NATS 1750 A (Fall 2017): Assignment 2, Version 1.0 - November 11, 2017

Due: December 4, 2017 by 11 pm EST via Moodle, no late penalty until December 12, 2017

(Late Penalty: 25% per day - including weekends. Strictly enforced.)

Instructions:

- You are expected to provide answers for *every* question. You are encouraged to show all of your work so that marks can be awarded for partially correct answers.
- Although you are encouraged to collaborate with your classmates, each of you is expected to submit a separate and distinct assignment - a point that will require acknowledgement upon submission.

Earth's present atmosphere is theorized to have evolved from one based upon outgassing of the planet's interior.

Consider that period in Earth's history when outgassed water vapour has condensed to form a significant ocean. During this same period, suppose that there are only two mechanisms for removing CO_2 from Earth's atmosphere - namely photosynthesis and dissolution. (Note: CO_2 is dissolved into water through the process of dissolution.)

1. Given that the metal Calcium Oxide (CaO) is abundant in Earth's crust, and reacts with CO_2 according to the following chemical reaction

   $$CaO(s) + CO_2(g) \rightarrow CaCO_3(s),$$

   provide a process-flow representation for this mechanism that *removes* CO_2 from Earth's early atmosphere. (Note: $CaCO_3$ forms as a **precipitate** - i.e., a solid that forms from a solution.) [3 marks]

2. Suppose the product of the mineral carbonation (carbonation is the process of dissolving carbon dioxide in liquid) reaction detailed in Question 1 above:
   a. Precipitates at a rate of 2 cm/yr. How long will it take for a 0.5 m layer to accumulate? [3 marks]
   b. Produces sediment that is compacted to a 4.5:1 ratio during lithification process - e.g., due to burial pressure. Determine the resulting thickness of the originally 0.5 m layer accumulated in Question 2(a). [3 marks]
   c. Produces spheres of $CaCO_3$ with a radius of 2 mm.
      i. Determine the corresponding terminal velocity (in m/s) of these spheres in water from $\mathbf{v_T \approx (151\ r)^{1/2}}$, where r is the radius in m. [3 marks]
      ii. Assuming and ocean depth of 2 km for an off-shore operation, calculate

the settling time - i.e., the time it takes each of the spheres to descend through the ocean and settle out as sediment. [2 marks]

3. After the process of lithification completes, what is the resulting class and type of sedimentary rock? Obtain a photograph of a representative sample of this rock. (Note: Please attempt to provide an original photo. If you are unable to do so, please indicate your source. Note that you may be audited to prove originality.) [4 marks + 2 bonus marks for an original photo.]

4. Enhance your Question 1 process-flow diagram to account for Question 3. [3 marks]

Over the past 400,000 years, but excluding the past 200 years, paleoclimatological evidence suggests that the concentration of CO_2, i.e., [CO_2], has barely exceeded 300 ppm.

5. Calculate the percentage reduction in the [CO_2] from volcanic-outgassing levels to this peak value of 300 ppm. (Note: Volcanic-outgassing levels for CO_2 are provided in the "Appendix" below.) [3 marks]

Inspired by the results of Question 5, an interdisciplinary team undertakes to geoengineer the sequestration of CO_2 through very-large-scale mineral carbonation (VeLaMiCarb). (Geoengineering is a direct manipulation of the Earth system.) The VeLaMiCarb team's approach includes isolating the resulting precipitate (i.e., $CaCO_3$(s)), and ultimately burying it in underground vaults impermeable to groundwater.

6. Obtain [CO_2] versus time data for the past 5 years from the Mauna Loa Observatory. (Note that you can download a high-quality version of this graphical plot in various formats. See "Resources" below for access information.) [2 marks]

7. Using the graphical plot acquired in Question 6:
    a. Estimate the current [CO_2] in ppm. [1 mark]
    b. Estimate the annual increase in the [CO_2]. Include an annotated version of the plot in your solution that illustrates how this rate was calculated. [5 marks]

8. Based on your answer to Question 7(b), determine how long it will take the current value of [CO_2] to double. (This will subsequently be referred to as the "2x[CO_2] climate scenario".) [3 marks]

9. Suppose the EBCM-determined energy,[1] E_{2CO2}, associated with this doubling of the [CO_2] is 1423.9 W/m^2. Estimate the temperature difference, resulting from the 2x[CO_2] climate scenario, using the Stefan-Boltzman Law $\mathbf{T = (E_{2CO2}/4\sigma)^{1/4} - T_0}$, where σ and T_0

[1] EBCM is a very simple climate model originally developed for NATS 1780 (Weather and Climate). Additional information is provided via the "Resources" below.

are the constants 5.67x10^{-8} W/$m^2 \cdot K^4$ and 275.8 K, respectively. [3 marks]

10. Rahmstorf (see "Resources" below) estimated that temperature differences account for sea-level changes according to the proportionality constant 3.4 mm/yr per °C. Using the temperature difference obtained in Question 9, estimate the change in sea level for the time span obtained as the answer to Question 8 - i.e., for the 2x[CO_2] climate scenario. [3 marks]

11. Estimate the wavelength of maximum intensity corresponding to Earth radiating as a black body in the 2x[CO_2] climate scenario using Wien's Displacement Law, $\boldsymbol{\lambda_{max} = w/T}$, where w = 2897 x 10^{-6} m·K. [3 marks]

12. In which part of the EM spectrum (below) is Earth radiating under the 2x[CO_2] climate scenario? What is the fate of this radiation? [3 marks]

13. Suppose the current estimate for the [CO_2], i.e., the answer to Question 7(a), corresponds to storage of 775 GtC in Earth's atmosphere. (1 GtC is a GigaTon of C.) If the intention of the geoengineered sequestration of CO_2 is to *completely offset* the effect of the 2x[CO_2] climate scenario, what should be VeLaMiCarb's target for C removal over the time frame dictated by your answer for Question 8 above? Explain. [3 marks]

14. It is stated that: "The VeLaMiCarb team's approach includes isolating the resulting precipitate (i.e., $CaCO_3$(s)), and ultimately burying it in underground vaults impermeable to groundwater." Why is groundwater isolation an important design consideration? (Hint: The rock type identified in Question 3 is highly susceptible to acid rain.) [2 marks]

15. Enhance your Question 4 process-flow diagram to account for the VeLaMiCarb approach. [3 marks]

16. Does this VeLaMiCarb initiative favour the importance of a systems-based approach? Explain. [2 marks]

17. Why might geoengineering, along the lines of the VeLaMiCarb initiative, become a necessity? Explain. [5 marks]

Resources

Lumb, I., NATS 1780 lecture on "Climate and Climate Change", Slides | Capture (start - 1:08:54), 24 November 2016. (Includes background, optional content on EBCM.)

Lumb, I., NATS 1780 lecture on the "Origin and Evolution of Earth's Atmosphere", Slides | Capture (1:08:54 - end), 24 November 2016. (Includes background, optional content.)

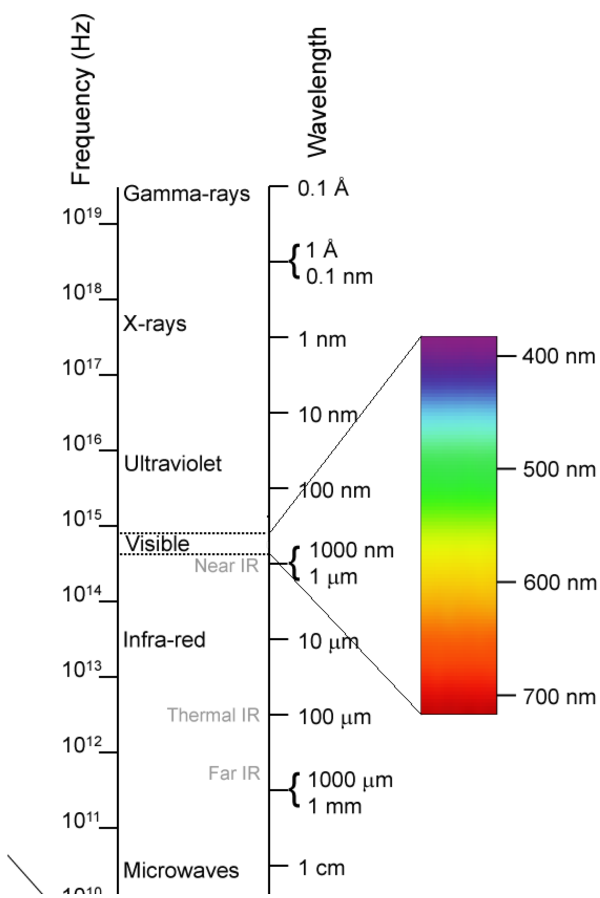
NOAA Earth System Research Laboratory, Trends in Atmospheric Carbon Dioxide. Available online at https://www.esrl.noaa.gov/gmd/ccgg/trends/.

Rahmstorf, S., A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Science, **315**, 368-370, 2007. Available online at http://science.sciencemag.org/content/315/5810/368. (Includes background, optional content.)

Appendix

Volcano Halemaumau (Hawaii) [% by volume]

H_2O ~ 68%, CO_2 ~ 13%	N_2 ~ 8%, SO_2, H_2S, etc. ~11%



A portion of the electromagnetic (EM) spectrum.

