AOSC / CHEM 433 & AOSC 633

Problem Set #2 Due: Thursday, 28 February 2019 (at start of class)
433: 125 points; 633: 165 points

Late penalty: No late penalty for this Problem Set since some of the material helpful for completion will be covered in class on Tuesday, 26 February. We'll review this Problem Set on Monday, March 4, 5 pm, **in ATL 2428**. To receive credit for his Problem Set, your solutions must be turned in prior to the start of this review.

We'll return graded solutions on March 4 for anyone who turns in completed solutions by Friday, March 1 at 9 pm. On Friday, can either hand solutions to Ross (ATL 2403), Walt (ATL 4100), or place under Ross's door.

1. Atmospheric Lifetimes (433: 30 points; 633: 40 points)

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

In Lecture 6, we noted that the lifetime for the removal of a chemical compound can be described as the atmospheric burden divided by the loss rate: i.e.,

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

a) (5 points) Given the current volume mixing ratio for CH_4 of 1876.6 parts per billion (ppb) from NOAA presented on slide 10 of Lecture 6 (handout) and the mass of the atmosphere we have previously used, find the total atmospheric burden of CH_4, in units of terra gram (Tg).

Note: 1 Tg = 10^{12} gram ; 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:

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

Using the value for the atmospheric burden of CH_4 found in part a) and values of the tropospheric loss rate and stratospheric loss rate given on Figure 1-9 of Paris, Beacon of Hope (i.e., graph labeled "Global Methane Budget, 2000 to 2009" presented on Slide 11 of Lecture the graph labeled "Sources and Sinks of CH_4" shown on Slide 8 of Lecture 6 (handout), calculate the lifetime for removal of atmospheric CH_4 in both the troposphere and stratosphere.

Note: Atmospheric Burden appears in the numerator of both terms, 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 entire atmosphere 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 general 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.

Also, we'll ignore the fact that Fig 1-9 applies for different period of time that stops short of 2018, since the loss of CH_4 should not differ too much from year to year.

c) (10 points) If a compound is lost in the troposphere and in the stratosphere, the overall lifetime is given by:

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

Find the overall lifetime for CH_4 and, as always, please "show your work" rather than only stating an answer.

d) (5 points) Compare the value for τ_{OVERALL} found in part c) 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) <u>633 Students Only</u>: (10 additional 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 ***<u>and</u>*** comment on the "meaning" of this new lifetime, relative to the two lifetimes for CH_4 found in the prior section.

> **Note: One way to estimate the stratospheric burden of CH_4 is to multiply the atmospheric burden of CH_4 by the ratio of the mass of the stratosphere to the mass of the entire atmosphere. Pressure is proportional to the mass per unit area of the overlying atmospheric column. Knowledge of surface pressure and tropopause pressure should allow you to make an estimate the appropriate ratio.**

2. Radiative Forcing of Climate (433: 95 points; 633: 125 points)

Most of this problem can be completed using material presented as of Lecture 7, but material from Lecture 8 could be helpful for answering part iv) of c & d.

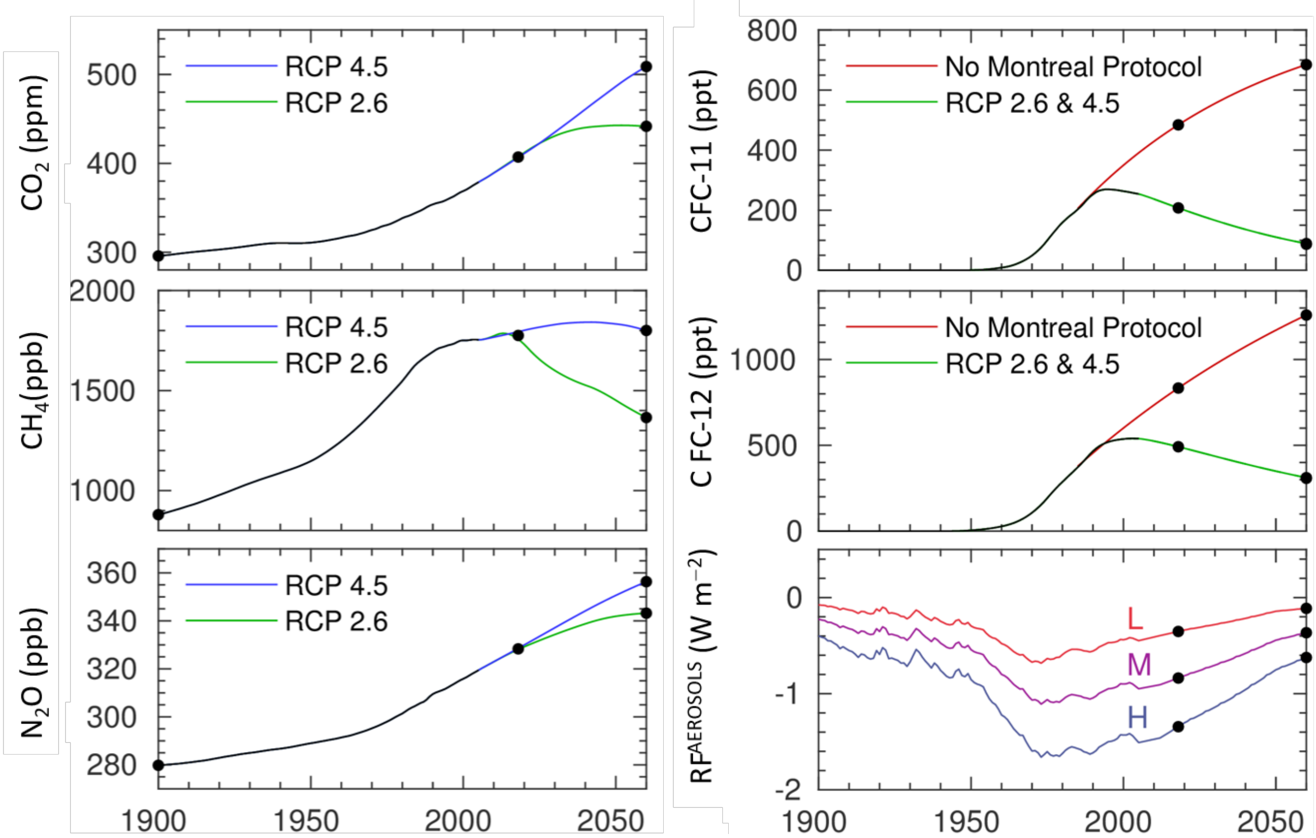
The figure below shows time series of the mixing ratio of CO_2, CH_4, N_2O, CFC-11, and CFC-12 from 1900 to 2060 for two scenarios, as well as the RF of climate due to tropospheric aerosols for three scenarios.

For CO_2, CH_4, and N_2O, mixing ratio time series from RCP 2.6 and 4.5 are shown, with circles denoting values of each species present in 1900, 2018, and 2060.

For CFC-11 and CFC-12, mixing ratio time series are identical for RCP 2.6 and RCP 4.5, since these compounds are controlled by the Montreal Protocol. The green line shows the expected decay of CFC-11 and CFC-12, given their atmospheric lifetimes of 52 and 102 years, respectively. The red lines for CFC-11 and CFC-12 show atmospheric mixing ratios that would have occurred without the Montreal Protocol, projected forward in time using the growth of production of each compound that existed in 1986, the year before the Montreal Protocol was signed, as described in the Concluding Remarks section of this paper published at the time the Protocol was being amended:

http://www.atmos.umd.edu/~rjs/class/spr2019/supplemental_readings/mcelroy_salawitch_1989.pdf

Finally, the last panel shows the RF of climate due to tropospheric aerosol for 3 of the possible 71 scenarios described by Smith and Bond (2014) : one with aerosol RF of climate in 2011 of -0.4 W m^{-2} (labeled "L" for low aerosol cooling), another with aerosol RF in 2011 of -0.9 W m^{-2} (labeled "M" for medium aerosol cooling), and a third **with aerosol RF in 2011 of -1.5 W m^{-2} (labeled "H" for high aerosol cooling)**.

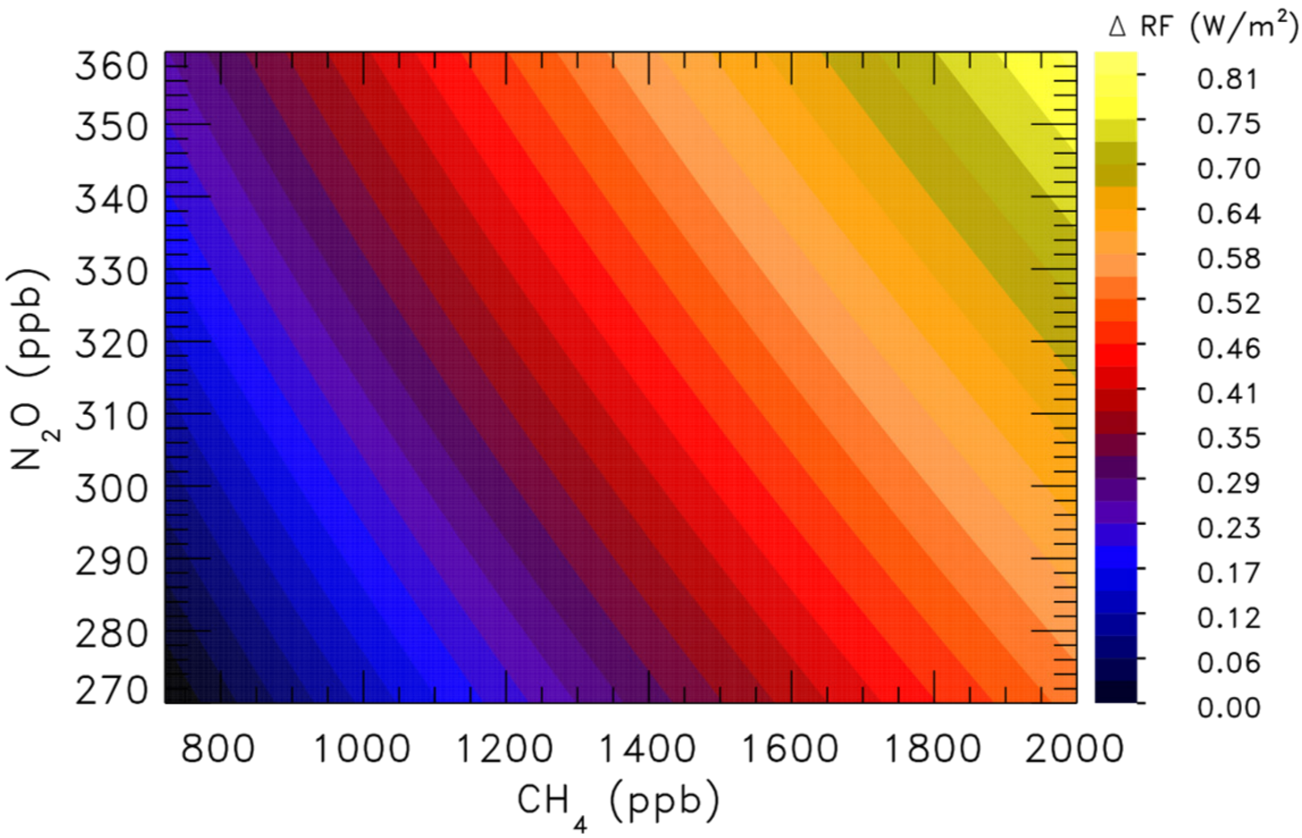


a) (20 points) Find the change in radiative forcing (ΔRF) of the climate system, between years 1900 and 2018 and also between years 1900 and 2060, due to CO_2, CH_4 & N_2O, CFC-11, as well as CFC-12. For the first time period, we'll assume the values of ΔRF for RCP 2.6 and RCP 4.5 are the same; these values can be found using the closed circles on the time series figure, which for 2018 "split the small difference" between RCP 2.6 and RCP 4.5. For the second time period, the values of ΔRF for RCP 2.6 and RCP 4.5 will of course differ

Compute the values of ΔRF, show your work, and ***place the results in the table on the next page***.

There are two options for obtaining ΔRF due to CH_4 & N_2O:

> ***Students enrolled in 433*** **are welcome to use the figure below, which shows numerical evaluation of the formula shown on slide 28 of Lecture 7 (handout), or by using this formula. If you choose to evaluate the formula, please follow the instructions for 633 students.**
>
> ***Students enrolled in 633*** **are asked to complete this problem via numerical evaluation of the formula shown on slide 28 of Lecture 7 (handout). For numerical evaluation, consider using a computational tool such as MATLAB, Python, FORTRAN, etc. However you evaluate the formula, please either "show your work" (if done by hand) or turn in a printout of your code, if completed in this manner.**
>
> **The correct version of the IPCC (2013) formula appears on the last page of this P Set.**



Also, as noted on the prior page, since CFC-11 and CFC-12 are controlled by the Montreal Protocol, the atmospheric mixing ratios for each compounds are identical for both RCP 2.6 and RCP 4.5. Please use the GREEN LINE for CFC-11 and CFC-12 for this part of the problem.

b) (5 points) Estimate ΔRF due to the rise in tropospheric O_3 by reading the value off of Figure 1-4 of *Paris, Beacon of Hope* (this figure has been shown numerous times, including slide 4 of Lecture 2 (handout)). Even though this value is for 1750 to 2011, let's assume it applies also to 1900 to 2018 because there was likely little change in the globally averaged RF due to tropospheric O_3 between 1750 and 1900, and between 2011 and 2018. Let's make a leap of faith and assume this same value also applies for 1900 to 2060.

Consequently, add the estimate for the ΔRF due to tropospheric O_3 to the table below. For sake of simplicity, the same numerical value should be used for all **three** cells that correspond to O_3 in the table.

Next sum ΔRF^{GHG} between years 1900 and 2018 and between years 1900 and 2060, by adding together the terms for CO_2, CH_4 & N_2O, CFC-11, CFC-12, and O_3 given in the table below.

	$\Delta RF^{\text{1900 to 2018}}$	$\Delta RF^{\text{1900 to 2060}}$	
GHG	RCP 2.6 & RCP 4.5	RCP 2.6	RCP 4.5
CO_2			
CH_4 & N_2O			
CFC-11			
CFC-12			
O_3			
ΔRF^{GHG}			

c) (20 points) The atmosphere undergoes forcings due to processes other than GHGs. The most important other forcing is release of pollutants that lead to the formation of aerosols in the troposphere; i.e., suspended particulate matter resulting from the combustion of fossil fuels, deforestation, and numerous other human activities.

First, copy the values for ΔRF^{GHG} from the prior table onto the table below.

Next, use the information present in the $RF^{AEROSOLS}$ panel of the first figure to fill in estimates of the ΔRF of climate due to tropospheric aerosols for each of the three scenarios (i.e., L, M, & H) for the time periods 1900 to **2018** and 1900 to 2060, in the table below.

Note, for the time period 1900 to 2060, the same values should be entered into the RCP 2.6 & RCP 4.5 columns.

	$\Delta RF^{\text{1900 to 2018}}$	$\Delta RF^{\text{1900 to 2060}}$	
GHG	RCP 2.6 & RCP 4.5	RCP 2.6	RCP 4.5
ΔRF^{GHG}			
$\Delta RF^{AEROSOLS}$ L			
$\Delta RF^{AEROSOLS}$ M			
$\Delta RF^{AEROSOLS}$ H			
ΔRF^{HUMANS} (Aer L)			
ΔRF^{HUMANS} (Aer M)			
ΔRF^{HUMANS} (Aer H)			

Finally, as we have enumerated several times in class, the total change in radiative forcing of climate due to humans is the sum of the perturbation due to rising GHGs and aerosols; i.e."

$$\Delta RF^{HUMANS} = \Delta RF^{GHG} + \Delta RF^{AEROSOLS}$$

Complete the last three rows of the table above, by combining the entry for ΔRF^{GHG} with the entries for $\Delta RF^{AEROSOLS}$.

d) (30 points … numbers) The rise in global mean surface temperature (ΔT) between 1900 and 2018 attributed to humans is 0.9°C (slide 45, Lecture 7 (handout)). This value has been placed in the appropriate box below.

First, copy the values for ΔRF^{HUMANS} from the prior table onto the table below.

Next, compute values of λ, the so-called climate sensitivity parameter first introduced in Lecture 4, based upon the value for ΔT over the time period 1900 to 2018 and the three possible estimates of ΔRF^{HUMANS} over this same period of time. Please show your work and be cognizant of units.

Third, compute values of the total feedback, f_{TOTAL}, that must have been present in the climate system for each of the three values of λ, again over the 1900 to 2018 time period.

Fourth, copy your values of λ that were found for 1900 to 2018 into the columns for 1900 to 2060. Here, we are assuming that whatever level of climate sensitivity had been inherent in the climate system over the time period 1900 to 2018 will persist out to year 2060.

Finally, for both RCP 2.6 and RCP 4.5, using the three entries for ΔRF^{HUMANS} over 1900 to 2060 combined with the climate sensitivity parameters for the three aerosol scenarios, estimate the rise in global mean surface temperature that will occur by year 2060, relative to 1900, for each of the aerosol scenarios.

	1900 to 2018	1900 to 2060	
GHG	RCP 2.6 & RCP 4.5	RCP 2.6	RCP 4.5
ΔRF^{HUMANS} (Aer L)			
ΔRF^{HUMANS} (Aer M)			
ΔRF^{HUMANS} (Aer H)			
ΔT	0.9°C	No entry here	No entry here
λ (Aer L)			
λ (Aer M)			
λ (Aer H)			
f_{TOTAL} (Aer L)		No entry here	No entry here
f_{TOTAL} (Aer M)		No entry here	No entry here
f_{TOTAL} (Aer H)		No entry here	No entry here
ΔT (Aer L)	No entry here		
ΔT (Aer M)	No entry here		
ΔT (Aer H)	No entry here		

e) (20 points … discussion)

i) If we assume for the sake of argument that the feedback ***due to changes in surface albedo*** over 1900 to 2018 is zero and that the combined feedback due to water vapor and albedo is 0.45 as discussed during Lecture 8, then what are the implications of your three values of f_{TOTAL} for the size and magnitude of the cloud feedback?

ii) If we assume again for the sake of argument the preferred result for RF of climate due to black carbon aerosols published by Bond *et al*., *JGR*, 2013 happen to be correct, then what is the outlook for the achievement of either the goal (1.5°C warming) or upper limit (2.0°C warming) of the Paris Climate Agreement, for both RCP 2.6 and RCP 4.5.

f) 633 Students Only: (30 additional points)

iii) The first figure of this problem set contained two estimates for the RF of climate due to CFC-11 and CFC-12: one for the RCPs and the other for a scenario for which industrial production and human use of CFC-11 and CFC-12 continued, unabated, at a growth rate based on analysis of trends up to year 1986.

First, complete the table below assuming this "world avoided" scenario for CFC-11 and CFC-12 had actually happened. This could have happened, for example, had CFCs been shown to not cause any harm to Earth's ozone layer. **For the entry of ΔT between 1900 to 2018, use the values of f_{TOTAL} for the "Aer M" case from table on prior page, combined with the new value for ΔRF^{HUMANS} over the 1900 to 2018 time period upon consideration of "world avoided" for CFC-11 and CFC-12, again for the Aer M case.**

	1900 to 2018	1900 to 2060	
GHG	RCP 2.6 & RCP 4.5	RCP 2.6	RCP 4.5
ΔRF^{HUMANS} (Aer L)			
ΔRF^{HUMANS} (Aer M)			
ΔRF^{HUMANS} (Aer H)			
ΔT		No entry here	No entry here
λ (Aer L)			
λ (Aer M)			
λ (Aer H)			
ΔT (Aer L)	No entry here		
ΔT (Aer M)	No entry here		
ΔT (Aer H)	No entry here		

Finally, based on this new completed table, ***offer some thoughts on whether environmentalists would have sought*** to control the growth of CFC-11 and CFC-12 due to the consequences for global warming of continued industrial production of these compounds ***at the 1986 rate***.

Corrected Formula

Table 8.SM.1 | Supplementary for Table 8.3: RF formulae for CO_2, CH_4 and N_2O.

Gas	RF (in W m^{-2})	Constant α
CO_2	$\Delta F = \alpha \ln(C/C_0)$	5.35
CH_4	$\Delta F = \alpha\left(\sqrt{M} - \sqrt{M_0}\right) - \left(f(M,N_0) - f(M_0,N_0)\right)$	0.036
N_2O	$\Delta F = \alpha\left(\sqrt{N} - \sqrt{N_0}\right) - \left(f(M_0,N) - f(M_0,N_0)\right)$	0.12

Notes:

$f(M, N) = 0.47 \ln [1+2.01\times10^{-5} (MN)^{0.75} + 5.31\times10^{-15} M (MN)^{1.52}]$

C is CO_2 in ppm.

M is CH_4 in ppb.

N is N_2O in ppb.

The subscript 0 denotes the unperturbed molar fraction for the species being evaluated. However, note that for the CH_4 forcing N_0 should refer to present-day N_2O, and for the N_2O forcing M_0 should refer to present-day CH_4.

IPCC Fifth Assessment Report, 2013