(1) How might you label the boxes below if you’re modeling the inventory of carbon in the ocean? Your input comes from river sources and your output comes from carbon burial.

(2) If the system described above in the box model is at steady state, what does that mean with respect to inputs and outputs?
Introduction
At any given time, the inventory of an element in a reservoir (like the ocean or the atmosphere) is defined as the input (sources) minus the output (sinks). When the input of an element into the reservoir is equal to the output of that element from the reservoir, the reservoir is at steady state. At steady state, the residence time of an element in a reservoir is defined as the inventory (amount in the reservoir) divided by the flux (rate at which the element entering or exiting the reservoir on units of amount per time):\

\[ \tau = \frac{I_o}{q} \]  

where \( \tau \) = residence time (years) \( I_o \) = Inventory of element (moles) \( q \) = Flux (moles/year)

Part 1: An Oceanic Carbon Box Model
On geologic timescales, carbon enters the oceans primarily through riverine input. Carbon exits the ocean by being deposited on the ocean floor (and subsequently buried), either in the calcium carbonate shells of foraminifera and coccoliths or as organic carbon. Calcium carbonate shells (inorganic carbon) and organic carbon are deposited on the ocean floor in a 4:1 ratio (i.e., \( 4C_{inorg} \) for every \( 1C_{org} \)).

Box model components:
Ocean box inventory of carbon: \( I_o \)
Input to ocean box:
River Flux of carbon from continents: \( C_r \)
Output from Ocean Box:
Organic Carbon Flux \( C_{org} \)
Inorganic carbonate carbon flux \( C_{carb} \)

Initial conditions of your model:
Ocean box inventory of carbon = \( I_o \) = ?
Input:
River Flux of carbon from continents = \( C_r \) = 2.00 x 10^{13} moles/year
Output:
Ratio of \( C_{inorg} / C_{org} = R = 4.00 \)
Organic carbon flux = \( C_{inorg} / R = -4.00 \times 10^{12} \) moles / year
Inorganic (carbonate) carbon flux = -10 x (5.05 x 10^{-6}) moles/year
(bulk burial rate = Organic carbon flux + Carbonate carbon flux moles/year)

Notice that the sources are positive and the sinks are negative. **In STELLA, make all your fluxes positive, because it is a box-modeling program and recognizes that inputs are positive and outputs are negative.**

Questions
1. Draw a box diagram of the oceanic carbon cycle using STELLA (take a deep breath and don’t panic because we will do this together). Construct a graph to watch the output of the model
(again, we will do this together). Your graph should include lines for ocean inventory, 3 fluxes, and bulk burial rate. Make sure your model runs for 5.1 million years and in time intervals (DT) of 100,000 years.

**Print (or save to .pdf) your graph and model** to turn in with your lab report.

You have just created a model that shows the system at steady state without perturbations. How long does it take for the ocean to reach steady state? What is the inventory of the ocean, \( I_o \), when the system is at steady state? **Record this value and go back and change your Ocean reservoir value in the model to reflect this inventory.**

2. What is the residence time of carbon in the ocean given \( I_o \)? Show your work.

3. Now, we’re going to perturb our system. It is thought that the uplift of mountains (like the Himalayas) over geologic time may have increased continental weathering, thus increasing river flux of carbon to the oceans. Changes in the river flux of carbon can have an important effect on carbon in the oceans and on how it is exported from the oceans.

   a) At time equals 1.1 million years, increase the river flux of carbon instantaneously to twice the initial value in your model, and keep it at this new value for the rest of the time. What happens to the ocean inventory of carbon? What happens to the burial rate of \( \text{CaCO}_3 \) (aka., inorganic carbon)?

      To double the river flux starting at 1.1 million years, use the following “if, then, else” statement in a converter equation box:

      \[ \text{IF(time} \geq 1.1E6) \text{ THEN} (2.0E13) \text{ ELSE(0)} \]

   b) How long does it take for the ocean to reach steady state again?

   c) **Print the model and graph** of the system’s response to the perturbation over 5.10 million years.

4. At different times in the geologic past (and actually in different places in the world ocean today, like near Antarctica), productivity in the oceans was primarily in the form of diatoms and radiolarians which secrete shells made of silica rather than \( \text{CaCO}_3 \). This would have made the ratio between \( \text{CaCO}_3 \) and organic carbon smaller than today’s value (four).

   a) **Return to your original ocean carbon model** (i.e. delete the uplift of the Himalayas and re-adjust the river flux to its initial conditions), and decrease \( R \) from 4 to 1 gradually and steadily at the rate of 0.075 units per 100,000 years over a 4 million year time span starting at 1.1 million years.

      To reduce the burial ratio starting at 1.1 million years, use the following “if, then, else” statement in the “burial rate” converter equation box.

      \[ \text{IF(time} \geq 1.1E6) \text{ THEN}(4-(0.075*(time-1.1E6)/100000)) \text{ ELSE(4)} \]

   b) Does changing \( R \) change the bulk carbon burial rate (if you don’t already have a Bulk Burial converter box in your model to monitor changes in the bulk burial rate, add one now)? How?

   c) **Print the model and graph** of the system’s response to the perturbation over 5.10 million years.
Part 2: The atmospheric carbon box model

Box Model components:

Atmosphere box inventory of carbon: \( I_a \)
Input to atmosphere box:
- Fossil Fuels and deforestation: \( C_f \)
- Terrestrial biota / soils: \( C_{\text{bin}} \)
- Surface ocean: \( C_{\text{oin}} \)
Output from atmosphere box:
- Terrestrial biota / soils: \( C_{\text{bout}} \)
- Surface ocean: \( C_{\text{out}} \)

Atmosphere box inventory of carbon = \( I_a = 6.25 \times 10^{16} \) moles

Input to atmosphere box:
- Fossil Fuels and deforestation = \( C_f = 4.42 \times 10^{14} \) moles/year
- Terrestrial biota/soils = \( C_{\text{bin}} = 8.33 \times 10^{15} \) moles/year
- Surface Ocean = \( C_{\text{oin}} = 7.50 \times 10^{15} \) moles/year

Output from atmosphere box:
- Terrestrial biota / soils = \( C_{\text{bout}} = -8.33 \times 10^{15} \) moles/year
- Surface ocean = \( C_{\text{out}} = -7.67 \times 10^{15} \) moles/year

This model is appropriate for timescales shorter than 100 years.

Questions
1. Draw a box diagram of the atmospheric carbon cycle in STELLA. You should have one reservoir, 3 fluxes in, and 2 fluxes out. Note: Fluxes are given in moles C per year, not moles C per month, so you have to convert them to moles/month!

Set up this model the same way you set up the ocean model, except run the model for 5 years and use a time intervals of 1 month. Don’t forget to adjust the “sim speed” so your model runs <30sec.

Print the model and graph of the Atmosphere inventory and output results.

2. Is the carbon system in the atmosphere at steady state? Why or why not?

3. What process transfers carbon back and forth between the “terrestrial biota / soils” (plants, mostly) and the atmosphere? On what timescale does this transfer occur (i.e. Annually, seasonally, every thousand years)?

4. Add a volcanic explosion of \( 5.00 \times 10^{16} \) g (watch your units here!!!) carbon at time equals 12 months to your atmosphere (another if/then statement will help you here). Plot and print out its effect on the atmospheric reservoir of C over 5 years. What is the effect of the volcanic carbon input? Do you think it is accurate? What fluxes might change in our model to accommodate effects of a volcanic eruption?
**Special note:**
Showing your work for this lab means printing copies of ALL your plots and printing copies of the tables with your information. You will lose substantial points if you do not turn in copies of all of these things. You can print figures during lab or paste the “.pdf”s you created into a master document that you hand in. We are more than happy to help out with this process, so please let us know if you need help.

**Extra Credit:**
Keeling has measured carbon (in the form of CO₂) in the atmosphere at Mauna Loa, HI for many years (see attached figure). He has recorded an overall increase in atmospheric CO₂ with a yearly oscillation (the one described in #3) superimposed on the increase. Modify your model so that it takes into account this oscillation. Do this by reversing the process described in #3 every 6 months.

Recreate the Keeling curve by plotting atmospheric inventory of carbon vs. time over the 5 years of your model. **Print out your plot.**

**HINT:** Think about how you can add a converter and action connector that accounts for oscillations in time.