

ESS 312 Geochemistry

Simulating Steady State: The Carbon Cycle and the Effect of Burning Fossil Fuels

Objectives:

Many problems in earth sciences involve understanding how mass is transferred among different geochemical reservoirs (e.g., Carbon transfer from biosphere to atmosphere). In this lab we will explore mass balances and how multiple systems evolve when there is mass flux both out of and into each system, and how those systems respond when the balance is upset.

Using Excel simulations of how carbon is exchanged between the atmosphere, biosphere and shallow ocean, you will explore three important concepts:

Steady state behavior

Residence time

Reaction of steady-state systems to a perturbation

Introduction:

CO₂ is the most important of the “greenhouse” gases produced by human industrial and agricultural activity. The global annual emissions of CO₂ (primarily from fossil fuel burning and cement production) have increased from 0.1 Gt (Gt = gigatons = 1 billion or 10⁹ tons) of C per year in 1860 to approximately 6.0 Gt C/year in 1990. Estimates of future emissions are necessarily heavily dependent on models of economic growth, population growth and political stability. Predictions for emissions by the year 2100 range from present values to 36 Gt C/year.

Atmospheric CO₂ has the characteristic that it strongly absorbs infrared radiation given off from the earth’s surface. This energy is reradiated back to the earth, thus maintaining the surface temperature of the earth. An increase in CO₂ may enhance this effect, thus causing general warming. Although fraught with uncertainties and very difficult to calculate, the surface temperature effect of increasing CO₂ is estimated to be 1.5 – 4.8°C for a doubling of atmospheric CO₂.

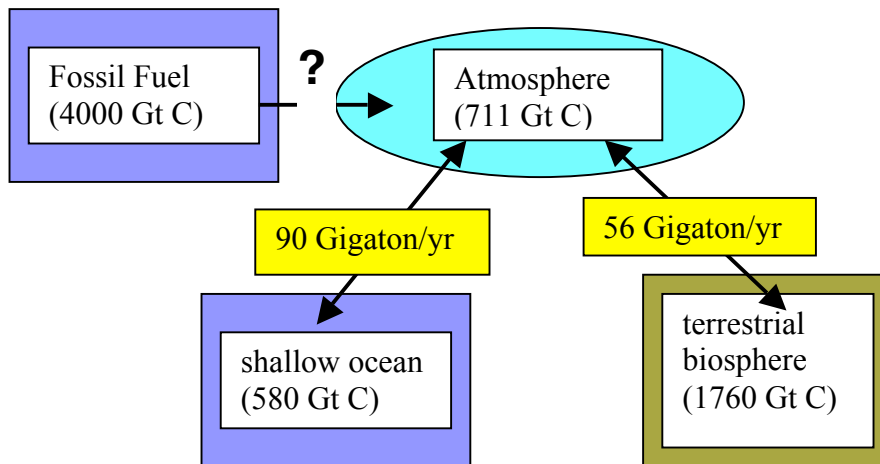
The influence of human activity on climate change is a fascinating, complex and important problem. An excellent source of information, data and model predictions is the Intergovernmental Panel on Climate Change (the IPCC) sponsored by the United Nations. Many international teams of scientists have been working together to produce 5-year reports evaluating many aspects of climate change including, of course, CO₂ emissions. Start at their web site <http://www.ipcc.ch/> where you can view summaries of their reports, technical and policy papers, and order specific documents. The site is well worth a visit.

Modeling the C cycle:

For the past 40 years the concentration of CO₂ in the atmosphere has been measured at the weather observatory on Mauna Loa volcano, Hawaii. From 1959 through 1990 the

increase in CO₂ carbon in the atmosphere was 81 Gt. However, over this same period of time at least 135 Gt C was released into the atmosphere by burning fossil fuels. Where is the missing C? On average, how long does anthropogenic C remain in the atmosphere? If we suddenly restrict the burning of fossil fuels to present levels (one option discussed at the Kyoto meeting) will the CO₂ concentration of the atmosphere decrease, remain the same, or continue to rise? Answering these questions depends on being able to model the carbon cycle. In this lab we will take a very simplistic approach that will not be very useful for predicting reality, but will be extremely useful for exploring and understanding the concepts required in building models of adequate complexity to model reality.

Over time-scales of human existence there are three important reservoirs in the carbon cycle: the atmosphere, the biosphere, and the shallow (<1000 m) oceans. The atmosphere exchanges C with both the biosphere and the oceans. It is not unidirectional; there are fluxes both in and out of each of these reservoirs. We can consider fossil fuels as a fourth C reservoir that is leaking into the atmosphere as a result of human exploitation.



Use the values for reservoir size and exchange rates given in the diagram above. The two-way arrows indicate exchange. For example, while the atmosphere provides 90 Gt C/year to the shallow ocean, it also takes up 90 Gt/year from the ocean.

We will use the following notation in our calculations and spreadsheets:

A_0 is the initial mass of C in the reservoir.

A is the mass of C at any time t .

F_{in} and F_{out} are the fluxes in and out of a reservoir per year.

k is the constant proportion of C *removed* from a reservoir each year.

An important assumption in all of the modeling that follows is that the proportion of flux (k) out of each reservoir is constant.

There are three parts to this lab. Please carefully follow directions and steps. You are provided with an Excel spreadsheet template to help make this more efficient. For each part of the lab, there is a different section of the template to work on. Each part of the template has a box model diagram describing the process you will model. Cells where you enter calculations are highlighted in color.

1. Unidirectional Transport (calculations start in column A):

- 1.1 Calculate the k value for the atmosphere. (Enter these calculations into column G). Note that one cannot define k for the ocean or biosphere since in this model nothing leaves. In effect, the residence time in these two reservoirs is infinite.
- 1.2 For the moment, we will assume that the only process is unidirectional removal of C from the atmosphere. Write an expression for the change in C mass in atmosphere with time, i.e. $dA/dt = ?$ (enter the expression – not a calculation – in C2)
- 1.3 Make a spreadsheet simulation that keeps track of the Carbon in each of the three reservoirs over 100 years. (Enter calculations in columns B, C and D). Add plots for Carbon mass versus time for the atmosphere, ocean and biosphere. (Fit these plots in rows E through J). A check on your work is to verify that the total amount of C in the whole system is constant.
- 1.4 How much time is required for the atmosphere to lose half of its C?
- 1.5 By now, this should remind you of something you've worked with in previous labs. Starting with your equation in 1.2, derive an exact equation that permits calculation of how much time is required for the atmosphere to lose half of its carbon. Compare with your spreadsheet simulation.

Provide a print-out of columns and graphs generated for Part 1.

2. Bidirectional Transport (calculations start in column K):

Now let's consider just the exchange between the atmosphere and the ocean (with the possibility for addition of C to the system by burning fossil fuel).

In a reservoir at steady state, $dA/dt = 0$. This means that $F_{in} - F_{out} = 0$. For all of the subsequent modeling, we will assume that the entire system we are analyzing starts at steady state, which means that for each reservoir the flux out equals the flux in at time zero, and until the system is perturbed.

- 2.1 Write two expressions for dA/dt (the flux) in terms of reservoir mass and k ; one for the atmosphere and one for the ocean. (Place the calculations for k in column P).

Residence time refers to the average amount of time a particle spends in a reservoir, in this case the average amount of time C resides in the atmosphere before being removed by some process. Residence time is defined as:

$$\tau = \frac{\text{amount in reservoir}}{\text{annual flux removed}} = \frac{A}{dA/dt}$$

2.1(a) Mathematically and in words, what is the relationship between k (proportion removed per year) and τ (residence time)?

2.1(b) Calculate the residence time of carbon in each of the two reservoirs. (Enter these calculations into column Q).

2.2 Set up five more columns on your spread sheet that keeps track of years (column K), anthropogenic C input (column L), C mass in atmosphere (column M), C mass in ocean (column N) and the ratio of C in the atmosphere to C in the ocean (column S). Use the expression from 2.1 to calculate atmosphere and ocean C masses. Set up the simulation for a time-span of 100 years and start with the human input set to zero. (hint: if you've done the programming correctly, you should see no change with time because we started by assuming steady state).

2.3 In year 6, put a one-time shot of 15 Gt of C into the atmosphere from fossil fuel burning. Make three graphs (fit them in columns O through R): atmosphere C vs. time, ocean C vs. time and the atmosphere/ocean C ratio vs. time (the template for this last plot is already provided in column V). (Provide a print out of these graphs and simulations; adjust scales on graphics as needed for clear presentation).

2.4 Discuss how the human perturbation affected the atmosphere and oceans. How long does it take for the system to return to steady state? What factors control the response time of the system? (you might play with values of k to get a sense of this).

2.5 Try out some other rate of fossil fuel burning to see how the systems respond. For example, you might try starting with 15 Gt in year 6 and increase the rate by 2% per year for 10 years, and then decrease the rate by 2% per year. Make sure that you put the increase and decrease rates in separate cells (L3 and L4) above your simulation so that you can change these rates just by changing the value in one cell.

3. Transport among three reservoirs (calculations start in column AC):

Remember that we are assuming the *proportion* of C removed from each system is always constant.

3.1 Write three expressions for dA/dt in terms of fluxes and k for 1) atmosphere, 2) ocean and 3) biosphere. (Enter k and residence time calculations in AJ and AK).

3.2 Set up six more columns in your spreadsheet, similar to what you did for 2.2 but add a column for C mass in the biosphere. (year, human input, atmosphere, biosphere, ocean go in AC, AD, AE, AF and AG, and atmosphere/ocean ratio goes in column T) Start with human input set to zero. Check for steady state.

3.3 In year 6, put a one-time shot of 15 Gt of C into the atmosphere from fossil fuel burning. Templates for three graphs are provided in column AI: atmosphere C vs. time, ocean C vs. time, and biosphere C vs. time. The atmosphere/ocean C ratio for this simulation is plotted on the same graph as for the bidirectional simulation for easy comparison (*provide a print out of these graphs and simulations*).

3.4 Discuss how the human perturbation affected the atmosphere oceans and biosphere. How long does it take for the system to return to steady state? What factors control the response time of the system? (you might play with values of k to get a sense of this).

3.5 Describe the differences (or similarities) for how the atmosphere and oceans responded to the human input with and without the presence of the third reservoir. In particular, explain the interesting behavior of C in the oceans. It would be useful to refer to your graph of the ratio of atmospheric to ocean C through time.

3.6 Set up a scenario in which human inputs increase from 15 Gt at year 6 by 2% per year for 20 years, and then decrease by 2% per year for all years thereafter. Again, set up the equations so that they refer to a single cell for increase and decrease rates (AD2 and AD3) so they can be easily changed for other simulations.

3.7 If you want the atmospheric C content to be no more than 900 Gt by the 80th year, what would you have to change the decrease rate to? (Use the graphical interface; on the plot of atmospheric C pull down the point at year 80 to a value of 900 (or whatever you want it) and then tell Excel (in the box that should pop up) to adjust the value in your cell containing the rate of decrease (AD3) until it achieves this goal).