Introductory Modeling: The Global Carbon Cycle and Climate Change

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Abstract

Models represent a simplification of systems observed in nature. Researchers use models to investigate complex processes that would be infeasible to study simultaneously or in one lifetime (or under one grant!). In this workshop we will present an introduction to dynamic steady-state directed graph models (a.k.a. quantified box and arrow diagrams) and associated analysis tools. After analyzing a small-scale carbon flow model of an intertidal oyster reef, we will consider a model of the global carbon cycle. Additional descriptive models will be provided to investigate the potential effects of human activity on the carbon cycle and resulting change in global climate.

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Introduction to Models and Budgets

Models represent a simplification of the real world. They describe the relationships between environmental and biological variables. Scientists use modeling as a tool to enable them to simulate complex processes observed in nature. Researchers generate models on the basis of many observations and large amounts of collected data. The accuracy of a model is limited by its design (are important components or relationships overlooked?) and the quality of the data used (were the data collected in a reliable, scientific manner?). In addition, models are only valid in describing the data used in the creation of the model. For example, a model that describes the relationships among trophic (feeding) levels in a freshwater lake is not applicable to trophic interactions in a forest ecosystem.

Budgets quantify models. They provide the mathematical balance of inputs and outputs for a given element (such as Carbon) or compound (such as water) in the environment. At *steady state*, the input of a given compound (into a system or component of the system) is equal to its output. Remember, although a system may be at "steady state," material and energy are always flowing among the components of a model. A steady state model is dynamic, not static. The models you will investigate in this lab are assumed to be at steady state.

It is important to note that budgets track only one material, or "currency," at a time, such as carbon, or water, or energy. The principle of a balanced ecological budget is similar to a financial budget, such as a checking account. Here, the currency that you track is money. A financial budget describes cash flow in terms of income (input) and expenses (output). Your checking account balance is determined by input minus output (income minus expenses). Is your financial budget at steady state?

An Example from the Biosphere

The model in **Figure 1** examines the global heat budget. Examination of the model shows that the total input of solar radiation to the earth is equal to the total output of radiation from earth to space. Of the total incoming radiation, 70% is absorbed and 30% is reflected back as short-wave radiation. The incoming radiation (70%) that gets absorbed is eventually reflected back as long-wave radiation. Thus, for 100% input there is 100% output (30% short-wave + 70% long-wave reflection).

As you look at Figure 1, answer the following questions:

- What types of dynamic factors occur here which do not appear in the model?
- On what currency is this model's budget based?
- What is the average incoming solar radiation for the earth?
- What are the units for this value? Is this a quantity or a rate?
- Examine the heat budget. What is the total % of radiation input for the global heat budget?
- What is the total % of output for the global heat budget?
- Is this budget balanced? Why? Show your work in the space below.

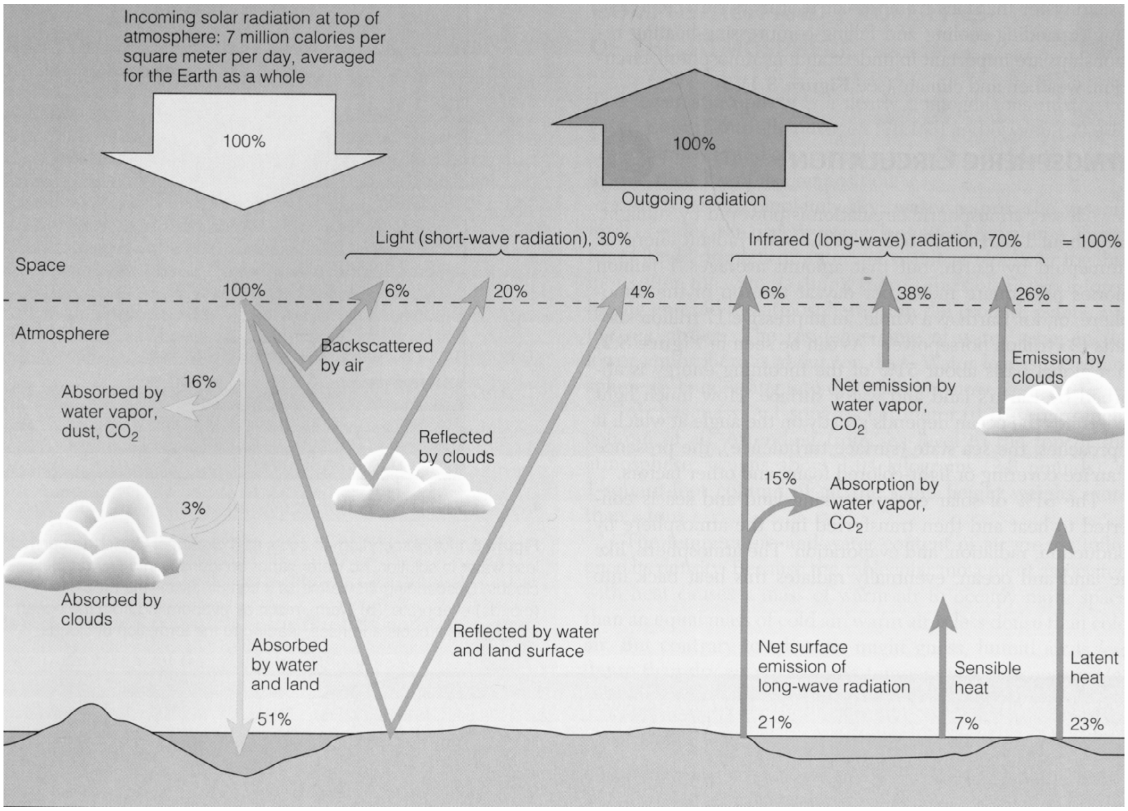

Figure 1. Estimated heat budget for the earth. From *Oceanography*, 4th edition, T. Garrison, 2002, p.188, Brooks/Cole Publishers.

Carbon Cycling through Biological Systems

You will now apply your knowledge of models and budgets to a model that describes how carbon moves through a living system: an oyster reef.

When we speak in ecological terms of carbon moving through a biological system, we are talking about the physical transfer of mass from one trophic level to the next. Consider a shallow ocean area along the coast. Aquatic plants take up carbon dioxide dissolved in the water. Through photosynthesis, plants convert carbon dioxide into glucose, a carbon-rich source of energy for growth. A small fish nibbles on some seaweed. In this action, carbon from the plant is transferred to the fish. The fish digests the carbon-rich cells of the seaweed, and through metabolism and growth, the fish incorporates the carbon molecules into its own cells. A larger fish then comes by and eats the small fish. Carbon "flows" from the small fish to the big fish. It is through these trophic transfers that carbon moves through a living system.

Box and Arrow Directed Graphs

In this section, we introduce a common type of model: the **box and arrow** diagram. These types of models are also known as “directed graphs,” or “digraphs,” because *quantified* diagrams are appropriate for analysis with graph theory analytical techniques. Figure 2 is a box and arrow model that shows the flow of carbon flow through an intertidal oyster reef in South Carolina. In general, box and arrow diagrams contain the following:

Reservoirs – these are the storage compartments of a model, such as Filter Feeders or Predators. They represent storage of whatever currency you are tracking, such as carbon.

Fluxes – these are transfers of currency between any two reservoirs, such as the flow of carbon from Filter Feeders to Predators.

Inputs – these are transfers of currency from the outside environment to your system. For example, in the Oyster Reef model, Filter Feeders receive an input of 4.1 g C/m^2/day (grams of carbon per square meter per day) from the outside environment.

Outputs – theses are transfers of currency from the system to the outside environment. For example, in the Oyster Reef model, Meiofauna contribute an output of 0.4 g C/m^2/day to the outside environment.

Inputs, outputs, and fluxes are rates. Rate values are given in units of mass per area per time (or mass per volume per time). Reservoirs do not have a time component. They are assumed to be storages of currency. Their amounts are given in units of mass per area (or mass per volume). In the oyster reef model, reservoir carbon values are given in g C/m^2 and inputs, outputs, and fluxes are given in g C/m^2/day.

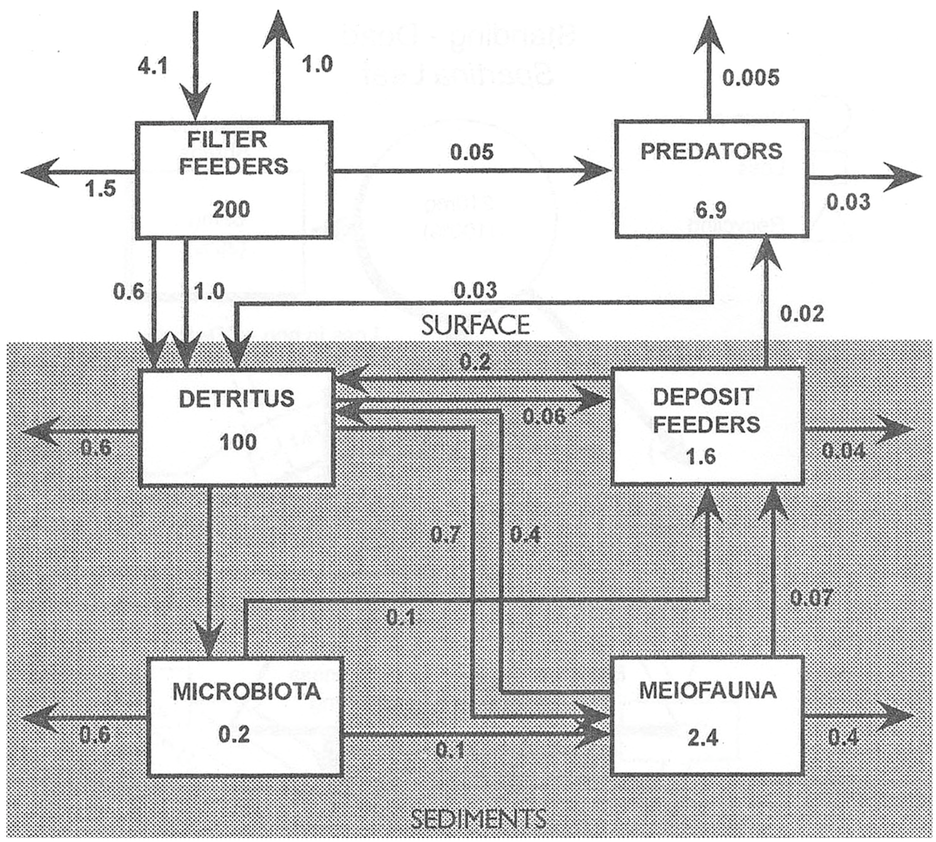

Figure 2. Carbon flow through a South Carolina intertidal oyster reef. From Practical Handbook of Marine Science, 3rd edition, Michael J. Kennish, 2001, p.583, CRC Press.

Question:

- **Which reservoir has the most connections with the other reservoirs? Provide an explanation from a biological perspective.**

Calculating Residence Time

In addition to knowing the reservoir storage values and flow rates of a model, we are interested in finding out the **residence time** material endures in each reservoir of a model. Residence time, or turnover rate, is important because it provides information about the dynamics of a model that is at steady state. Use the following equation to calculate residence time:

$$\text{Residence Time} = \frac{\text{Amount of element in reservoir}}{\text{Rate at which element is added (or removed)}}$$

For example, in Figure 2 the residence time of carbon in Predators equals:
[6.9g C ÷ (0.07g C/day)] = 98.6 days (approximately 98 days and 14 hours).

Note that in the denominator of the equation, you may use the *rate at which a material is added*, OR, the *rate at which a material is removed*, because at steady state these values are EQUAL (in = out!). This equation assumes your model is at steady state, which is the case for the models provided in this lab.

- *Calculate the residence time of carbon in each of the six reservoirs in the model in Figure 2 and record your results in the table below:*

Reservoir	Amount in reservoir (g C)	Rate of flux into (or out of) reservoir (g C/day)	Residence time (days)	Rank (1=longest time)
Filter Feeders				
Detritus				
Microbiota				
Predators				
Deposit Feeders				
Meiofauna				

- Which oyster reef reservoir has the *longest* residence time for carbon?
- Can you provide an explanation *from a biological perspective* as to why this reservoir has the longest residence time?

The Global Carbon Cycle and Climate Change

You will now apply your knowledge of models and budgets to a model that describes how carbon flows through that atmosphere and biosphere: the global carbon cycle. Figure 3 is a box and arrow model that shows the flow of carbon through the global carbon cycle.

In the global carbon cycle model, carbon storage values in each reservoir (values in boxes) are provided in units of Gt C, and flux and input values (values beside the arrows) are provided in Gt C/yr. Certain units are traditionally used to describe the large quantities of carbon in the global cycle. Gt C stands for gigatons of carbon, where giga = 10^9, or 1 billion. The "ton" unit used refers to a metric ton, which is equal to 1,000 kilograms or 2,204.6 pounds. We will explore global carbon units further in the last section of the lab. This model is simplified and does not consider input/output from freshwater components, as their contributions to the global carbon cycle are not well understood. In reality, many of the fluxes vary greatly from season to season, year to year, and across large time scales. Therefore, the flux values in the model represent averages over time. Note that anthropogenic (human) activities, such as changing land use and fossil fuel emissions, are considered in the model.

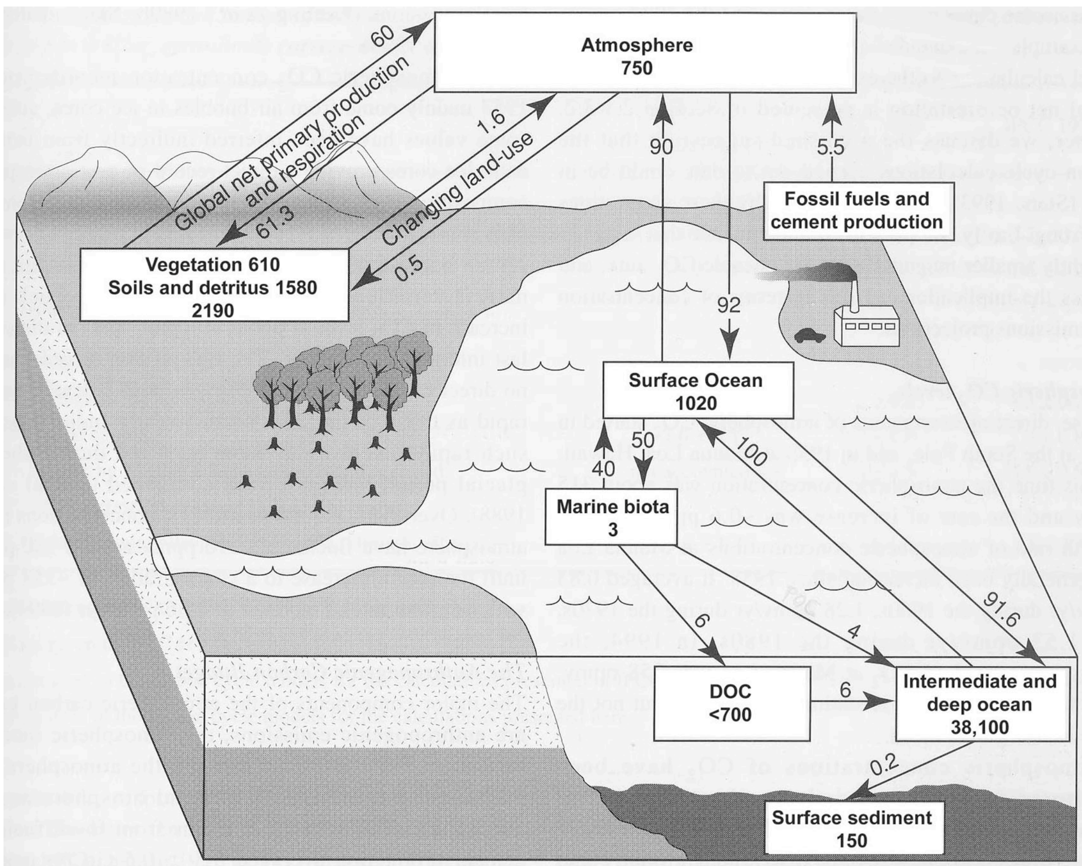

Figure 3. The global carbon cycle illustrating reservoirs, fluxes, and anthropogenic influences. From *Climate Change 1995: The Science of Climate Change*, J. T. Houghton, L. G. Meira Filho, B. A. Challander, N. Harris, A. Kattenberg, and K. Maskell, editors, 1996, p. 77, University of Cambridge publisher.

One way we can apply our knowledge of **residence time** is to consider the relationship between residence time and the anthropogenic influences of the global carbon cycle. For example, when we deforest large areas of land, are we affecting long-term or short-term storages of carbon? How soon will the other components of the cycle be affected? How long will our impacts last?

Again, the equation for residence time is:

$$\textit{Residence Time} = \frac{\textit{Amount of element in reservoir}}{\textit{Rate at which element is added (or removed)}}$$

- *Calculate the residence time for carbon each of the following reservoirs in the model and record your results in the following table:*

Reservoir	Amount in reservoir (Gt C)	Rate of flux into (or out of) reservoir (Gt C/yr)	Residence time (years)	Rank (1=longest time)
Atmosphere				
Veg, Soils and Detr.				
Surface Ocean				
Marine biota				
Dissolved organic C				
Int. & Deep Ocean				

- Which global carbon reservoir has the *shortest* residence time?
- Can you provide an explanation *from a biological perspective* as to why this reservoir has the shortest residence time?
- How does residence time for carbon in Vegetation, Soils and Detritus compare with residence time for carbon in the Atmosphere?
- What are the implications of these calculations for greenhouse gases and climate change?
- Discuss how human activities might influence the following dynamic components: land use and vegetation patterns, atmospheric composition, and oceanic geochemistry. Give specific examples.

Global Emissions and the Relative Change in Atmospheric Carbon: Using the Internet to Research the Global Carbon Cycle

In this section of the lab, you will use data from an internet resource to research the relationship between fossil fuel emissions, atmospheric carbon, and climate change. An excellent internet resource for information on fossil fuel emissions, atmospheric carbon, and temperature change is *http://cdiac.esd.ornl.gov/trends/trends.htm*. Information in this section of the lab comes from this website.

Your job is to solve the answer to the question: *Are atmospheric carbon increases proportionate to fossil fuel emissions?*

Remember, the carbon cycle is a system. If global emissions of CO_2 are being completely absorbed by the atmosphere, then we should see a proportionate increase in atmospheric carbon. To answer your question, you will compare data on global carbon emissions with data on atmospheric carbon levels from the last 45 years. Note that one of the challenges of solving your problem is that the data occur in different units.

The data you will use for your analysis should be entered in the following table. References for data and information from the website are provided at the end of the lab.

A	B	C	D	E
Year	**Global emissions**	**Global Atmospheric Carbon** ***Est. from Mauna Loa data***		**Annual increase in atmospheric carbon** ***5 year average***
	(Gt C/yr)	**$pC0_2$ (ppmv)**	**(Gt C)**	**(Gt C/yr)**
1960	**2.578**	**316.91**	**684.5**	______________
1965				**0.624**
1970				
1975				
1980				
1985				
1990				
1995				

Begin by opening the website *http://cdiac.esd.ornl.gov/trends/trends.htm* in order to retrieve **Global Emissions (Gt C/yr)** data (**for column B**). **Click** on *Carbon Dioxide Emissions from Fossil-Fuel Consumption*. **Click** on *Global (1751-1998)*. For a quick look at the pattern of increase in fossil fuel emissions click on *Graphics* (then click on the **Back** key). **Click** on *Digital Data (ASCII Fixed Format)*. A web page will open with data on global emissions from 1751-1998. The first column lists the year. The second column lists total global emissions in million metric tons of carbon. To convert these values to Gt C (gigatons), divide by 1,000. For example, consider data for 1960:

2,578 million metric tons of carbon = **2.578 Gt C**

Record data from the "Total" column into column B of your table in Gt C for years 1960, 1965, 1970, 1975, 1980, 1985, 1990, and 1995.

Return to the main web page *Online Trends, A Compendium of Data on Global Change* by repeatedly pressing the **Back** key on the menu at the top left of your screen. To retrieve **Global Atmospheric Carbon *Est. from Mauna Loa data* pCO_2 (ppmv)** data (**for column C**), **click** on *Atmospheric Carbon Dioxide and Carbon Isotope Records*. **Click** on *Atmospheric CO_2 Records from sites in the SIO air sampling network*.**Click** on *Mauna Loa, Hawaii*. A web page will open with information about the long-term CO_2 air samples collected in Mauna Loa. If you click on *Graphics*, you will get a quick view of the pattern of increase of atmospheric CO_2 levels from the last 45 years (then click on the **Back** key). **Click** on *Digital Data*. A web page will open with data on atmospheric CO_2 levels from 1958-2000. The first column lists the year. The second to last column from the right lists the average "Annual" CO_2 concentration in ppmv (parts per million by volume). **Record** data from the "Annual" column into column C of your table in **ppmv** for years 1960, 1965, 1970, 1975, 1980, 1985, 1990, and 1995.

In order to determine **Global Atmospheric Carbon (Gt C)** (**column D**), you must convert units of carbon from pCO_2 (ppmv) (*parts per million by volume*) to Gt C. This is necessary so that you may make a direct comparison between Global Emissions (Gt C/yr) (column **B**) and Increase in Atmospheric Carbon (Gt C/yr) (column **E**). In addition, this conversion is valuable to learn because almost all articles on the global carbon cycle and climate change provide atmospheric concentrations of carbon dioxide in pCO_2 (ppmv), whereas fossil fuel emissions are provided in Gt C.

The necessary conversion units are as follows:

$pC0_2$ (ppmv) = # mol C / 1.00*10^6 mol air (*parts divided by a million*)
mol of dry air in atmosphere = 1.80 * 10^{20} mol air
Weight of carbon = 12 g / mol C
grams in a ton = 1.00*10^6 g / ton (*1,000 g = 1 kg, 1,000 kg = 1 ton*)
tons in a gigaton = 1.00*10^9 ton / Gt

(The converted value for year 1960 has already been provided (column **D**). Use this value to double check your work.)

In order to determine the **Annual increase in atmospheric carbon *5 year average* (Gt C/yr)** (**column E**), use the following equation:

$$\textit{Five year average increase in atmopheric carbon (Gt C/yr)} = \frac{\textit{Gt C (year 5) – Gt C (year 1)}}{\textit{5 years}}$$

For example, the average annual increase in atmospheric carbon between years 1960 and 1965 is:

$$\frac{320.03 \text{ Gt C}_{(1965)} - 316.91 \text{ Gt C}_{(1960)}}{5 \text{ years}} = 0.624 \text{ Gt C/yr}$$

In other words, during the five years between 1960 and 1965, atmospheric carbon levels increased by an average of 0.624 gigatons of carbon each year.

And now, back to our original question…

Are atmospheric carbon increases proportionate to fossil fuel emissions?

To answer this question, create a graph of your data comparing carbon emissions (Gt C/yr; column **B**) with atmospheric CO_2 increases (Gt C/yr; column **E**). Use open circles for emissions data points, and use closed circles for data points for increases in atmospheric carbon. (Note that there is **no** data point for "Increases in Atmospheric Carbon" for the year **1960.)** Be sure to label your axes, provide units, and number the axes appropriately. The x-axis should be “Time.” The y-axis on the left side of the graph should be labeled, “Emissions (Gt C/yr),” and the y-axis on the right side of the graph should be labeled, “Increase in Atmospheric Carbon (Gt C/yr).” There are two y-axes because you are plotting two different sets of data.

If the atmosphere took up all the carbon released from fossil fuel emissions, the data points you graphed would overlap. In other words, for every Gt C that was released by emissions, there would be an equal (proportionate) increase in Gt C in the atmosphere.

- Compare the pattern of increase in atmospheric carbon with respect to the pattern of increase in emissions.
- What do your data tell you about the proportional response of atmospheric carbon to increases in emissions?
- Given your new, extensive understanding of the global carbon cycle, provide an explanation as to where the rest of the emitted carbon is being taken up.
- Do you think human activity can impact global climate? Defend your answer.