AOSC 680

Problem Set #1 (and only)　　　　Due: 29 Sept 2022 (at start of class)

Late penalty: 10 points per day late, unless there is a legitimate medical or extra-curricular activity circumstance ***brought to my attention prior to the due date!***

1. Effective Temperature (40 points): Can begin after Lecture 3.

Calculate the effective temperature of the Earth for the following cases. **Please show your work.**

a) (5 points) Current solar conditions (i.e., use the value of S given in class) and an albedo = 0.3 that we'll assume applies at the start of the sea-ice data record.

b) (10 points) As the Earth warms, snow and ice will melt. Indeed, scientists have reported a rather precipitous drop in so-called perennial sea ice in the Arctic ocean, as shown below:

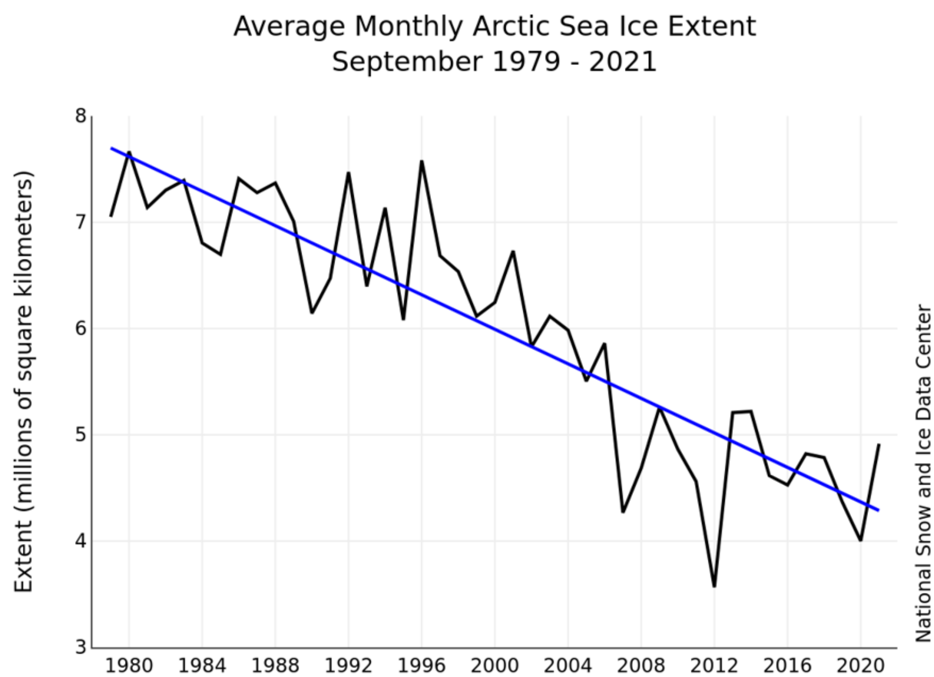

Figure from http://nsidc.org/arcticseaicenews/2021/10

Assuming that the albedo of the open ocean is 0.06, whereas the albedo of sea ice is 0.75:

https://tc.copernicus.org/articles/13/1695/2019/tc-13-1695-2019.pdf

and using the radius of Earth of 6370 km, estimate how much Earth's albedo would have changed, from the beginning of the Arctic Sea Ice Extent record (i.e., earliest part of blue line) to the end of this record (latest part of the blue line), based on loss of sea ice area. In your reply, **please state whether this change is either a rise or a fall in albedo.** Also, for this calculation, assume Earth's albedo was 0.30 at the start of the sea-ice data record shown above.

c) (10 points) Compute a new effective temperature for Earth, using the albedo found in part b)

d) (10 points) Compare the two effective temperatures found in a) and c), and state whether:

i) the difference is physically consistent with what you expect given the direction of the change in albedo

ii) there is genuine concern about the impact of melting Arctic sea ice on the habitat for polar bears and the ecology of the Arctic. Here, we would like your focus to be on the numerical calculations you have conducted. Consequently, state whether or not your calculations support the notion that loss of sea-ice is an ***important concern*** as a "feedback" (i.e., amplification) for the warming of climate due to rising levels of greenhouse gases (GHGs).

e) (5 points) Conduct a brief web search for how Earth's albedo has actually changed over time and assess whether or not the focus of this question (i.e., change albedo due to declining sea ice) has actually been realized?

If so, provide a direct URL link to this evidence.

If not, summarize in a sentence or two what other factors might be driving Earth's overall albedo.

2. Global Warming Potential (40 points): can begin after Lecture 2.

The global warming potential (GWP) equation for a gas, Z, can be written as follows (you may want to review your notes and/or the appropriate reading for the definition of terms):

$$\mathrm{GWP} = \frac{\int_0^{\mathit{Time\ Horizon}} a_Z \times [Z(t)]\, dt}{\int_0^{\mathit{Time\ Horizon}} a_{CO2} \times [CO_2(t)]\, dt}$$

The time dependent response, Z(*t*), to an injection into the atmosphere of a "unit pulse" of a gas is often written as a simple exponential decay:

$$Z(t) = Z_o\, e^{\frac{-t}{\tau}}$$

where τ is the atmospheric lifetime and Z_o is the initial abundance of the gas in question

a) (15 points) Integrate the expression for Z(t), from an initial time of zero to a final time of T_{FINAL}. and state the units of the resulting expression for this integral.

b) (15 points) Find the GWP for gas Z over time horizons of 20, 50, and 100 years, using the information in the following table and assuming that:

- Gas Z is 80 times more *radiatively efficient* than CO_2 (on a per mass basis)
- the atmospheric lifetime of Z is 12 years
- the value for Z_o is 1000 kg
- the following numerical values apply for release of 1000 kg of CO_2

Time Horizon (yrs)	$\int_0^{\mathit{Time\ Horizon}} [CO_2(t)]\, dt$ (kg • year)
20	14,400
50	28,900
100	48,500

State your answers and please ***show your work*.**

c) (5 points) Explain why the numerical values for the GWP of Gas Z vary in the manner you have found in part b).

d) (5 points) Suppose you are asked to testify on behalf of a progressive organization such as the Sierra Club, on the environmental effects of gas Z, particularly in relation to global warming. Specifically, a proposal has been put forth to use gas Z in an emergent industry, and the application will likely lead to some leakage of gas Z to the atmosphere.

If the policy goal is to restrict the rise of global T relative to pre-industrial to no more than 1.5°C *at any time in the future*, which ***time horizon*** for the GWP for gas Z would you use in your testimony? State the time horizon followed by a sentence or two to support this decision.

3. Atmospheric Lifetimes (40 points); can start now, but may not want to complete until after Lecture 6.

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

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

a) (5 points) Given a volume mixing ratio for CH_4 of 1.9 parts per million (appropriate for year 2021 as stated at:

https://cen.acs.org/environment/greenhouse-gases/Atmospheric-levels-methane-post-record/100/i13

and using the mass of Earth's atmosphere given in Lecture 1, find the total atmospheric mass of CH_4 in units of terra gm (Tg).

Notes: 1 Tg = 10^{12} gm

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The lifetime for removal of atmospheric CH_4 in the troposphere can be found from:

$$\tau_{\text{TROPOSPHERE}} = \frac{\text{Atmospheric Mass of CH}_4}{\text{Tropospheric Loss Rate}}$$

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

$$\tau_{\text{STRATOSPHERE}} = \frac{\text{Atmospheric Mass of CH}_4}{\text{Stratospheric Loss Rate}}$$

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.

b) (10 points) Compute $\tau_{\text{TROPOSPHERE}}$, using the value for the atmospheric mass of CH_4 found in part a) as well as a value of the total tropospheric loss of CH_4 found by summing the soil, tropospheric Cl, and tropospheric OH terms shown in Figure 1-9 of *Paris Climate Agreement: Beacon of Hope* https://link.springer.com/content/pdf/10.1007/978-3-319-46939-3_1.pdf

c) (5 points) Compute $\tau_{\text{STRATOSPHERE}}$, using the value for the stratospheric loss of CH_4 read off of Figure 1-9 of *Paris Climate Agreement: Beacon of Hope*.

Note: The *Atmospheric* Mass of CH_4 appears in the numerator of the expression for $\tau_{\text{STRATOSPHERE}}$, rather than Stratospheric Burden, because we seek to know how long, on average, a particular molecule of CH_4 released into the *Atmosphere* will likely persist. Once air reaches the stratosphere, a particular molecule of CH_4 in this air mass will have a greater chance of being removed, compared to the removal time in 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 mass in the numerator of both terms.

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

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

First, compute τ_{OVERALL} using values for $\tau_{\text{TROPOSPHERE}}$ and $\tau_{\text{STRATOSPHERE}}$ from parts c) and d).

Next, compare your value for τ_{OVERALL} 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) (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:

$$\tau'_{\text{STRATOSPHERE}} = \frac{\text{Stratospheric Mass of CH}_4}{\text{Stratospheric Loss Rate}}$$

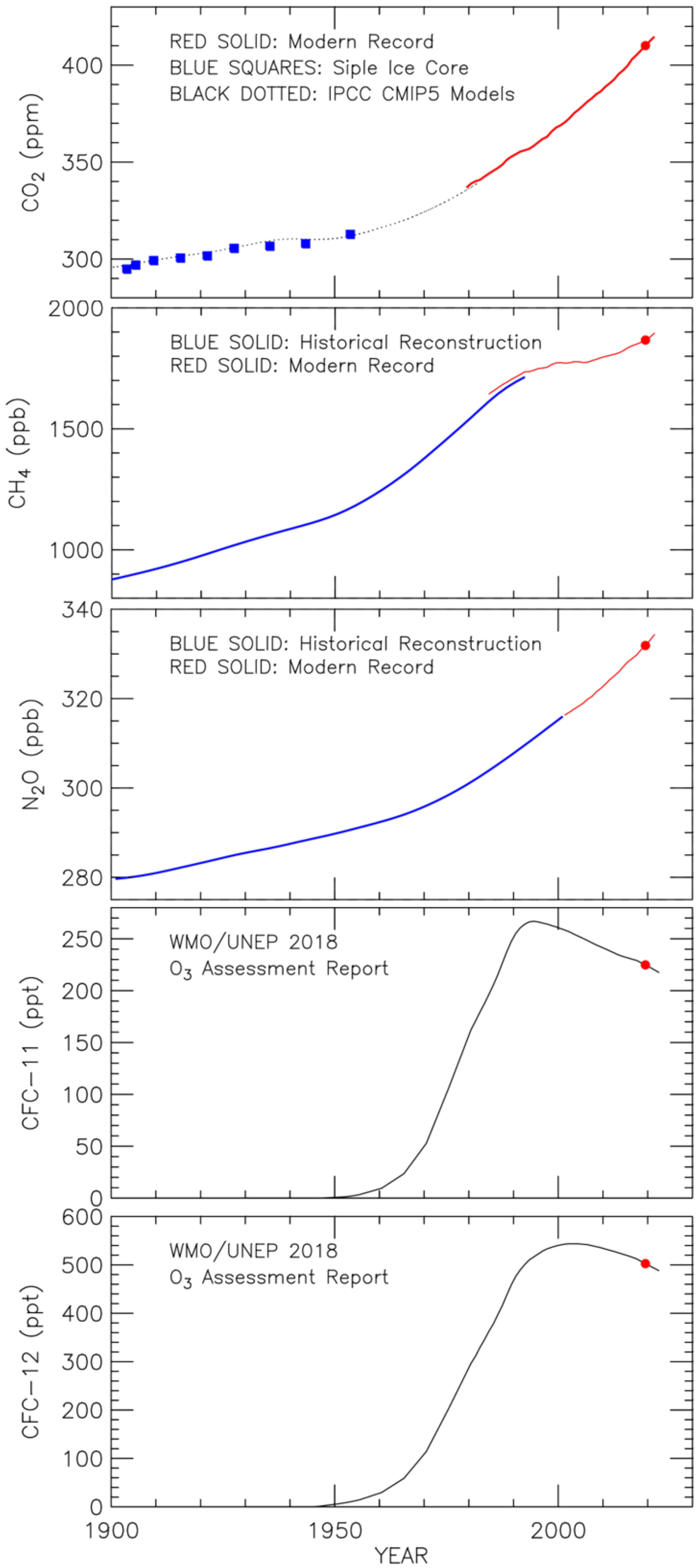
where the prime denotes this is a different stratospheric lifetime.

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

> **Note: To estimate the stratospheric mass of CH_4, you can multiply the atmospheric mass of CH_4 by the ratio of the mass of the stratosphere to the mass of the entire atmosphere. You should be able to estimate the mass of the stratosphere, relative to the mass of the entire atmosphere, based upon knowledge of the mean pressure of the tropopause, since the tropopause lies between the troposphere and the stratosphere. If you are confused about how to use tropopause pressure in this calculation, please review the definition of atmospheric pressure described in Lecture 3.**

4. Radiative Forcing of Climate (100 points) Can start now, but may not want to complete until after Lecture 7.

Figure shows time series of CO_2, CH_4, N_2O, CFC-11, and CFC-12 from 1900 to 2021, with values in 2019 marked by the red circle.



a) (20 points) Using values for the abundance of various gases read off of the figure, find **the total change in radiative forcing (ΔRF)** of the climate system, between years 1900 and 2019, due to:

CO_2, CH_4, N_2O, and the 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.**
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> **For the ΔRF due to CH_4 and N_2O, you 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).**
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> **Of course, remember to include CO_2 in your sum!**

b) (10 points) We have seen Figure 7.6 from IPCC (2021) that shows ΔRF of climate between 1750 and 2019 numerous times in class.

Compare and contrast your calculated values of ΔRF in part a) to those given in Figure 7.6.

> Here, we will assume humans exerted only a tiny influence on climate between 1750 and 1900, so any differences you find should be attributed to some factor other than a different start date.

c) (20 points) Add the small contribution to ΔRF from tropospheric O_3 read off of Fig 7.6 of IPCC (2021) to your sum found in part a). This quantity shall be called $\mathbf{\Delta RF_{GHG}}$.

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 of *Paris: Beacon of Hope*, over 1850 to 2019 (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 1850 to 2019 (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 1850 to 2019 (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, and assuming 1750 to 2019 is equivalent to 1850 to 2019 is equivalent to 1900 to 2019, 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 figure shown in class, by how much did global mean surface temperature rise from 1900 to 2019? Please provide a single, numerical value, with appropriate units, denoted as $\Delta T_{1900\ to\ 2019}$ ***<u>and</u>*** state the origin of this estimate.

e) (10 points) Estimate three possible values of λ_{ACTUAL} of Earth's climate over the 1900 to 2019 time horizon: i.e., compute 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 $\lambda_{ACTUAL-1}$, $\lambda_{ACTUAL-2}$, and $\lambda_{ACTUAL-3}$.

f) (5 points) If atmospheric CO_2 happens to double relative to the pre-industrial level, how much will the **RF of climate** 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 that CH_4, N_2O, etc, are constant). Here, we are looking for *three numerical values*.

h) (5 points) In a few sentences, explain why your calculation in g) either **supports** or **refutes** 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) (5 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 of *Paris Climate Agreement: Beacon of Hope*, which 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) (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!