Modeling the Carbon Cycle

Strategy -- Divide and Conquer

As you can see from the lengthy discussion of the flow processes involved in the global carbon cycle, it is a fairly complex one. In fact, it is complicated enough that we may have difficulty interpreting and understanding the results of experiments. A strategy for dealing with this complexity is to first consider separately the two major portions of the carbon cycle -- the terrestrial portion and the oceanic portion. By experimenting with these two components, we can acquire a level of understanding that will aid us in interpreting the results of the whole global carbon cycle. This is a little like the divide and conquer idea, although we should acknowledge that with our level of uncertainty about some aspects of the carbon cycle, we are still a ways from a definitive understanding.

Before we embark on our adventure of modeling the global carbon cycle, it is important to point out that the present-day carbon cycle is far from a steady state. This means that if, as is typical, we want to begin by creating a steady-state model that will serve as our experimental control, we should not pattern our model after the present day situation. Instead, we will use the carbon cycle as it is believed to have existed in the time just before the onset of the industrial revolution, which marks the time when human alterations of the carbon cycle began in earnest. Adopting this pre-industrial case as our steady state has another advantage in that since we know the history of CO_2 emissions from human activities pretty well and we know the present state of the carbon cycle pretty well and we even know the rate of change of various parts of the carbon cycle, we can perform a very good test on our model of the carbon cycle. If we add to our steady state model the CO_2 emission history for the last 100 years, we should end up with a carbon cycle in a state very similar to today's . This will be provide us with a very nice way of assessing the significance of our modeling results.

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A Simple Model of the Terrestrial Carbon Cycle

The terrestrial portion of the carbon cycle includes just three reservoirs -- the atmosphere, the land biota, and the soil, but it involves two complex flows.

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Model Construction

The structure of the terrestrial carbon cycle is relatively simple, as can be seen in Figure 7.11; this model design can be used, along with the equations below, to create a working model of this subsystem of the carbon cycle.

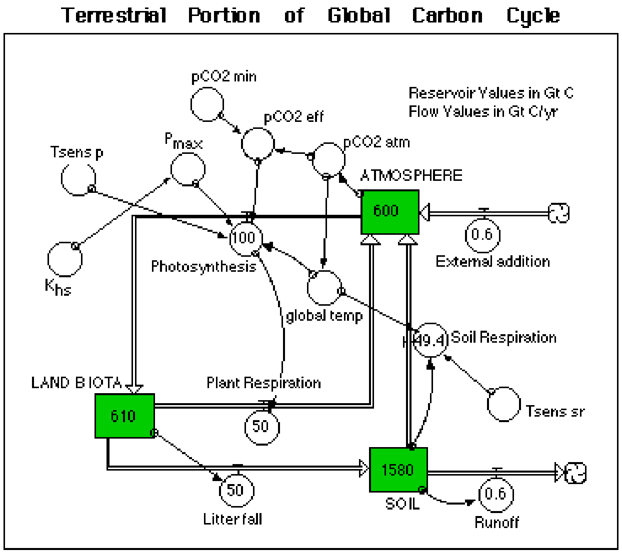

Figure 7.11. Simple model of the terrestrial portion of the carbon cycle, with reservoirs set to reflect the pre-industrial condition of the global carbon cycle. The initial values of the flows, in Gt C/yr are shown; these are not constants — they will vary as other components of the system change.

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EQUATIONS FOR MODEL OF SIMPLE TERRESTRIAL CARBON CYCLE

RESERVOIRS:

INIT Atmosphere = 600 {Gt C -- 1 Gt=1e15 g -- from IPCC, 1995}
INIT Land_Biota = 610 { Gt C -- 1 Gt=1e15 g -- from IPCC, 1995}
INIT Soil = 1580 { Gt C -- 1 Gt=1e15 g -- from IPCC, 1995}

FLOWS: (all in Gt C/yr)

Soil_Respiration = (49.4/INIT(Soil))*Soil*(1+(Tsens_sr*global_temp)) {initial value from Siegenthaler and Sarmiento, 1993}
Plant_Respiration = Photosynthesis*(50/100) {equation modified from Gifford, 1993; initial value from Siegenthaler and Sarmiento, 1993}
External_addition = 0.6 {volcanic emissions or fossil fuel burning, etc.} }
Photosynthesis = (Pmax*(pCO2_eff/(pCO2_eff+Khs)))*(1+(Tsens_p*global_temp)) {equation modified from Gifford, initial value from S&S}
Litter_fall = 50*(Land_Biota/610) {modified from Gifford, 1993 initial value from S&S}
Runoff = .6*Soil/INIT(Soil) {value from S&S}

CONVERTERS:

Khs = 62.5 {ppm CO2; this is the half-saturation value -- the level of atmospheric C at which the rate of photosynthesis is half of the ultimate saturation value, given that particular temperature; modified from Gifford, 1993}
Pmax = ((Khs+250)*100)/250 {Gt C/yr; this is the maximum rate of photosynthesis possible at the saturation level of CO2, ignoring the temperature effect -- from Gifford, 1993}
global_temp = (pCO2_atm-280)*.01 {°C relative to today's temp of 15; from K&S, 1994}
pCO2_atm = Atmosphere*(280/600) {ppm}
pCO2_min = 30 {ppm -- no photosynthesis can occur below this level; from Gifford, 1993}
pCO2_eff = pCO2_atm-pCO2_min {ppm; the effective atmospheric CO2 concentration}
Tsens_p = .04 {°C-1; temperature sensitivity factor for photosynthesis; after Gifford}
Tsens_sr = .10 {°C-1; temperature sensitivity factor for soil respiration; after Gifford}
Atmos_Change = Atmosphere-600 { Gt C; change in atmospheric carbon -- used to compare results of various experiments}
Land_Biota_Change = Land_Biota-610 {Gt C}
Soil_Change = Soil-1580 {Gt C}
Total_Change = Atmos_Change+Land_Biota_Change+Soil_Change {Gt C}

Using the equations and model structure of Figure 7.11, you should end up with a steady-state model that is intended to represent the state of the carbon cycle just before the industrial revolution began, approximately 100 years ago. It is worth mentioning that even then, before serious anthropogenic changes were imposed, the global carbon cycle was probably not in a steady state. Natural variations in almost all parts of this system will tend to keep the system constantly changing, but changing far less than at present.

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Experiments with the Simple Terrestrial Model

To help compare the results of the following experiments, the terrestrial carbon cycle model has a few added converters (with names like Soil_Change, etc.) that keep track of how much each of the reservoirs has changed. Be sure to make use of these values in summarizing the results of these experiments.

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TC1. Response Time -- Effect of an Initial Doubling of Atmospheric Carbon

As always, one of the most important characteristics of a system is its response time -- how quickly it responds to a change, and whether or not the system returns to its original state, or a new steady state. The simplest way of doing this is to run the model after we have doubled the initial amount of atmospheric carbon, from 600 Gt to 1200 Gt. Before running the model, it will be helpful to quickly study the three reservoirs involved in this system, and determine the response time of each reservoir under the assumption that it is not connected to other reservoirs. This will help us understand which parts of the system are the fastest and which are the slowest.

Make a prediction about how the system will respond, and then run the model for 100 years, with a time step of 0.5, using the Runge-Kutta 2 integration method. Does the system quickly return to the original steady state? Or are there complicating factors that tend to slow the response of the overall system? Is the system really in a steady state after 100 years? Or does this system have a sort of split personality, wherein it responds very quickly to some change, but the response is only partial, and it takes a much longer time for the system to fully respond to some change? Try running the model for 1000 years to see if the system really is in a steady state after just 100 years.

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TC2. Effect of Fossil Fuel Emissions

The initial steady-state model contains a flow called external additions, which initially has a value of 0.6 Gt C/yr, representing volcanic and metamorphic emissions. By increasing this to 6.6, we can investigate how the system responds to the emissions resulting from fossil fuel burning. Note that we are effectively imposing a sudden increase in fossil fuel emissions, from 0 to 6, with 6 representing the approximate emissions (Gt of C) in 1990. Later, we can simulate the historical increase in fossil fuel emissions, but in this experiment, our goal is to understand the general response of the system to an increased atmospheric input, coming from outside of the system. Be sure to return the initial amount of carbon in the atmospheric reservoir to 600 before running this experiment.

How do you think the system will respond to this change? Where will all of the added carbon end up? How much will accumulate in the various reservoirs? Will the system reach a new steady state? If so, how will it differ from the initial steady state?

After making these predictions (answers to the above questions), run the model for 100 years and study the results. You may find it necessary to run the model for a longer period of time to help answer some of the questions.

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TC3. Effects of Forest Burning and Soil Disruption

Our next experiment is intended to understand how deforestation and land-use changes affect the carbon cycle. Together, these changes are thought to add an extra 1.5 Gt C/yr to the atmosphere. Here, we will consider three experiments that represent a range of possibilities. As in the previous experiments, we will be tampering with flows rather than reservoir sizes; the changes will be instantaneous and will not try to capture the history of these changes, leaving that for another experiment. First, be sure to undo the changes you made for any previous experiments, so that you are beginning with the steady-state version of the model.

a) Forest Burning

When forests are cut down with the intention of clearing land, a large portion of the biomass is often burned, making up 50% to 70% of the 1.5 Gt C/yr total emissions. It is important to note that these emissions do not represent all of the carbon from all of the trees that are cut down each year, since in many cases, the trees are used for things like building and paper, which is obviously quite different from burning.

How can we represent this process of burning in our carbon cycle model? It should be fairly clear that this burning represents a transfer of carbon from the land biota reservoir to the atmosphere. There are two ways of representing this transfer. We can either create a new flow called burning, or we can add to the flow called plant respiration. I recommend making a new flow, because it will be easier to see how you are representing this process. If the model were very large and you were cramped for space, I would recommend adding to the existing plant respiration flow. Either way, make the burning flow transfer 1 Gt C/yr from the land biota to the atmosphere, and then try to predict how the system will respond. In making your prediction, it might be helpful to recall what you learned from the first experiment. After, you've made a prediction, run the model for 100 years, in order to facilitate a quantitative comparison with the results from the other experiments.

b) Deforestation With No Burning

As mentioned above, not all of the plant material that is cut down during forest clearing is burned; some of it is left in slash piles on the floor of the former forest. In this case, the carbon is effectively transferred to the soil rather than being burned. In reality, little is known about the magnitude of this flow, but we can nevertheless investigate what happens as a result of this process. Let's examine a case in which the same amount of carbon that is burned, 1 Gt C/yr, is added to the soil instead. This means disabling the flow that represents burning and either adding to the litterfall flow or creating a new flow called forest cutting. In either case, make the flow be a constant 1 Gt C/yr.

How will the system respond to this change? How will the response differ from the previous experiment, where burning took place? After, you've made a prediction, run the model for 100 years, in order to facilitate a quantitative comparison with the results from the other experiments.

c) Agricultural disruption of soil

When soils are tilled, the decomposition of organic material increases, and so the total emission of CO_2 from soil respiration increases. The reason this occurs is that as the soils are broken up and turned over, new soil surfaces are exposed to oxygen and water, and when this occurs, the soil microorganisms can quickly consume organic material that had previously been in long-term storage. Normally, some of the organic carbon ends up in places that receive little oxygen and/or water, and under these conditions, the microorganisms are not able to get at and consume all of the organic carbon, so it remains stored in the soil. It is estimated that this agricultural disruption of soils results in an increase in soil respiration by around 0.5 Gt C/yr. As before, this flow could be represented separately in our model, or it could be simply added on to the existing equation for soil respiration.

After you've changed the model to represent this process, try to predict how the system will respond. Then run the model for 100 years and study the results, comparing them with the previous results.

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TC4. Combining Anthropogenic Effects

Now, we turn to the question of whether or not the effects of fossil fuel emissions and deforestation and land-use changes are additive or is there some interaction that occurs to make the cumulative effect greater or less than the sum of the separate effects. This is a very simple experiment to do since you have already simulated and studied the separate effects. For this experiment, let's look at what happens when we incorporate fossil fuel burning (at a rate of 6 Gt C/yr) along with deforestation/burning (1 Gt C/yr), and agricultural enhancement of soil respiration (0.5 Gt C/yr).

To answer the question posed in this experiment, you need to have the results of the previous experiments on hand, so if you have not done them, they must be done in order to complete this experiment.

As always, take some time to make a prediction about how the system will respond, then run the model for 100 years and study the results, comparing them with the separate effects of the different anthropogenic changes.

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TC5. Modifying the Temperature Sensitivities

In this experiment, we will investigate the effects of altering the temperature sensitivities of the flows that we expect to vary according to the temperature -- photosynthesis and soil respiration processes (plant respiration is also sensitive to temperature, but in the same way that photosynthesis is). Our goal here is to understand how important these temperature sensitivity factors are in controlling the response of the terrestrial carbon cycle to anthropogenic changes.

To simplify matters, we will consider the two temperature sensitivity factors separately; first we will alter the photosynthetic sensitivity and then the soil respiration. In both cases, we will utilize the sensitivity analysis command in STELLA to run through a variety of simulations. To do this, select Sensi Specs from the Run menu and you will see the sensitivity set-up window. First, set the number of runs to 3, then select Tsens_p from the Allowable column and send it over to the Selected column using the >> key. Then click on Tsens_p in the Selected column and click the Incremental button below (it is the default). Enter 0 in the Start box and 0.08 in the End box, then hit the Set button and you should see the values of the different sensitivity runs shown in the column in the middle right of this window; with 3 runs, the second run should have a value of 0.04, which is the standard case and thus represents our control in this experiment. Before leaving this window, make sure that the Sensitivity On box, located in the lower right, is checked. Next, modify the graph pad so that you make three separate graphs, each of them a time series and a comparative graph (this last part is important). On one graph, plot the land biota reservoir; plot the soil reservoir on another, and plot global temperature on the third. It is necessary to have three graphs because when STELLA plots a comparative graph, it can only plot one model component. With this set-up, STELLA will run through three simulations and show the results in the form of three graphs.

Do the same thing with the Tsens_sr, the soil respiration temperature sensitivity factor, varying it from 0 (no temperature dependence) to 0.2 in three steps. You will have to go through and redefine the three graphs in order to remove the graphed results of the first sensitivity analysis before running this second set of simulations.

In both cases, try to make a prediction about how the model will compare with the control model results. It may also be helpful to keep track of the results by recording the total amount of change that each reservoir undergoes in the 100 years of each model run.

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TC6. Modifying the Photosynthesis Parameters

a) Changing the "Greening Potential"

Another uncertain part of the equation for photosynthesis is the half-saturation value, K_{hs}, which represents the atmospheric CO_2 concentration (ppm) at which the photosynthetic rate is one half of its maximum value (P_{max}). In our model, adjusting this value amounts to adjusting P_{max}, which changes what some people call the greening potential for the land biota -- how much extra carbon can be taken up and stored. Low values of K_{hs} correspond to low greening potentials and higher K_{hs} values correspond to higher greening potentials. In this experiment, we will investigate three different greening potentials. The condition of no greening will be represented by a half-saturation of 0 ppm, yielding a P_{max} of 100 Gt C/yr, the maximum greening will be represented by a K_{hs} value of 100 ppm (gives a P_{max} of 140), and K_{hs} = 62.5 ppm (gives a P_{max} of 125) will represent the standard value -- the best guess based on the available experimental data.

Once again, we will make use of the sensitivity analysis feature of STELLA. The set-up for this experiment, within the sensitivity specs window are similar to that described above except that this time, instead of selecting a variation type of Incremental, we will choose Ad Hoc and then enter 0, 62.5, and 100 as the values for the three different runs. As before, after making your prediction, run the model for 100 years and examine the results in the form of three comparative graphs, plotting the soil and land biota reservoirs, and the global temperature, which is a measure of the atmosphere reservoir. The second run of this sensitivity analysis, as before, serves as a control, representing the standard model's response to the anthropogenic changes.

b) Making Photosynthesis Dependent on the Land Biota Reservoir

Some people who have worked on models of the global carbon cycle have proposed that the amount of carbon taken up by photosynthesis is in part a function of the amount of carbon stored in the land biota reservoir. The thinking here is that more carbon in the land biota reservoir means more plants and more plants means greater uptake of CO_2 from the atmosphere. This obviously makes sense if we imagine an extreme case; decrease land plants so that they cover only the tiniest fraction (imagine a single, lonely plant). In this case, the rate of photosynthesis will clearly be different than the present and so will the size of the land biota carbon reservoir -- clearly the global rate of photosynthesis is a function of the size of the land biota reservoir in some cases. But, these cases are probably limited to situations where the land plants occupy some small portion of the maximum possible area. In later, more advanced stages of development or coverage, the plants begin to be limited in their growth by nutrients such as nitrogen. When this stage is reached -- and we are probably close to it now -- the global rate of photosynthesis should be insensitive to small variations in the size of the land biota carbon reservoir, although it can still respond to changes in atmospheric CO_2 and global temperature (especially to the extent that it is linked to precipitation). Nevertheless, our goal here is to explore the possibility that the size of the land biota reservoir ought to be a parameter in the equation for global photosynthesis.

How can we represent this change? The simplest way is to draw a connector arrow from the land biota reservoir to the photosynthesis flow and multiply the existing equation for photosynthesis by a term that represents the relative amount of carbon in the land biota reservoir -- relative to the initial amount. That multiplying term is simply obtained by dividing the amount in the land biota reservoir by the initial amount in the land biota reservoir.

The next question is: What kind of experimental control do we want to use? Let's use two separate controls to get a better idea of how this change affects the system. For the first control, we will use the standard model with an initial doubling of the atmospheric content, as we did in experiment #1 above. For our second control, meaning a second experiment, we will use the response of the standard model to the cumulative affects of humans, represented by experiment #4 above.

Think carefully as you try to make the predictions in these experiments; we have created a very complex flow, dependent in part on the reservoir it drains, and in part of the reservoir it feeds.

A fascinating feature of this new model comes to light when you examine scatter plots of the rate of photosynthesis plotted (on the y-axis) as a function of the atmosphere reservoir (on the x-axis) for the two experiments (control and modified version of the model) involving a doubling of the atmospheric reservoir.

How do you go about evaluating the results of this experiment? Remember that our goal was essentially to investigate the feasibility of the assumption that the relative size of the land biota carbon reservoir ought to be an important parameter in the equation for global photosynthesis. The main question to ask in examining your results is -- has this modification resulted in more realistic or less realistic behavior of the model? This may be a bit difficult to answer, but consider what we do know about the real carbon cycle -- atmospheric carbon is now at about 750 Gt and it is rising at a rate of about 3 Gt/yr, and furthermore, that rate is has been increasing exponentially. The only problem in using the real carbon cycle as a guide in judging the results of this experiment is that in this case, we have not tried to represent the history of fossil fuel emissions, which has reached the value of 6 Gt C/yr after exponentially-increasing during the past 100 years.

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A More Complex Terrestrial Carbon Cycle Model

In the version of the terrestrial carbon cycle that we have been experimenting with thus far, we have lumped the litter and other fast-turnover soil carbon in with the larger mass of soil carbon that has a slower turnover. Without too much trouble, we can separate those different parts of the soil carbon and experiment with a more complex and more realistic model. This simply involves adding a new reservoir, and then adding and renaming several flows.

Model Construction

The structure of the more complex terrestrial carbon cycle is shown in Figure 7.12; this model design can be used, along with the equations below, to create a working model of this subsystem of the carbon cycle.

A More Complex Terrestrial Carbon Cycle

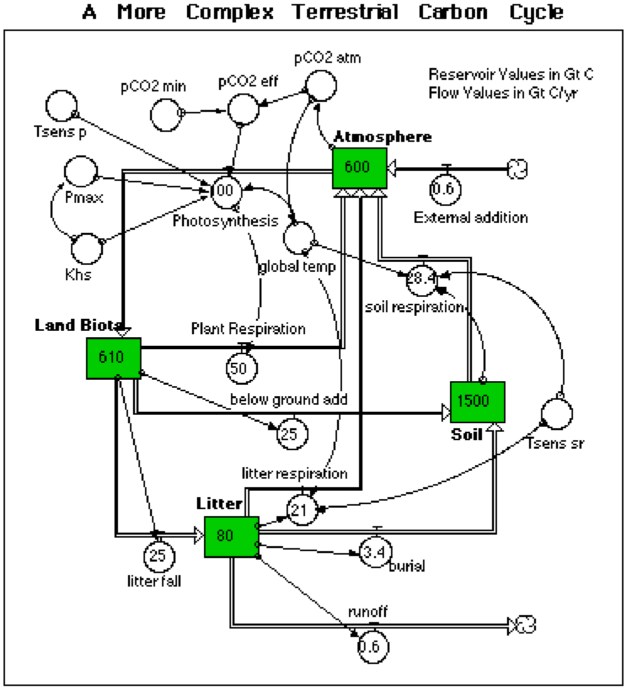

Figure 7.12. More realistic, complex model of the terrestrial portion of the carbon cycle, with reservoirs set to reflect the pre-industrial condition of the global carbon cycle. Here, net primary production (photosynthesis minus respiration) can be transferred to the litter at the soil surface or to the deeper soil carbon reservoir through the shedding of material from plant roots — below-ground addition. This scheme breaks the soil carbon reservoir of the simpler model into two seprate pools, with very different residence times — about 3 yrs for litter and about 50 yrs for the rest of the soil carbon.

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EQUATIONS FOR MODEL OF SIMPLE TERRESTRIAL CARBON CYCLE

Reservoirs:

INIT Atmosphere = 600 {Gt C -- 1 Gt=1e15 g -- from IPCC, 1994}
INIT Land_Biota = 610 {610 Gt C from IPCC, 1994}
INIT Litter = 80 {Gt C}
INIT Soil = 1500 {Gt C}

Flows:

External_addition = 0.6 {volcanic emissions or fossil fuel burning, etc.}
Photosynthesis = (Pmax*(pCO2_eff/(pCO2_eff+Khs)))*(1+(Tsens_p*global_temp))
Plant_Respiration = Photosynthesis*(50/100)
Litter_Fall = Land_Biota*(25/INIT(Land_Biota))
Litter_Respiration = Litter*(21/INIT(Litter))*(1+(Tsens_sr*global_temp))
Below_Ground_Add) * dt
Burial = Litter*(3.4/80)
Soil_Respiration = Soil*(28.4/INIT(Soil))*(1+(Tsens_sr*global_temp))
Runoff = Litter*(.6/INIT(Litter))

Converters:

global_temp = (pCO2_atm-280)*.01 {°C relative to today's temp of 15}
Khs = 62.5
pCO2_atm = Atmosphere*(280/600)
pCO2_eff = pCO2_atm-pCO2_min
pCO2_min = 30 {ppm -- no photosynthesis can occur below this level}
Pmax = ((Khs+250)*100)/250
Tsens_p = 0.04
Tsens_sr = .10

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Experiments with the More Complex Terrestrial Model

In order to understand how this added complexity affects the system dynamics, you are encouraged to undertake the set of experiments (TC1-6) outlined above for the simpler version of the terrestrial carbon cycle.

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A Simple Ocean-Atmosphere Carbon Cycle

We begin our exploration of the oceanic part of the global carbon cycle by constructing and experimenting with a simple model of the ocean-atmosphere system, then progressing to a more realistic and complex ocean model that separates the ocean into cold and warm domains.

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Model Construction

Our simple ocean-atmosphere carbon cycle will be an open system, like our terrestrial carbon cycle models, with just three reservoirs, representing the atmosphere, the surface water of the ocean (to a depth of 100 m), the marine biota, and the deep ocean (everything below 100 m). The atmosphere is set to the pre-industrial level, and the model parameters are set up to create a steady state, or at least as close to it as possible.

I have tried to keep this model as simple as possible and yet still incorporate the carbonate chemistry that is such an important feature of this system. The biologic pump is handled in the simplest way possible Transfers of carbon through upwelling and downwelling are similarly combined into a bi-flow called Ocean Turnover. But, in terms of the mathematics, these changes make no difference, so we have not really altered the model. The structure of this model is shown in Figure 7.13.

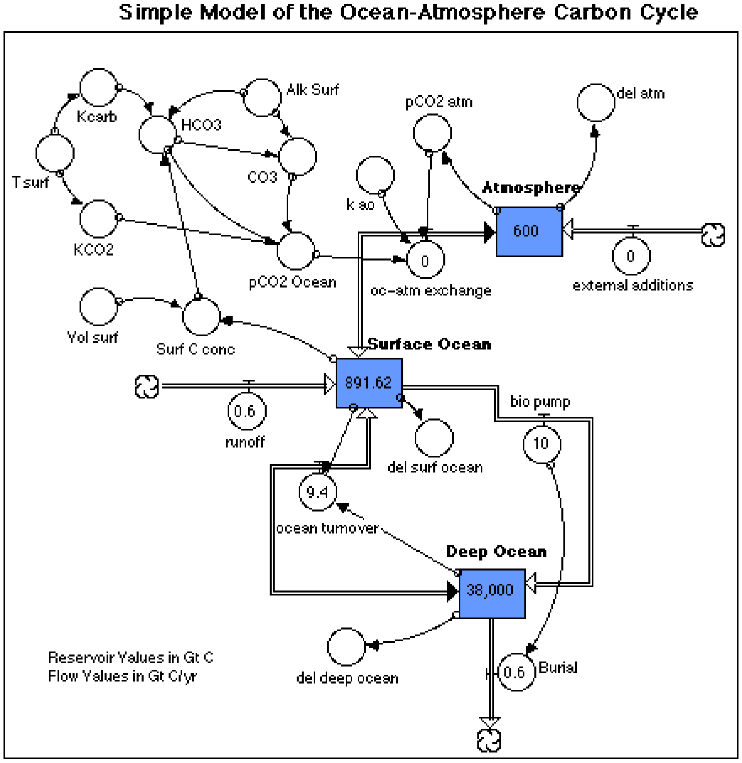

Figure 7.13 Simple model of the ocean-atmosphere carbon cycle with reservoirs set to presumed pre-industrial conditions. The initial value of the surface ocean carbon reservoir is fine-tuned to get the system into a near steady-state condition. Here, the biologic pump is simply a constant value. The flow called ocean turnover represents the net result of upwelling and downwelling.

Note that there are some additional converters that are called del_atm, del_surf_ocean, and del_deep_ocean; these flows are set up so that they will monitor the rate of change of these three reservoirs in Gt C/yr so that they can be compared with the estimates of the current and recent rates of change of various reservoirs in the real version of the carbon cycle. The above diagram, along with the equations listed below can be used to construct the steady-state version of this model that will serve as the control for our experiments. Note that the model as defined here is not quite in a steady state to begin with; but most of the quantities change so slightly that we can effectively consider the model to be in a steady state. As always, if you have trouble getting the model into a steady state, open the copy of this model included with the diskette.

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EQUATIONS FOR MODEL OF SIMPLE OCEAN - ATMOSPHERE CARBON CYCLE

Reservoirs:

INIT Atmosphere = 600 {Gt C}
INIT Surface_Ocean = 891.62591 {Gt C}
INIT Deep_Ocean = 38000 {Gt C}

Flows:

external_additions = 0 {volcanic emissions or fossil fuel burning, etc.}

oc--atm_exchange = k_ao*(pCO2_atm-pCO2_Ocean)

bio_pump = 10
ocean_turnover = 100*(Deep_Ocean/INIT(Deep_Ocean))-90.6*(Surface_Ocean/INIT(Surface_Ocean)) {this is upwelling minus downwelling}
burial = 0.6*(bio_pump/10)
runoff = 0.6

Converters:

Alk_Surf = 2.22 {slightly modified from Walker, 1993}

CO3 = (Alk_Surf-HCO3)/2 {following Walker, 1993}
HCO3 = (Surf_C_conc-SQRT(Surf_C_conc^2-Alk_Surf*(2*Surf_C_conc-Alk_Surf)*(1-4*Kcarb)))/(1- 4*Kcarb) {following Walker, 1993}
Kcarb = .000575+.000006*(T_surf-278) {following Walker, 1993}
KCO2 = .035+.0019*(T_surf-278) {following Walker, 1993}
k_ao = .278 {Gt C/yr/ppm -- the observationally-derived rate constant; this is for the entire surface area of the ocean}
pCO2_atm = Atmosphere*(280/600)
pCO2_Ocean = 280*KCO2*(HCO3^2/CO3) {following Walker, 1993}
Surf_C_conc = (Surface_Ocean/12000)/Vol_surf {1e18 moles/m^3}
T_surf = 288 {°K following Walker, 1993}}
Vol_surf = .0363 {units are 1E18 m^3 -- this is the upper 100 m}
del_atm = (Atmosphere-600)-(DELAY(Atmosphere,1)-600)
del_deep_ocean = (Deep_Ocean-INIT(Deep_Ocean))-(DELAY(Deep_Ocean, 1)-INIT(Deep_Ocean))
del_surf_ocean = (Surface_Ocean-INIT(Surface_Ocean))-(DELAY(Surface_Ocean, 1)- INIT(Surface_Ocean))

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Experiments

OC1. Response Time -- Effect of an Initial Doubling of Atmospheric Carbon

The first question we will ask of this ocean-atmosphere system is: what is its response time? How quickly will it respond to a change? Does the system return to its original state, or does it find a new steady state? A simple way of investigating these questions is to run the model after we have doubled the initial amount of atmospheric carbon, from 600 Gt to 1200 Gt. Before running the model, it will be helpful to quickly study the four reservoirs involved in this system, and determine the response time of each reservoir under the assumption that it is not connected to other reservoirs. Assume that the atmosphere-ocean exchange is actually the sum of two flows going in opposite directions and equal to one another, with a value of 74 Gt C/yr going each way (in effect, the real ocean is divided into cold and warm parts that absorb and release CO_2, but here they are lumped together) This exercise will help us understand which parts of the system are the fastest and which are the slowest.

Make a prediction about how the system will respond, and then run the model for 100 years, with a time step of 0.25, using the Runge-Kutta 2 integration method. Does the system quickly return to the original steady state? Or are there complicating factors that tend to slow the response of the overall system? Is the system really in a steady state after 100 years? Or does this system have a sort of split personality, wherein it responds very quickly to some change, but the response is only partial, and it takes a much longer time for the system to fully respond to some change? Try running the model for 1000 years to see if the system really is in a steady state after just 100 years.

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OC2. Effect of Fossil Fuel Emissions

a) Response to a Steady Rate of Anthropogenic Emissions

The initial steady-state model contains a flow called external additions, which initially has a value of 0 Gt C/yr. By increasing this to 7.5, we can investigate how the system responds to the emissions resulting from the combination of fossil fuel burning, deforestation, and land-use changes. Note that we are effectively imposing a sudden increase in anthropogenic emissions, from 0 to 7.5, with 7.5 representing the approximate current emissions in 1990. Later, we can simulate the historical increase in fossil fuel emissions, but in this experiment, our goal is to understand the general response of the system to an increased atmospheric input, coming from outside of the system. Be sure to return the initial amount of carbon in the atmospheric reservoir to 600 before running this experiment.

How do you thin the system will respond to this change? Where will all of the added carbon end up? How much will accumulate in the various reservoirs? Will the system reach a new steady state? If so, how will it differ from the initial steady state?

After making these predictions, run the model for 100 years and study the results. You may find it necessary to run the model for a longer period of time to help answer some of the questions.

b) Response to Historical Changes in Anthropogenic Emissions

Here, we will make the rate of external additions change over time in such a way as to mimic the history of anthropogenic emissions resulting from the combination of deforestation and land-use changes (i.e., tree-burning and agricultural disruption of soils). The point of doing this is two-fold; first to see how the system responds to a changing rate of external additions and secondly, to compare the final state of the model and the final rate of change of the atmosphere and ocean reservoirs with the figures for how these reservoirs are changing today. For reference, the atmosphere is increasing at about 3.2 ± 0.2 Gt C/ yr and the oceans are increasing at around 2.0 ± 0.6 Gt C/yr; atmospheric carbon is at about 750 Gt, and concentration of CO_2 in the atmosphere is about 350 ppm. We should bear in mind that since we don't have the terrestrial part of the system hooked up yet, the atmosphere in this case will probably end up with much higher levels than we will see with the connected subsystems. The point here is to see if the rate of uptake of the oceans is approximately in agreement with what is occurring in the real world.

To carry out this experiment, we will double click on the flow called external additions and set it equal to time, then click the Become Graph button; set the time range from 0 to 100 and the external additions range from 0 to 10, and set the number of data points to 11. Then enter the following data into the graph:

Year	**Anthro Emissions** Gt C/yr
0	0.950
10	1.125
20	1.455
30	1.609
40	1.778
50	2.000
60	2.438
70	3.686
80	5.384
90	6.542
100	7.598

data represent the history of emissions from 1890 to 1990, compiled from Marland and Boden, 1993 and Houghton, 1993

As always, make a prediction about how the system will respond, then run the model and check the results with your predictions, and also with the current rates of change for the ocean reservoir.

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OC3. Making the Water Temperature Change with Atmospheric CO_2

It is likely that as the Earth warms up, the surface waters of the oceans will also warm, and as you may recall from our discussion of the way that the carbonate chemistry of the oceans works, temperature has an affect on the partitioning of carbon between the different forms (CO_2 gas, carbonate, and bicarbonate ions), with the result that it controls the concentration of CO_2 in the water, and thus how much exchange occurs between the atmosphere and the ocean. More specifically, we know that increasing the temperature raises the concentration of CO_2 in the water and thus causes the water to give up CO_2 to the atmosphere if the ocean-atmosphere system was in equilibrium before the temperature change. You may also recall from an earlier chapter that because of the high heat capacity of water, it heats up and cools down relatively slowly. But in the interest of keeping things simple for now, let's just assume that the global air temperature will be the same as the global water temperature, meaning that the water heats up very quickly.

To carry out this experiment, we need to first add a converter that monitors the global temperature, and we will use the same formulation that we used in the terrestrial part of the carbon cycle. Then make an arrow connecting the global temperature converter to the converter called T_surf and redefine T_surf so that it is:

T_surf = 288+Global_Temp

We will compare this modified model with the results from the previous experiment with the historical changes in anthropogenic emissions. Before running the model, take time to predict how this change will alter the behavior of the system. Be sure to undo this last change before proceeding to the next experiment.

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OC4. Altering the Strength of the Biologic Pump

To get a sense for how different strengths of the biologic pump affect the operation of the whole system, do a sensitivity analysis in which you do four runs, varying the pump from a value of 0 to 15 Gt C/yr. The value of 0 represent a biologically sterile ocean and the value of 15 represents an approximate maximum. As always, be sure to make detailed predictions before running this sensitivity analysis.

With this new model, we can also incorporate a temperature sensitivity, as we did in part a) above. Reinstate the temperature sensitivity and then run the model with the anthropogenic emissions added in. How will this new version of the model compare with the standard model's response to anthropogenic emissions? Make some predictions and then run the model for 100 years. How does this model compare with the real carbon cycle, in terms of the rates of change of the reservoirs.

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A More Complex Ocean-Atmosphere Model

Having toyed with the simple version of the ocean-atmosphere carbon cycle, we are ready to graduate to a version of the model that has greater complexity in the ocean realm. Here, we separate the surface ocean into two boxes; a warm one that represents the tropical and temperate oceans and a cold one representing the polar oceans. Since these two surface oceans reservoirs have different temperatures and starting concentrations of carbon, we have to do two separate calculations involving the carbonate chemistry. The cold surface ocean is set up so that it absorbs 74 Gt C/yr from the atmosphere, while the warm surface ocean reservoir is set up to release 74 Gt C/yr to the atmosphere, thus providing for a steady state. The polar oceans, cooling and salinity increases lead to the sinking of water masses that then travel throughout the deeper parts of the oceans; this downwelling process transfers a great deal of carbon into the deep ocean. The converse of this process is upwelling that mainly occurs in the warmer parts of the oceans, thus transferring carbon to the warm shallow ocean reservoir. The circle is completed by the motions of surface currents that move water from equatorial regions to polar regions and back again; but since the downwelling occurs in the polar regions, less surface water flows back from the poles to the equator, leaving a net transfer from the warm to the cold parts of the surface ocean. This process is here called advection. In this model, we will incorporate a lesson learned from the last set of experiments and bypass the marine biota reservoirs in the form of direct flows -- biologic pumps -- from the surface ocean reservoirs to the deep ocean.

The design of this more complex model, shown in Figure 7.14, along with the equations listed below can be used to construct the steady-state version of this model that will serve as the control for the next set of experiments. Note that this model, like the previous one, is not quite in a steady state to begin with; but most of the quantities change so slightly that we can effectively consider the model to be in a steady state.

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Model Construction

A More Complex Ocean - Atmosphere Carbon Cycle

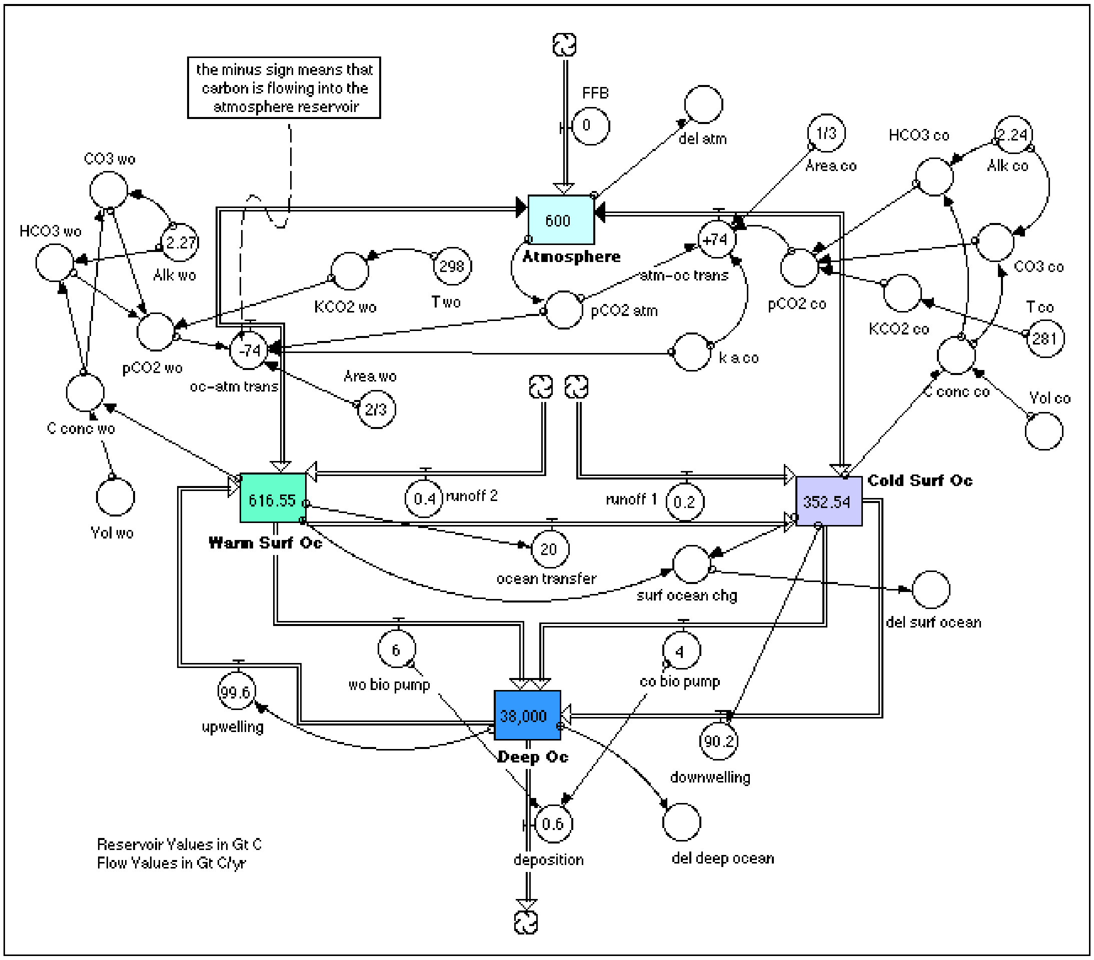

Figure 7.14 A more complex model of the ocean-atmosphere carbon cycle with reservoirs set to presumed pre-industrial conditions. The initial value of the surface ocean carbon reservoirs are fine-tuned to get the system into a near steady-state condition. The surface ocean is here divided into two reservoirs, a warm one making up 2/3 of the oceans and a cold one making up the remaining 1/3. The cold ocean is the source of downwelling currents while most upwelling transfers water from the deep oceans to the warm shallow ocean. Surface currents transport water back and forth between the warm ocean and the cold ocean, but there is a net transfer from the warm to the cold, shown as the ocean transfer flow. The warm surface waters release carbon to the atmosphere, while the cold waters absorb atmospheric carbon dioxide.

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EQUATIONS FOR MODEL OF SIMPLE OCEAN - ATMOSPHERE CARBON CYCLE

Reservoirs:

INIT Atmosphere = 600 {Gt C -- 1 Gt=1e15 g -- from IPCC, 1994}
INIT Cold_Surf_Oc = 335.566821 {Gt C -- 1 Gt=1e15 g -- modified K&S, 1994}
INIT Deep_Oc = 38000 {Gt C -- 1 Gt=1e15 g -- from Kwon & Schnoor, 1994}
INIT Warm_Surf_Oc = 615.563121 {Gt C -- 1 Gt=1e15 g -- from K&S, 1994}

Flows:

FFB = 0 {volcanic emissions or fossil fuel burning, etc.}

atm--oc_trans = Area_co*k_atm--oc*(pCO2_atm-pCO2_co) {after Walker and K&S and B&P, set to give a flux of 74 Gt C/yr following S&S}

oc--atm_trans = Area_wo*k_atm--oc*(pCO2_atm-pCO2_wo) {after Walker and K&S and B&P, set to give a flux of -74 Gt C/yr following S&S}
runoff_1 = .2 {Gt C/yr }
runoff_2 = .4 {Gt C/yr }
advection = 20*(Warm_Surf_Oc/INIT(Warm_Surf_Oc))
downwelling = 90.2*(Cold_Surf_Oc/INIT(Cold_Surf_Oc))
upwelling = 99.6*(deep_oc/INIT(deep_oc))
co_bio_pump = 4 {Gt C/yr }

wo_bio_pump = 6 {Gt C/yr }
deposition = .6*((co_bio_pump+wo_bio_pump)/10)

Converters:

Alk_co = 2.18 {modified from K&S}
Alk_wo = 2.24 {modified from K&S}
Area_co = 1/3 {fractional area}
Area_wo = 2/3 {fractional area}
CO3_co = Alk_co-C_conc_co
CO3_wo = Alk_wo-C_conc_wo
C_conc_co = (Cold_Surf_Oc/12000)/Vol_co {1e18 moles/m^3}
C_conc_wo = (Warm_Surf_Oc/12000)/Vol_wo {1e18 moles/m^3}
HCO3_co = (2*C_conc_co)-Alk_co
HCO3_wo = (2*C_conc_wo)-Alk_wo
KCO2_co = .035+.0019*(T_co-278)
KCO2_wo = .035+.0019*(T_wo-278)
k_atm-oc = .278 {Gt C/ yr ppm -- the observationally-derived rate constant, after Broecker and Peng}
pCO2_atm = Atmosphere*(280/600)
pCO2_co = 280*KCO2_co*(HCO3_co^2/CO3_co) {this is from Walker, 1993, slightly modified}
pCO2_wo = 280*KCO2_wo*(HCO3_wo^2/CO3_wo) {this is from Walker, 1993, slightly modified}
T_co = 281 {°K from K&S}
T_wo = 298 {°K from K&S}
Vol_co = .0121 {1E18 m^3 this is the upper 100 m}
Vol_wo = .0242 {1E18 m^3 this is the upper 100 m}
del_atm = (Atmosphere-600)-(DELAY(Atmosphere,1)-600)
del_deep_ocean = (deep_oc-INIT(deep_oc))-(DELAY(deep_oc, 1)-INIT(deep_oc))
surf_ocean_chg = (Cold_Surf_Oc+Warm_Surf_Oc)-(INIT(Warm_Surf_Oc)+INIT(Cold_Surf_Oc))
del_surf_ocean = surf_ocean_chg-DELAY(surf_ocean_chg,1)
global_temp = (pCO2_atm-280)*.01 {°C relative to pre-industrial temp of 15}

Experiments

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OC5-8. Repeat of experiments OC1-3 for the simple ocean-atmosphere model, described above.

In all of these experiments, compare the results from this model with those from the simpler ocean-atmosphere model to see how the increased complexity affects the behavior of the system.

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OC9. Altering Advection

What would happen if we change the advection flow in the ocean? This would be equivalent to increasing or decreasing the vigor of surface circulation in the oceans, and as such, it is not likely to occur quickly, but we nevertheless explore this question through a few simple experiments. It is also worth asking why the surface circulation might change. In a simple sense, the vigor of the surface circulation is a function of the strength of winds, which are in turn related to the temperature change between the equator and the poles. If this temperature difference is greater, winds (and thus advection) are expected to be stronger than when the difference is smaller. Since the equatorial regions cool less than the polar regions during an ice age, the temperature gradient at these time is higher than when the Earth is ice free. We might expect that with further warming, this trend will continue, decreasing the vigor of the surface circulation and thus decreasing the transfer of carbon through advection.

The experimental set-up here will be simple. We will use the model with the history of anthropogenic emissions as our control, and then alter the strength of the advection flow by changing the steady-state flow value in the equation for advection from 20 to 25 and then to 15. Then make predictions and run the model. Keep in mind that the magnitude of change here is probably much greater than we could expect in a hundred years.

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OC10. Altering Downwelling and Upwelling

Taken together, these two processes are responsible for the vertical mixing of the oceans. Sometimes this is referred to as ventilation of the oceans because the downwelling waters originate at the surface, where they pick up oxygen from the atmosphere; this is the main way that oxygen gets into the deep oceans. The strength of upwelling is, like advection, a function of the strength of winds across the surface; strong winds blowing offshore or diverging from each other move surface waters aside, allowing deeper waters to rise up to the surface. As mentioned above, wind strength is in part a function of the temperature difference between the equator and the poles, and this difference is expected to decrease with global warming. Most downwelling flows originate in the polar regions when surface waters become colder and therefore denser than their surroundings; downwelling can also occur when the salinity increases -- this could be due to formation of ice from sea water, or from very strong evaporation.

Let's do some simple experiments to investigate what happens when downwelling and upwelling are changed. First, alter the downwelling flow by increasing, then decreasing the value of the steady-state flow value (i.e., change the 90.2 in the equation to 100.2 in the first experiment, then 80.2 in the second experiment). Then do the same for upwelling. Use the model with the history of anthropogenic emissions as the control for these experiments.

By this point, you should be pretty familiar with the operation of the carbon cycle, so we will take the next step and combine the terrestrial and ocean carbon cycles to make a complete global carbon cycle.

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A Global Carbon Cycle Model

Here, finally, we combine the terrestrial and oceanic components of the carbon cycle to form a global model; two versions are developed here, just as was done for the separate components in the above exercises.

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Model Construction

The task of combining the separate ocean and terrestrial systems is relatively easy and involves copying all of one model and then pasting it into the other model, then making the connections and eliminating redundancy. You may find it necessary to destroy some of the flows and re-draw them in order to end up with a system design that is easy to understand. Since we have already created simple and complex versions of the two subsystems, we will create two versions of the global carbon cycle. The simple version will include the terrestrial model with just three reservoirs (atmosphere, soil, and land biota) and the ocean model with just one surface water reservoir; the complex one will consist of the terrestrial model that include a litter reservoir and the ocean model that includes two surface water reservoirs.

The structures of each model are shown in Figures 7.15 and 7.16. When you paste the contents of one model into another, you will have a few obvious problems to deal with. One problem is that you will have two reservoirs for the atmosphere. You need to blow up one of these atmosphere reservoirs and then connect the flows that went in and out of it to the other atmosphere reservoir. Since the oceanic atmosphere has fewer flows going in and out, it makes sense to get rid of it rather than the atmosphere attached to the terrestrial model. The ocean-atmosphere exchange flow will then have a cloud attached to the end where the atmosphere used to be; this flow can be connected to the remaining atmosphere reservoir by moving the reservoir directly on top of the cloud symbol until the cloud symbol lights up. But, making the connection this way may not lead to a very clean-looking model. It may be better to also blow up the ocean-atmosphere exchange flow and draw a new flow, giving you the freedom to provide enough bends in the flow to give you a diagram structure that is easier to follow.

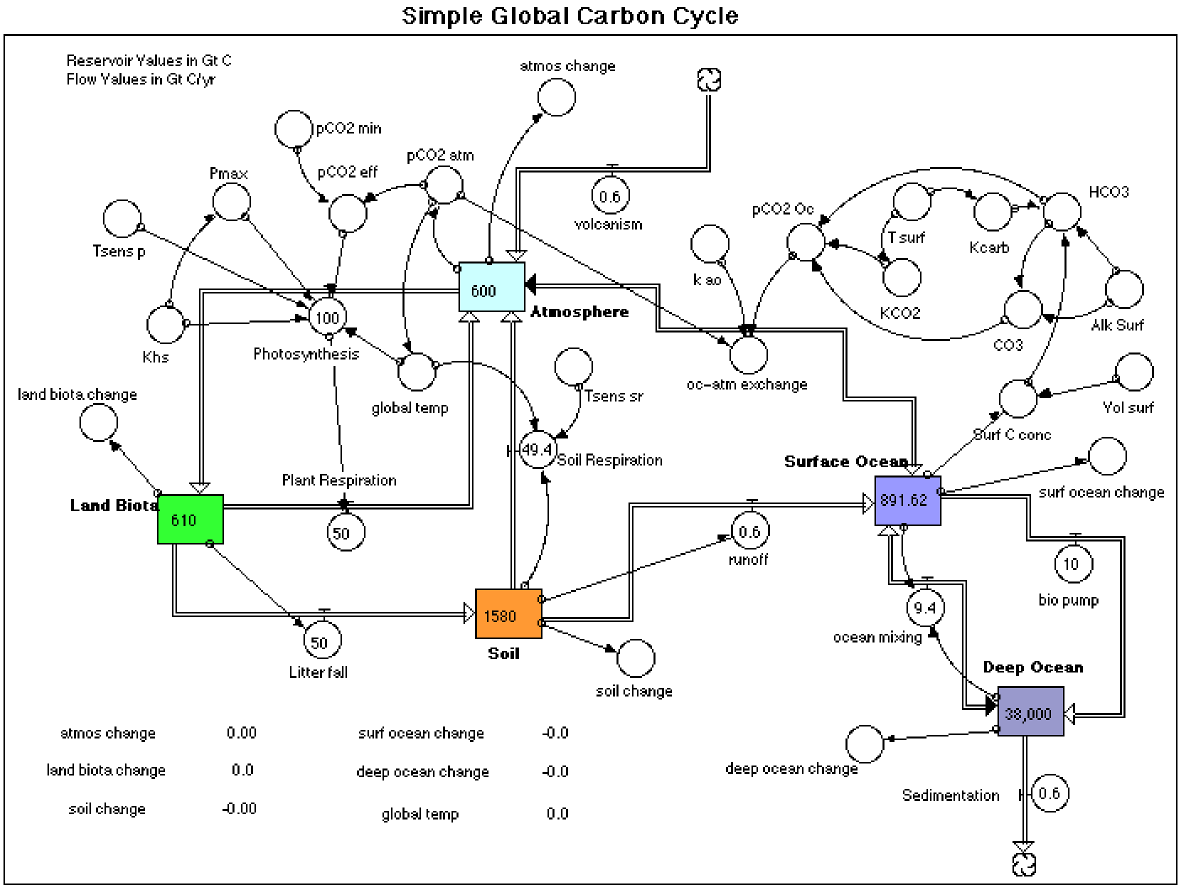

Figure 7.15. Small, simple version of the global carbon cycle — a combination of the simple terrestrial model and the simple ocean-atmosphere models represented in Figures 7.11 and 7.13. This model includes 6 numeric displays that show the ending results of a variety of converters that monitor different parts of the model, providing a simple representation of the final outcome of an experiment.

A More Complex Global Carbon Cycle

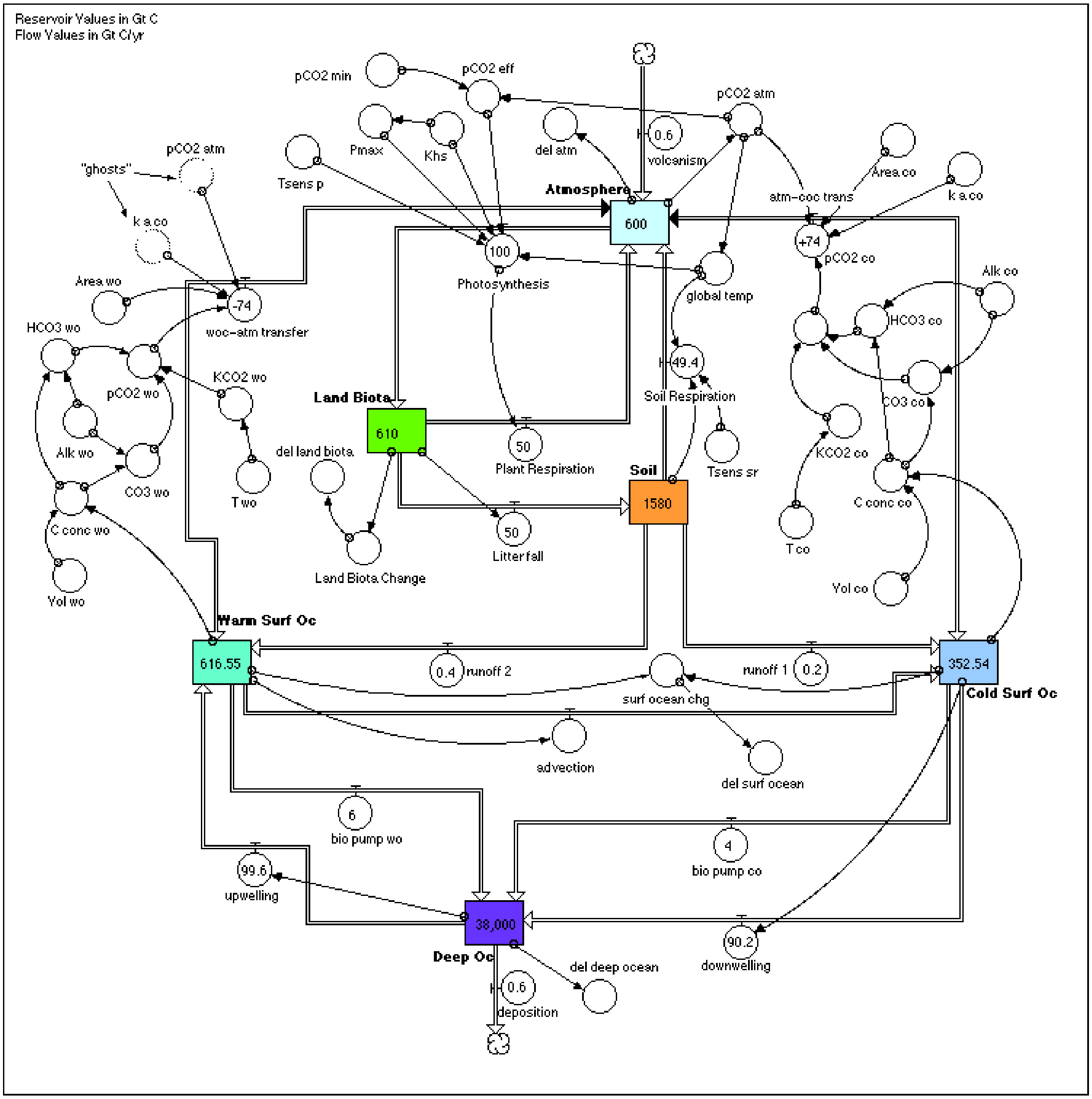

Figure 7.16. A more complex version of the global carbon cycle — a combination of the simple terrestrial model and the more complex ocean-atmosphere models represented in Figures 7.11 and 7.14. This model includes a variety of converters that monitor different parts of the model, providing a simple representation of the final outcome of an experiment. The converters beginning with the word del monitor the rate of change of different reservoirs.

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Model Equations

The model equations are simply those used in the simple terrestrial model and the complex oceanic model described above.

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Experiments

The following experiments could be carried out with either of the two models described above.

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GC1. Comparing the Model with the Real World

With our global carbon cycle model, we can finally do an important experiment in which we take advantage of humankind's inadvertent experiment with the natural carbon cycle. By running the model with the history of increasing anthropogenic emissions, we can compare our model with the present state of the carbon cycle to see whether or not our model gives results that are consistent with the real world carbon cycle. This test of the model will give us some sense for how much attention we should pay to the actual numbers generated by our model. It should be stressed, however, that even if our model gives results that are consistent with the present state, that is not a guarantee that our model captures the essence of the real system well enough to allow us to accurately and confidently predict what will occur in the future. Part of the reason for saying this is that there may very well be thresholds in the natural system, separating realms of very different behavior. So it might be the case that with another degree of warming, downwelling may begin to decline rapidly, severely limiting the amount of carbon that the oceans can absorb from the atmosphere.

Use the emissions history given below for fossil fuel burning and land-use changes.

Year	Fossil Fuel Gt C/yr	Land-Use GtC/yr
0	0.350	0.6
10	0.525	0.6
20	0.805	0.65
30	0.959	0.65
40	1.078	0.7
50	1.300	0.7
60	1.638	0.8
70	2.586	1.1
80	4.084	1.3
90	5.292	1.25
100	6.098	1.5

data represent the history of emissions from 1890 to 1990,

compiled from Marland and Boden, 1993 and Houghton, 1993

Partition the land-use changes into 75% tree-burning and 25% soil disruption. This can be done by first creating a converter called Land-Use Emissions and make it a graphical function of time, entering the above data, then creating two new converters nearby, labeling one Forest Burning and the other Soil Disrupt. Draw connector arrows from Land-Use Emissions to each of these new converters and then define each of them as the appropriate fraction of Land-Use Emissions. In comparing the model with the real world, you should pay attention to the ending model values for the atmosphere reservoir and the rates of change for the atmosphere and ocean, which can be compared with the real world. Run the model for each of the three previously-modeled greening scenarios for the land biota, characterized by K_{hs} values of 0, 62.5, and 100. Which greening scenario gives the best match with the real world? What do these models results suggest for the resolution to the problem of the missing sink ?

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GC2. The Future

a) Business-as-Usual

The next question we will investigate is one of tremendous importance -- what will happen in the future if we continue on our present course? Continuing on our present course means projecting the curve of fossil fuel emissions on an exponential curve into the future, following the projections for global population to a certain extent; this is sometimes called the business-as-usual scenario that implies no policy/behavioral responses to changing climate. It may well be that population will stabilize before the next 100 years (let's hope so), but for our purposes here, let's simply extend the emissions curve to 100 years into the future as if there was no stabilization. At present rates of consumption, we should run out of liquid petroleum before the end of this time, but we will still have plenty of coal reserves on hand that could be utilized, so the emissions scenario we will use is not unrealistic, although it is not the most optimistic (we'll explore more optimistic scenarios later).

To set up this experiment, we'll have to modify the graphs for fossil fuel burning and land-use changes, extending both to 200 years. Continue the general trend of the fossil fuel burning curve in order to reach a rate of 20 Gt C/yr at 200 years. The land-use curve is not expected to change too much in the future; we are rapidly approaching the limit of massive land-clearing and tree-burning, but there will be continued burning and soil disruption at more of a steady rate in the future. We will represent this by making the land-use emissions curve remain steady at a value of 2 Gt C/yr until 200 years. The table below summarizes the values used to project the model into the future. This experiment should be run with the range of K_{hs} values from the previous experiment, including the value that gives the best match with the present state of the carbon cycle.

Summarize the results of these experiments in the form of a table that gives an accounting the changes of the various reservoirs and the global temperature change and the ending rates of change of the atmosphere, ocean, and land biota reservoirs.

b) Stabilization

How will the system respond to a stabilization at the current emissions levels? This means running the model with the standard emissions for the first 100 years and then keeping the emissions steady for the next 100 years. This scenario implies that through some combination of dramatic changes in the population growth rate and fossil fuel consumption per person, the emissions are kept constant at the present rates. This scenario clearly involves major policy changes and a great deal of discipline and cooperation among the people of the world. It is possible that technological break-throughs may provide acceptable energy alternatives and huge increases in energy efficiency, thus enabling us to continue consuming energy at high rates, but it is quite likely that this scenario will involve a reduction in energy use per person, especially in high-use countries such as the U.S. A. To the extent that our economy is helped along by our intensive energy use, a reduction in energy use probably implies a reduction in the per capita income and a reduction in economic growth. This may force countries to strive for economic steady states rather than economic growth. These are clearly difficult adjustments, and this is an optimistic scenario, but one worth investigating with our model.

As in the previous experiments, run the model with this emissions scenario under the range of K_{hs} values used above. How long do you think it will take for the system to stabilize after the emissions have stabilized? Does the time-to-stabilization change for the different Khs values? What are some implications of this time-to-stabilization for political success of policies designed to curtail emissions? Before running the model, try to predict, at least in a general way, what will happen in this scenario. Summarize the results of these experiments in the form of a table that gives an accounting the changes of the various reservoirs and the global temperature change and the ending rates of change of the atmosphere, ocean, and land biota reservoirs.

c) Reduction

Now let's imagine that globally, we go on an incredible austerity program and/or that there are amazing, un-dreamed of technological advances (of course, we would be foolish to assume that such technological developments area going to save the day). Clearly, this is the most unrealistic of the scenarios explored here, but it defines one end of a spectrum of scenarios, so it is a good scenario to explore -- it helps place some boundaries on what the future could hold.

So, after running the model for 100 years, bringing us up to the present, we suddenly eliminate all emissions from fossil fuel burning and land-use changes. How long will it take for the system to recover? What is the state of the system after 100 years? How does the range of K_{hs} values alter the recovery of the system? Before running the model, try to predict, at least in a general way, what will happen in this scenario. Summarize the results of these experiments in the form of a table that gives an accounting the changes of the various reservoirs and the global temperature change and the ending rates of change of the atmosphere, ocean, and land biota reservoirs.

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Summary

The global carbon cycle is one of the most important of the biogeochemical cycles since it controls the atmospheric concentration of CO_2. It is also one of the most complex and interesting of the cycles since it integrates biospheric, atmospheric, geospheric, and hydrospheric phenomena. In the form of the carbon cycle, we really begin to understand how all of these four realms of the whole Earth system interact with each other. The fact that we have, over the last one hundred years, been conducting a large experiment with the global carbon cycle is cause for concern. This system is important, big, and complex and it is only through this kind of modeling that we can begin to make some general predictions about what might happen (realizing that these model results are limited by the fact that we do not yet fully understand some parts of this system).

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