in CO_2 and assuming that CO_2 is uniformly distributed throughout the world with a volume mixing ratio of 400 parts per million (ppm).

Hint: First express the answer in grams. Then, convert to Giga tons (10^9 tons). Here, we are using *metric tons*: **1 metric ton = 10^3 kg ; therefore, 1 Giga ton = 10^{15} grams.**

d) (5 points). What fraction of the mass of carbon in Earth's atmosphere is presently released by the burning of fossil fuels?

> **Graduate students: the proper calculations *are not* that extensive but it may take some time to figure out how to proceed. Please do your best to think this through and strive to have the answer reflect your own work, rather than consultation with other students. Honestly, it is likely going to be as easy to "think this through" than search the internet for answers, as the graduate student questions are by design not reflected by content on the web.**
>
> **Please see Ross or Pam if you are stuck.**