AOSC 433/633 & CHEM 433 Atmospheric Chemistry and Climate

Problem Set #2 Due: Thurs, 23 Feb 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!***

Final deadline: Monday, 27 February, 6 pm: ***no credit*** will be given after final deadline.

Please "show your work", "carry units" while plugging numbers into equations, and express answers using a *reasonable* number of significant digits.

Ross & Pam will be present during posted office hrs and are happy to arrange other times to meet.

Information needed to complete this assignment is contained in the lecture notes and reading assignments. However it is fine to use any resource (book, website, etc) to complete this assignment provided the answers you provide reflect *your understanding of the solution*. While we encourage students to share notes and discuss course material, we also expect that problem set solutions reflect individual efforts.

Please get started early!

1. Atmospheric Lifetimes (30 points for 433, 40 points for 633)

This problem can be completed using material presented as of Lecture 6.

In class we have stated that the lifetime for the removal of a chemical compound can be described as the burden divided by the loss rate: i.e.,

$$\tau = \frac{\text{Burden}}{\text{Loss Rate}}$$

a) (5 points) Given a volume mixing ratio for CH_4 of 1.85 parts per million and the mass of the atmosphere of 5.27×10^{21} gm, find the total atmospheric burden of CH_4, in units of terra gm (Tg of CH_4).

Notes: 1 Tg = 10^{12} gm ; also, "burden" means "mass"

b) (10 points) The lifetime for removal of atmospheric CH_4 in the troposphere can be found from:

$$\tau_{\text{TROPOSPHERE}} = \frac{\text{Atmospheric Burden}}{\text{Tropospheric Loss Rate}}$$

and the lifetime for removal of atmospheric CH_4 in the stratosphere can be found from:

$$\tau_{\text{STRATOSPHERE}} = \frac{\text{Atmospheric Burden}}{\text{Stratospheric Loss Rate}}$$

Reaction of CH_4 with OH is the dominant loss term in the troposphere: other losses occur due to reactions with atomic chlorine [Cl] and decomposition by soil.

Using the value for the atmospheric burden of CH_4 found in part a) and a value of the total tropospheric loss of CH4 found by summing the soil, tropospheric Cl, and tropospheric OH terms in Fig. 1-9 of Paris: Beacon of Hope (also appears on slide 12 of Lecture 6), estimate $\tau_{\text{TROPOSPHERE}}$.

c) (5 points) Using a value for stratospheric loss of CH_4 read off the same figure, and the atmospheric burden found in a), provide an estimate of $\tau_{\text{STRATOSPHERE}}$.

Note: Atmospheric Burden appears in the numerator, rather than Stratospheric Burden or Tropospheric Burden, because we seek to know how long, on average, a particular molecule of CH_4 released to the <u>Atmosphere</u> will likely persist. Once air reaches the stratosphere, a particular molecule of CH_4 will have a greater chance of being removed, since there is so much less air in the stratosphere compared to the troposphere. However, the flow of air into the stratosphere is a slow process because mixing between tropospheric and stratospheric air masses is generally restricted by the permanent temperature inversion that marks the tropopause. Since we are interested in the overall atmospheric lifetime of CH_4, we use the atmospheric burden in the numerator of both terms.

d) (10 points) If a compound is lost in the troposphere and in the stratosphere, the appropriate way to find the overall lifetime is to evaluate the following expression:

$$\frac{1}{\tau_{\text{OVERALL}}} = \frac{1}{\tau_{\text{TROPOSPHERE}}} + \frac{1}{\tau_{\text{STRATOSPHERE}}}$$

Find the overall lifetime for CH_4 ***and*** compare your value for τ_{OVERALL} found here to various values for the lifetime of CH_4 that have been discussed in class. Please comment on which of these agrees best with your calculation and which is furthest from your calculation.

e) **633 students only (10 points)** There are certainly instances where scientists would like to know how rapidly CH_4 is lost in the stratosphere, once air has crossed the tropopause. In this case, the appropriate equation is:

$$\tau'_{\text{STRATOSPHERE}} = \frac{\text{Stratospheric Burden}}{\text{Stratospheric Loss Rate}}$$

where the prime denotes this is a different stratospheric lifetime.

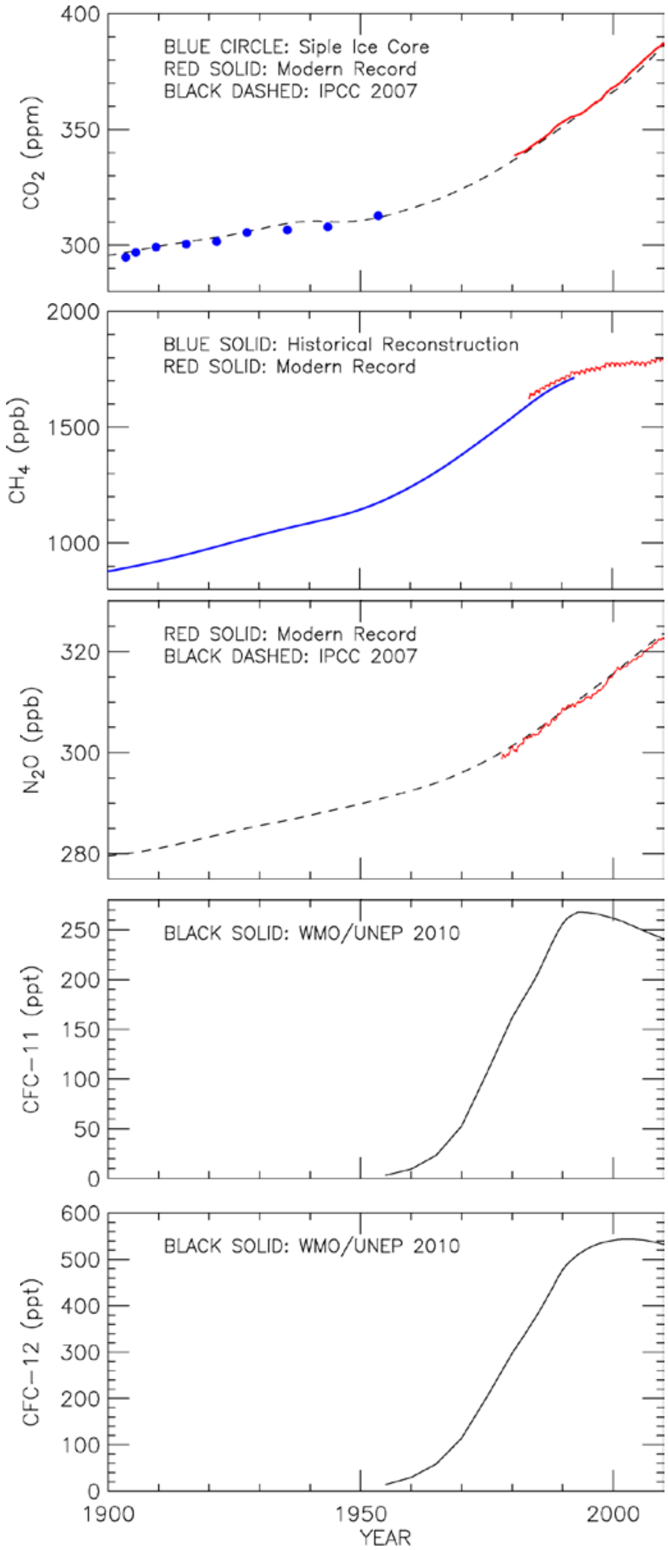
Provide an estimate of $\tau'_{\text{STRATOSPHERE}}$ for CH_4.

Note: To estimate the stratospheric burden of CH_4, you can multiply the atmospheric burden of CH_4 by the ratio of the mass of the stratosphere to the mass of the total atmosphere. Please try to figure out how to compute this multiplicative factor.

2. Radiative Forcing of Climate (95 points for 433, 105 points for 633)

This problem can be completed using material presented as of Lecture 7.

The figure below shows time series of CO_2, CH_4, N_2O, CFC-11, and CFC-12 from 1900 to 2010.



a) (20 points) Find the total change in radiative forcing (ΔRF) of the climate system, between years 1900 and 2010, due to CO_2, CH_4, N_2O, and halocarbons CFC-11& CFC-12.

Notes: Sum the RF terms for CFC-11 and CFC-12 to obtain RF due to halocarbons; this is a good approach since F-11 & F-12 are the most radiatively active halocarbons.

There are two options for obtaining ΔRF due to CH_4 and N_2O.

Students enrolled in 433 **may use may use either the graphical representation of the formula that accounts for the overlap between CH_4 and N_2O absorption bands that was shown in Lecture 7, or else may code up the various formula.**

Students enrolled in 633 **are asked to code up the various formula that accounts for the overlap between CH_4 and N_2O absorption bands that was shown in Lecture 7. Consider using a computational tool such as Excel, MATLAB, FORTRAN, IDL, or Python (i.e., whatever language that seems easiest).**

All students: however you solve the problem, please state the initial and final conditions for CH_4 and N_2O and the method used to calculate ΔRF.

Of course, remember to include CO_2 in your sum!

b) (10 points) We have seen Fig. 1.4 of *Paris: Beacon of Hope* repeatedly in class. This figure shows ΔRF of climate between 1750 and 2011 from IPCC (2013).

Compare and contrast your calculated values of ΔRF in part a) to those given in this figure.

Comment on whether it seems appropriate to compare your value of ΔRF found for 1900 to 2010 to the values on this figure, which is based on 1750 to 2011?

c) (20 points) Add the small contribution to ΔRF from tropospheric O_3 read off of Fig 1.4 to your sum found in part a). This quantity shall be called ΔRF_{GHG}.

The atmosphere undergoes external forcings due to processes other than GHGs. The most important other external forcing is due to tropospheric aerosols, formed following human release of particulate matter and certain gases due to deforestation and the combustion of fossil fuel. Seventy-one plausible scenarios for $\Delta RF_{AEROSOL}$ are shown in Fig. 1.10 of *Paris: Beacon of Hope.*

i) Provide an estimate of the UPPER LIMIT for the *absolute value* of $\Delta RF_{AEROSOL}$ from Fig. 1.10, over 1900 to 2010 (i.e., the *largest amount of aerosol cooling*). We shall refer to this term as $\Delta RF_{AEROSOL\text{-}UPPER\ LIMIT}$.

ii) Provide an estimate of the LOWER LIMIT for the *absolute value* of $\Delta RF_{AEROSOL}$ from Fig. 1.10, over 1900 to 2010 (i.e., the *smallest amount of aerosol cooling*). We shall refer to this term as $\Delta RF_{AEROSOL\text{-}LOWER\ LIMIT}$.

iii) Provide an estimate of the MEDIAN VALUE for the *absolute value* of $\Delta RF_{AEROSOL}$ from Fig. 1.10, over 1900 to 2010 (i.e., this is the *amount of aerosol cooling* denoted by the black line on the Aerosols panel of Fig. 1.10). We shall refer to this term as $\Delta RF_{AEROSOL\text{-}MEDIAN}$.

iv) Using the value for ΔRF_{GHG} found above, compute three values for total RF due to all human activities:

$\Delta RF_{HUMAN\text{-}1} = \Delta RF_{GHG} + \Delta RF_{AEROSOL\text{-}UPPER\ LIMIT}$

$\Delta RF_{HUMAN\text{-}2} = \Delta RF_{GHG} + \Delta RF_{AEROSOL\text{-}LOWER\ LIMIT}$

$\Delta RF_{HUMAN\text{-}3} = \Delta RF_{GHG} + \Delta RF_{AEROSOL\text{-}MEDIAN}$

d) (5 points) Based on a different figure in *Paris: Beacon of Hope*, how much did global mean surface temperature rise from 1900 to 2010? Please provide a single, numerical value, with appropriate units, denoted as $\Delta T_{1900\ \mathrm{to}\ 2010}$ and state the origin of this estimate.

e) (10 points) Estimate λ_{ACTUAL} of Earth's climate over the 1900 to 2010 time horizon: i.e., the sensitivity of surface temperature for RF, for each of the three values of ΔRF^{HUMAN} given in part c)

Please denote these three values as $\lambda_{ACTUAL\text{-}1}$, $\lambda_{ACTUAL\text{-}2}$, and $\lambda_{ACTUAL\text{-}3}$.

f) (5 points) If atmospheric CO_2 happens to double, how much will the <u>RF of climate</u> change? Note that here we are looking for a single numerical value.

g) (10 points) Estimate how much global mean surface temperature will rise, in response to a doubling of atmospheric CO_2, for each of the three values of λ_{ACTUAL} found in part e). Here assume that RF of climate responds only to rising CO_2 (i.e., assume CH_4, N_2O, etc, are constant). Note that here we are looking for three numerical values.

h) (5 points) In a few sentences, explain why your calculation in g) either <u>**supports**</u> or <u>**refutes**</u> the contention "it is much easier to understand the past than predict the future". Please use either the word "support" or "refute" in your reply.

i) (10 points) If we want to paint an optimistic future for the threat to humanity posed by climate change, which of the 71 plausible scenarios for total ΔRF due to anthropogenic aerosols shown in Fig. 1.10 should we hope is correct?

Please be specific by noting either color, or some numerical value, and also please write a sentence or two to justify your reply.

j) **633 students only (10 points)** Based on all of the above, what aspect of the climate system would enable a more accurate prediction of future global warming, if only we could obtain a precise measurement of this quantity? Please state what it is you would want to measure, and add a sentence or two noting how perhaps this quantity could be determined.

Upon completion of this problem … congrats, you are ready to become a climate modeler!