A simple carbon cycle model

A simple carbon cycle model is available at:
`http://www.shodor.org/master/environmental/general/carbon/carboncs.html`
A link to this webpage is also provided from the course webpage. This model was originally developed through Cornell University and the Massachusetts Institute of Technology as an educational tool, but they no longer maintain the model. However, the model is runnable at the above site.

1. The model consists of differential equations related to the rates of change of five quantities ("stocks" or "reservoirs"). These are the carbon quantities in each of (i) the atmosphere, (ii) the surface ocean, (iii) the deep ocean, (iv) the terrestrial biosphere, and (v) the soil and decaying matter. The model is symbolically shown in the webpage above, in the way in which it would be written using the system modeling package STELLA. The equations related to this are also available in pseudo-code in the link provided from the webpage. Study the symbolic (STELLA) presentation and the equations carefully. Write a list of the quantities which change each of the five stocks, and give explanations for the form in which they are given in this particular model, and explain why they have this effect on the stocks. Then, give explanations for why the equations for each term (say, upwelling) takes this form. You will probably not be able to justify the exact numbers used in some of the equations, but try to justify the forms of the equations as much as you can. For example, if you examine the upwelling of carbon, you could state that this moves carbon from the deep ocean to the surface ocean, and its rate is proportional to the amount of carbon in the deep ocean (which is a reasonable hypothesis). You would not need to argue why the proportionality constant is 0.002. Give similar arguments for all of the features in the model (giving a good description of the form of the photosynthesis equations would be particularly favorably viewed).

2. You can access the "runnable model" through the link at the bottom of the webpage. In this, you are able to change the initial values of each of the stocks. Note that the units which are being used for each of these quantities are Gigatons of Carbon (GtC). You are also able to change two other quantities related to carbon flow: the fossil fuel contribution to atmospheric carbon, and also the deforestation rate which affects the carbon in both the terrestrial biosphere (i.e., trees!) and the atmosphere. These quantities are *fluxes* (that is, rates of change), and therefore the units are Gigatons of Carbon per year. You are also able to change two other quantities: how long you would like to run the model, and the time-step (dt, or DT – this is really the Δt that we would get when rewriting the differential equation form as an implementable discrete system). Both of these quantities are in years, and note that $DT = 0.25$ (that is, three months) is the "standard" value used for most models when attempting to model global changes of the order of 100 years. There are also several other parameters you can change, relating to the plot that you get. The plot that is output from this model is *only* of the atmospheric carbon. Run the model with the default values, and adjust the Y-axis in order to get a plot which includes all the information.

3. Note from the plot title that your plot is of the *carbon-dioxide* amount in the atmosphere (and *not* the carbon amount). The runnable model has therefore performed a conversion which it has not told us about. Examine the value in the output graph at time zero, and compare this to the initial value for the carbon in the atmosphere that was used as an input to the model. Clearly, these values are different; the first gives the carbon-dioxide amount, while the second gives the carbon amount, at the present time. Can you figure out how to get one number from the other? (Hint: basic chemistry tells us that a molecule of carbon-dioxide consists of one atom of carbon and two atoms of oxygen, and carbon and oxygen have atomic weights of 12 and 16 respectively.) What is important to us from a global warming perspective is the

of the greenhouse gas carbon-dioxide in the atmosphere, and hence the output graph from the runnable model is in the correct format.

4. Do some research into determining best estimates for:

   (i) The contribution to atmospheric carbon from fossil fuel burning, and

   (ii) The contribution to atmospheric carbon (or the reduction of terrestrial biosphere carbon, which in this model is considered equivalent) from deforestation.

   Give references for your numbers. Make sure that you convert your numbers to the units appropriate to the runnable model.

5. Run the model with the data you determined above, but with all other parameters at their default values. Produce a plot of the variation of the atmospheric carbon-dioxide over the next 50 years. How much carbon-dioxide will there be in the atmosphere in fifty years, according to this model (give a rough answer – you will not be able to give a very accurate number since you will have to obtain the number from your graph)? Include the graph in your solutions. Interpret your results.

6. The Intergovernmental Panel of Climate Change (IPCC) is a international body affiliated to the United Nations based in Switzerland, with a website at `http://www.ipcc.ch/`. They regularly produce reports on climate change, one of which is provided in the course webpage. The IPCC's 2001 Third Assessment Report on mid-range climate sensitivity estimates that a 1 degree Celsius (Centigrade) increase in average global temperature will occur for every 300 extra Gigatons of carbon-dioxide that is added to the atmosphere. Given that the average global temperature today is 15 degrees Celsius, estimate what the average global temperature would be 50 years from today. Convert your answers to Fahrenheit, if you prefer.

7. Next, try to find estimates for the current values of the carbon present in each of the five stocks. (Note: if by chance you get your numbers in terms of carbon-dioxide, make sure you use convert them to *carbon* quantities, which are needed as input for the runnable model.) Once again, make sure you provide references for your estimates. Also using the estimates that you found for the fossil fuel and deforestation rates, recompute the atmospheric carbon-dioxide and global average temperature estimates 50 years from now.

8. The runnable model that we are working with is, of course, incredibly simplistic. Discuss its deficiencies. Find a list of global carbon models that are genuinely used by the international community. Note that most of these models will include the coupling of the carbon cycle to many other environmentally relevant entities, since carbon is linked intimately to many other things. Try to write a sentence or two about each of them, specifying their principle characteristics. One hint in this is to search for "Global Climate Models" (sometimes called "GCMs") in sources such as Wikipedia. The following article, which was provided in class and is also available from the course webpage, also lists some such models.

   Schröter et al. Ecosystems service supply and vulnerability to global change in Europe. *Science*, **310**, No. 5752, 1333–1337 (2005).