Global Warming and System Dynamics

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Abstract

Global warming has emerged as the dominant environmental problem of our time. The next fifty years will be a period of growing accumulation of greenhouse gasses (GHG) in the atmosphere and rising temperatures. It could also be a period in which the nations of the world adopt more stringent policies to control the emissions of carbon dioxide (CO2) and other GHG. If emissions are cut sufficiently, it is possible to stabilize GHG within the first half of the century. The risks of global warming could be reduced, but not eliminated. This paper describes recent applications of system dynamics to improve our understanding of climate change, and it looks ahead to the potential contributions in the future.

Organization

This paper begins with some reflections on climate and environmental concerns of the 1950s and 1960s, the time period that marks the beginning of the field of system dynamics. The paper then turns to the climate system, a highly nonlinear, exceedingly complex system that responds in a sluggish manner to changes in anthropogenic emissions. The paper describes the complexity of the climatic system and classifies the types of models used by research scientists to understand that system. System dynamics models of climate change have been used in an educational manner in the past, and this is likely to be where the most useful contributions will be made in the future.

The appendices point to additional areas where we can contribute. Appendix A describes how system dynamics can contribute to the debate over the best combination of policies to reduce GHG emissions. For many policymakers, the key question is how to put a price on carbon -- with a carbon tax or a carbon market? Most economists prefer the carbon tax, but political factors are leading Europe and the US to carbon markets. Appendix B provides a brief summary of a system dynamics case study of the electric power industry. This industry was selected because it is expected to play a pivotal role in the next twenty years. System dynamics was used to show that the power industry could lead the way in reducing CO2 emissions, and it could do so by relying on technologies that exist today.

Further Reading

This paper draws from my description of *Global Climate Change and the Pivotal Role of the Electric Power Industry* to appear in a book on electricity markets (Ford 2008). Additional information is available from articles that appeared in 2006 (Bowen 2006, *The Economist* 2006, *Technology Review* 2006) and in summary reports by the Intergovernmental Panel on Climate Change (IPCC 2001, 2007). Readers interested in the long history of research on climate change are referred to *The Discovery of Global Warming* (Weart 2003). Other popular books are authored by Schneider (1990), Flannery (2005) and Gore (2006).

Reflections on the 1950s and 1960s

The System Dynamics Society meets in Boston in 2007 to celebrate the 50th anniversary of the field. It will be an opportunity to reflect on the early ideas and accomplishments of the field. This paper offers some reflections on two environmental trends from 50 years ago that help us think about the challenge of global warming. The first trend involves the cooling trend of the 1950s – 1960s. A second trend involves the growing use of toxic chemicals like the pesticide dichloro-diphenyl-trichloro-ethane (DDT).

Looking Back 50 Years: The Cooling Trend

The 1950s and 1960s were puzzling decades for climate scientists. Global average temperatures were declining, but atmospheric CO2 was increasing. CO2 is one of the greenhouse gasses that trap part of the infrared waves the re-radiate from the surface of the earth. This "greenhouse effect" tends to cause higher temperatures. But average global temperatures were falling, not rising.

This puzzling situation is now understood to be caused by a combination of increased CO2 and increased sulfates in the atmosphere. Sulfates are short-lived aerosols which act to reflect sunlight back into space, thereby contributing to the cooling of the planet. A major source is sulfur dioxide emissions which were increasing during the 1950s and 1960s. Thanks to climate research and modeling of the past fifty years, we now know that sulfates and other aerosols masked the warming trend. The cooling trend reminds us of the value of computer modeling to understand the complexities of the climate system.

Looking Back 50 Years: DDT and *Silent Spring*

The 1950s and 1960s are also remembered for the discovery of the long-lived and wide spread impacts of DDT. This pesticide was used with spectacular success when it was first applied in the 1940s. Its dangerous side effects were evident by the 1950s, and Rachel Carson explained the spread of DDT in the soils, oceans and wetlands and its impact on birds. Her 1962 book *Silent Spring* is often used to mark the birth of the modern environmental movement. DDT is extremely stable, and it remains in the soils and ocean long after its initial application. Scientists warned that dangerous levels of DDT could appear in fish decades after a decline in its use. System dynamics modeling has been used to demonstrate the sluggish response of DDT concentrations to changes in its application (Randers 1973, Ford 1999). These models help us understand that DDT levels in fish would remain dangerously high for three or four decades after efforts to restrict its use.

The long-lasting impact of DDT is analogous to the long-lasting effect of CO2 emissions. Unfortunately, the problem with CO2 is even more challenging since the impacts of anthropogenic CO2 emissions today will contribute to increased concentration in the atmosphere for over a hundred years due to the circular flows in the global carbon cycle.

The Global Carbon Cycle

Figure 1 is a UNEP schematic showing the carbon flows in a visual manner. Figure 2 summarizes the key stocks and flows, with estimates of current storage in GT, gigatons of carbon.[1] The flows are measured in GT/year of carbon and are depicted with numbers rounded off to the nearest GT/year.

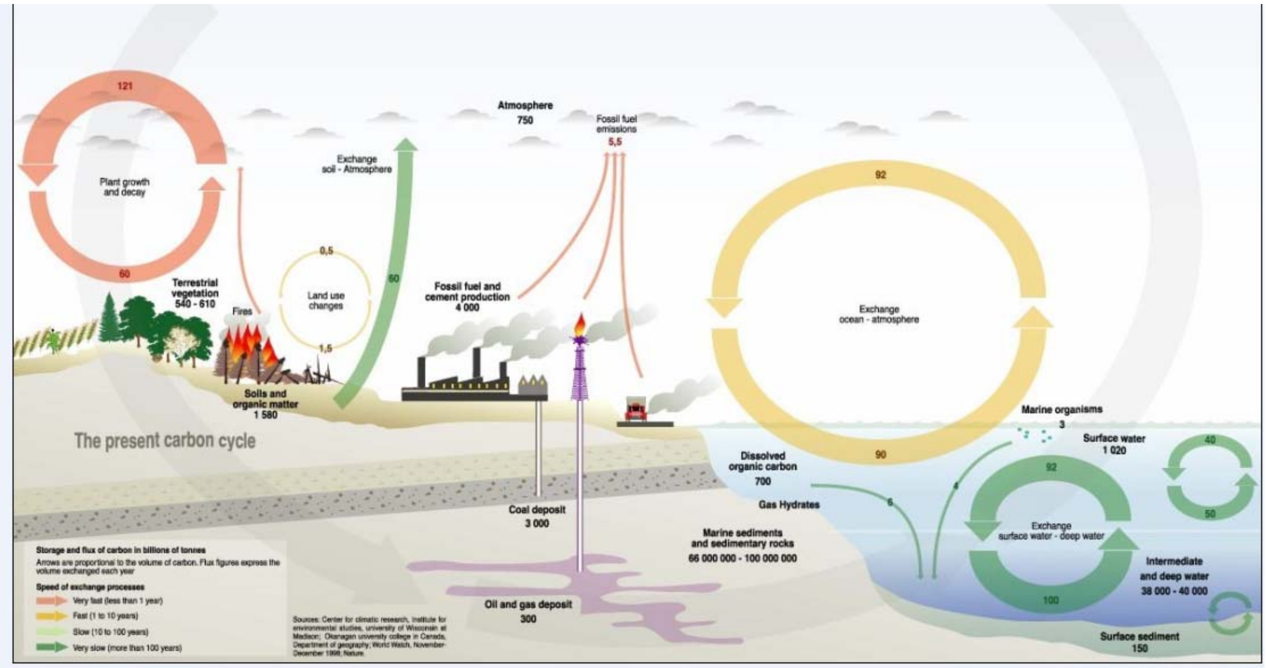

Figure 1.The global carbon cycle.

Source: United Nations Environmental Program (UNEP) http://www.unep.org/

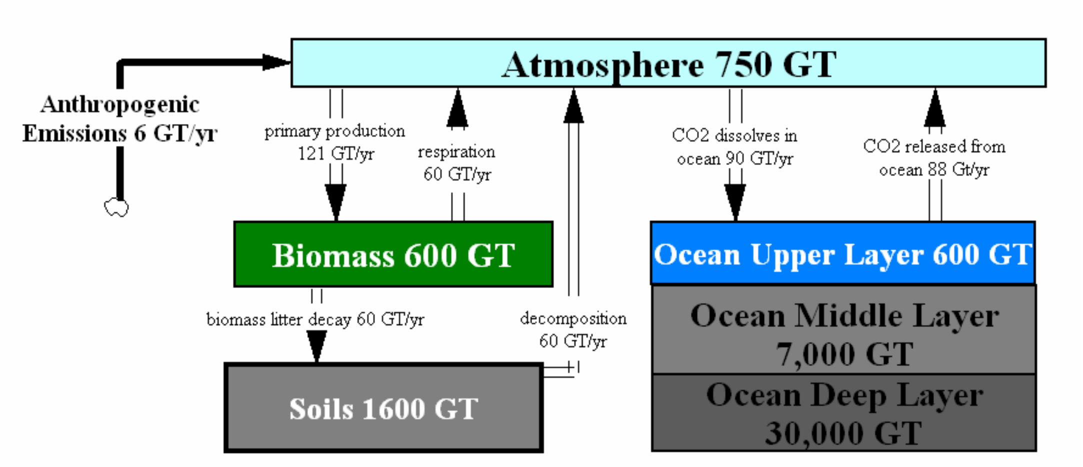

Figure 2. Depiction of carbon flows and storage from educational websites.

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[1] Carbon is the C in CO2. When the carbon is stored in the form of CO2, it may be customary to report the weight of the CO2. To convert from tons of C to tons of CO2, multiply by 3.67.

The many flows in Figure 2 make it difficult to anticipate the growth in atmospheric carbon over the coming decades, so it is useful to simplify the picture by concentrating on a single flow to the atmosphere.

Figure 3 shows the simplest possible way to anticipate the change in atmospheric carbon from anthropogenic emissions. We eliminate all the other flows and ask ourselves about the accumulation of CO2 in the atmosphere due solely to the man-made emissions of CO2. This simple exercise will provide a rough estimate of atmospheric CO2 at the end of the century.

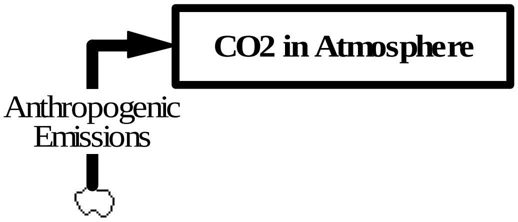

Figure 3. The simplest possible model of accumulation of CO2 in the atmosphere.

The anthropogenic emissions are growing at around 1.4 %/year, so they would reach around 7.5 GT/year in 15 years. During this short interval, around 100 GT would be added to the atmosphere. Now, suppose that emissions remain constant at 7.5 GT/yr over the next one hundred years. This would add another 750 GT to the atmosphere. Atmospheric storage would then be over twice as large, and the CO2 concentration would be over 700 ppmv by the end of the century.

This calculation is a useful starting point to anticipate future CO2 concentrations. It is based on the simplest possible model which assumes that emissions enter the atmosphere and remain there forever. However, we know that CO2 is removed rather quickly by primary production of terrestrial biomass or by absorption in the ocean's upper layer. But the removal of CO2 from the atmosphere does not mean that the carbon is removed from the system. Rather, it circulates through the system, reentering the atmosphere at one point, exiting the atmosphere again at a later point, and returning to the atmosphere yet again further in the future.[2] The dynamic consequences of these circular flows are not easily understood.[3] Our intuition can be improved by concentrating on the net flows to the terrestrial system and to the ocean system.

The left side of Figure 2 shows the net flows to the terrestrial system. Total flows out of the atmosphere exceed the inflow by 1 GT/year. This imbalance suggests that around 1 GT/yr of carbon is added to the stock of biomass/soil so the carbon stored in the biomass/soil would grow over time (perhaps due to extensive reforestation of previously cleared land.) The right side of Figure 2 shows the flows from the atmosphere to the ocean. The flow out of the atmosphere exceeds the inflow by 2 GT/year. The total, net-flow out of the atmosphere is 3 GT/year which

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[2] The overall effect of these circular flows is that CO2 emitted into the atmosphere today "will contribute to increased concentration of this gas and the associated climate change for over a hundred years" (Houghton 2004, p. 227).

[3] Sterman and Sweeney (2007) describe the poor reasoning by highly educated adults when asked about CO2 accumulation in the atmosphere. Many of subjects tended to misperceive the sluggish response of atmospheric CO2. The experiments showed that many subjects tend to match the pattern of atmospheric CO2 with the pattern of anthropogenic emissions (i.e., a "pattern matching" subject would conclude that atmospheric CO2 will decline this year if anthropogenic emissions were to decline this year.) This type of thinking can lead to a "wait and see" attitude about climate policy that is inappropriate when today's emissions contribute to higher concentrations over the next hundred years.

means that natural processes are acting to negate approximately half of the current anthropogenic load (IPCC 2001, Socolow 2004).

As the use of fossil fuels grows over time, the anthropogenic load will increase. But scientists do not think that natural processes can continue to negate 50% of an ever increasing anthropogenic load. On the terrestrial side of the system, there are limits on the net flow associated with reforestation of previously cleared land. And there are limits to the carbon sequestration in plants and soils due to carbon nitrogen constraints. On the ocean side of the system, the current absorption of 2 GT/year is already sufficiently high to disrupt the chemistry of the ocean's upper layer. Higher CO2 can reduce the concentration of carbonate, the ocean's main buffering agent, thus affecting the ocean's ability to absorb CO2 over long time periods.

Climate Models and Uncertainty

Scientists use a variety of models to keep track of the greenhouse gasses and their impact on the climate, as explained in the box below. Some of the models combine simulations of the atmosphere, soils, biomass and ocean response to anthropogenic emissions. The more developed models include CO2, methane, nitrous oxides and other GHG emissions, and they keep track of their changing concentrations in the atmosphere.

Models of the Climate System

A wide variety of models are used to improve our understanding of climate change. All of the models provide a useful perspective on the highly nonlinear dynamics of the climate system. Claussen (2000) classifies the models according to the degree of complexity: simple, intermediate and comprehensive.

The simple models are described in a primer by the IPCC (1977). They are sometimes called "box models" since they represent the storage in the system by highly aggregated stocks like those shown in Figure 2. The models generally produce zonally-or globally-averaged results, and only for temperature and temperature changes (and not for other variables such as rainfall). The parameters are usually selected to match the results from more complicated models, and the parameters can be altered for purposes of sensitivity analysis. Also, the models can be initialized in a steady state without the computational cost of the more complex models. The simple models can be simulated faster on the computer, and the results are easier to interpret. This makes them valuable in conducting extensive sensitivity studies and in scenario analysis.

The comprehensive models are maintained by large research centers, including NASA, NCAR, NOAA, and the Hadley Center in the UK. The term "comprehensive" refers to the goal of capturing all the important processes and simulating them in a highly detailed manner. The models are sometimes called GCMs (General Circulation Models). They can be used to describe circulation in the atmosphere or the ocean. Some models simulate both the ocean and atmospheric circulation in a simultaneous, interacting fashion. They are said to be "coupled general circulation models" (CGCMs) and are considered to be the "most comprehensive" of the models available (Claussen 2000). They are particularly useful when a high spatial resolution is required. However, a disadvantage of the CGCMs is that only a limited number of multi-decadal experiments can be performed even when using the most powerful computers.

Intermediate models help scientists bridge the gap between the simple and the comprehensive models. Claussen (2000) describes eleven models of intermediate complexity. They aim to "preserve the geographic integrity of the Earth system" while still providing the opportunity for multiple simulations to "explore the parameter space with some completeness. Thus, they are more suitable for assessing uncertainty." The uncertainty analysis by Webster (2003) is summarized here.

This paper reports the uncertainty analysis using one of the eleven models of "intermediate complexity." The model was developed at MIT as part of a long-term research program on the science and policy of global change (http://web.mit.edu/globalchange/www/). One of the principal goals is to help researchers and policy makers appreciate the range of uncertainty in climate impacts from growing emissions. Webster (2003) began with an estimate of anthropogenic emissions growing to around 19 GT/year by 2100. The mean projection of atmospheric CO2 was around 700 ppmv by 2100. To put this result in perspective, it is useful to construct the simplest possible model that can reproduce the mean results.

Figure 4A demonstrates how this may be done. It shows the simplest possible model to explain the mean projection by Webster (2003). The stock accumulates the effect of three exogenous flows. Anthropogenic emissions are set to match the mean projection by Webster (2003), and the net removals are subject to user experimentation.

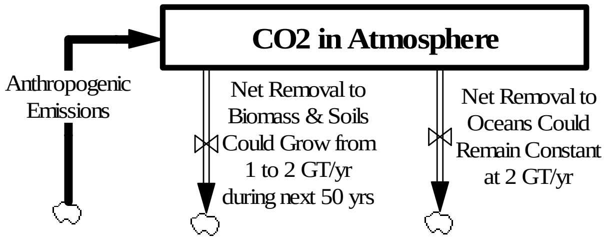

Figure 4A. Assumptions to match results in Fig. 4B.

Figure 4B puts the mean result in perspective by showing three different ways to accumulate the emissions. The top curve shows the growth in CO2 concentration if there were no net removal of CO2 from the atmosphere by natural processes. The concentration would grow to 880 ppmv by the year 2100. The middle curve assumes the natural processes continue to negate 3 GT/yr of the emissions. Atmospheric CO2 would grow to 740 ppmv. The lowest curve shows CO2 concentration growing to 700 ppmv, the best match with the mean projection by Webster (2003).

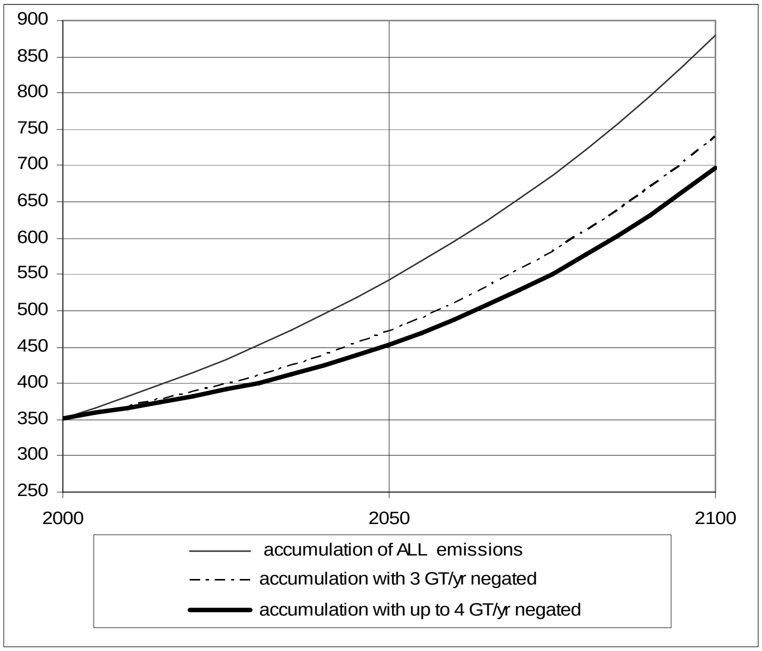

Figure 4B. Estimates of atmospheric CO2 concentration emissions grow from 6 to 19 GT/yr during the century.

The lowest curve represents CO2 accumulation with the assumptions explained by the long names assigned to the flows in Figure 4A. The net flows out of the atmosphere would increase from 3 to 4 GT/yr during the first half of the century and remain at 4 GT/yr for the second half. These results make sense if the natural processes are currently about 75% of their satiation limit. As more CO2 accumulates in the system, net removal will reach a limit of around 4 GT/yr. Webster (2003, p. 310) explains that the removal would be split evenly between the terrestrial and ocean systems.

Range of Results from Uncertain Parameters

Webster (2003) calculates the mean temperature impact as a 2.4ºC warming (relative to the temperature in the year 1990). The 2.4ºC is a major impact; for example, the warming over the 21st century would be four times higher than the 0.6ºC observed in the previous century. The goal of the analysis was to show the uncertainty in the climate impacts. Figure 5 summarizes a statistical analysis of 250 simulations by showing the 5%, 50%, 95% estimates of CO2 concentrations and temperature impacts as indicated by results in the year 2100.

The "business as usual results" assumes no policy intervention to limit emissions. The most likely result is a CO2 concentration around 700 ppmv and a global average surface temperature 2.4ºC above the temperature in 1990. However, with a policy to control emissions, there would be a cap on emissions with the goal of stabilizing atmospheric CO2 at around 550 ppmv. The most likely result is a CO2 concentration of 512 ppmv and a global average surface temperature 1.7ºC above the temperature in 1990. The 5 to 95% range is greatly reduced with the stabilization policy. Atmospheric CO2 could range from 466 to 580 ppmv, and the temperature impact would range from 0.8 to 3.2ºC.

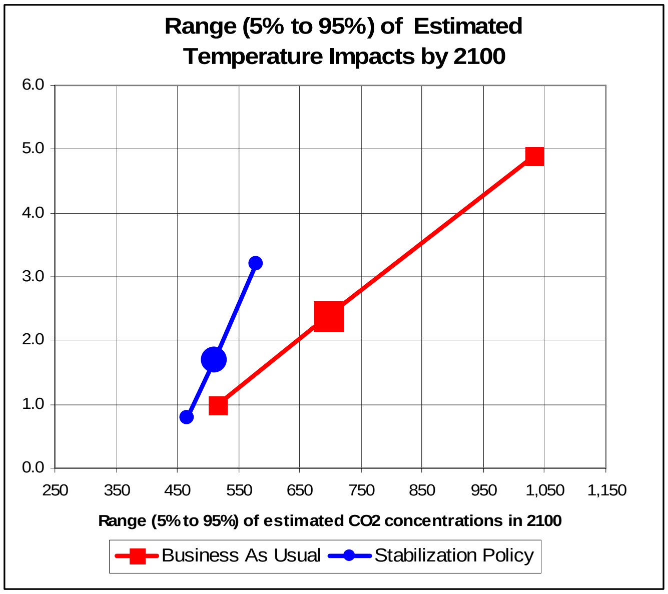

Figure 5. Summary of the 5%, 50%, 95% range of impacts from Webster (2003).

Structural Uncertainty

The 5% to 95% uncertainty bands portray the large range of impacts from the uncertain parameters. But parametric uncertainty is only part of the uncertainty. Changes in the fundamental structure of the model could also change the range of results. Examples of structural changes include the addition of new pollutants or the inclusion of new feedback effects between the atmospheric and terrestrial systems. These sources of uncertainty are much more difficult to quantify. Ultimately, statements about structural uncertainty come down to the scientists' intuition on whether the omitted structure will act in a stabilizing or a destabilizing manner. In some cases, adding new relationships to a model will close negative feedback loops which can act to stabilize the simulated system (Ford 1999). In many of these cases, the new structure could lead to a narrower band of uncertainty. However, the customary process of model development is to first include most of the pervasive, well understood, negative feedback loops at work in the system. The less understood feedback loops are often left to future work (when more evidence about their role becomes available.) These omitted feedbacks can often be positive feedback loops that act to destabilize the system, as explained in the box below.

Destabilizing Feedback and Rapid Climate Change

Understanding the role of positive feedback has been crucial to scientists' research and eventual "discovery" of rapid climate change. Weart (2003, 2007) explains that "swings in temperature that were believed in the 1950s to take tens of thousands of years, and in the 1980s to take hundreds of years, were now found to take only decades." Examples of positive feedback loops include:

- <u>methane from permafrost</u>: Higher temperatures can cause the permafrost to shrink, releasing the methane embedded in the clathrate sediments to the atmosphere. More methane in the atmosphere could lead to further warming and still greater shrinking of the permafrost.
- <u>methane from bogs and swamps</u>: Higher temperatures can accelerate the decomposition of dead organic matter in bogs and swamps, also releasing methane to the atmosphere.
- <u>water vapor</u>: Higher temperatures lead to more water vapor in the atmosphere which can lead to an increase in long wave absorption. With more absorption, there could be still greater warming and more water vapor in the air.
- <u>soil decomposition</u>: Higher temperatures tend to cause faster decomposition of soil carbon, releasing more CO2 into the atmosphere, thus trapping more radiation and increasing the temperature still further.
- <u>sea ice/albedo flip</u>: The sea ice has a higher albedo than the surrounding water. As the ice melts, there is an increase in ice-free water which leads to more heat absorbtion. This increases the polar temperatures causing still further melting of the sea ice.

The water vapor and soil decomposition feedbacks involve a combination of stabilizing and destabilizing feedbacks acting in tandem. With increased water vapor, for example, there may be greater short wave reflection which acts as a stabilizing feedback effect. The relative strength of the water vapor feedback effects is said to be a key factor influencing climate sensitivity (IPCC 2007, p. 9).

The soil decomposition also involves a combination of destabilizing and stabilizing effects. Higher CO2 concentrations can lead to greater biomass growth (due to the "fertilization effect," subject to sufficient nitrogen in the soil to support the growth). This is a stabilizing feedback since increased biomass growth removes CO2 from the atmosphere. Sorting out the relative power of the soil carbon feedbacks requires detailed analysis with "fully coupled" models. Such analyses show the possibility for soil carbon to change from a net sink to a net source of carbon to the atmosphere.

The destabilizing effect of the sea ice/albedo flip is described in detail by Hansen (2007). He argues that the IPCC models do not represent the amplifying effect of the sea ice feedback and their projections understate the possibility of a rapid rise in sea-level.

System Dynamics Models of Climate Change

I turn now to the role of system dynamics in understanding the challenges of global warming. Previous work by Richardson (2007) and by Fiddaman (2002) provide good examples of previous contributions. Figures 6 and 7 show how the carbon cycle is represented in each of the models.

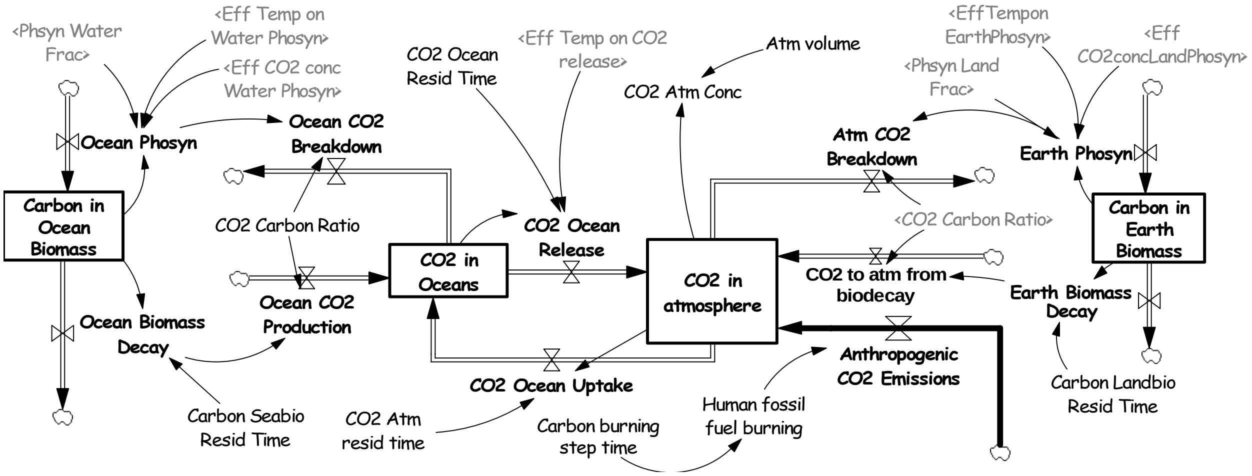

Figure 6. Representation of the carbon cycle in the model by Richardson (2007)

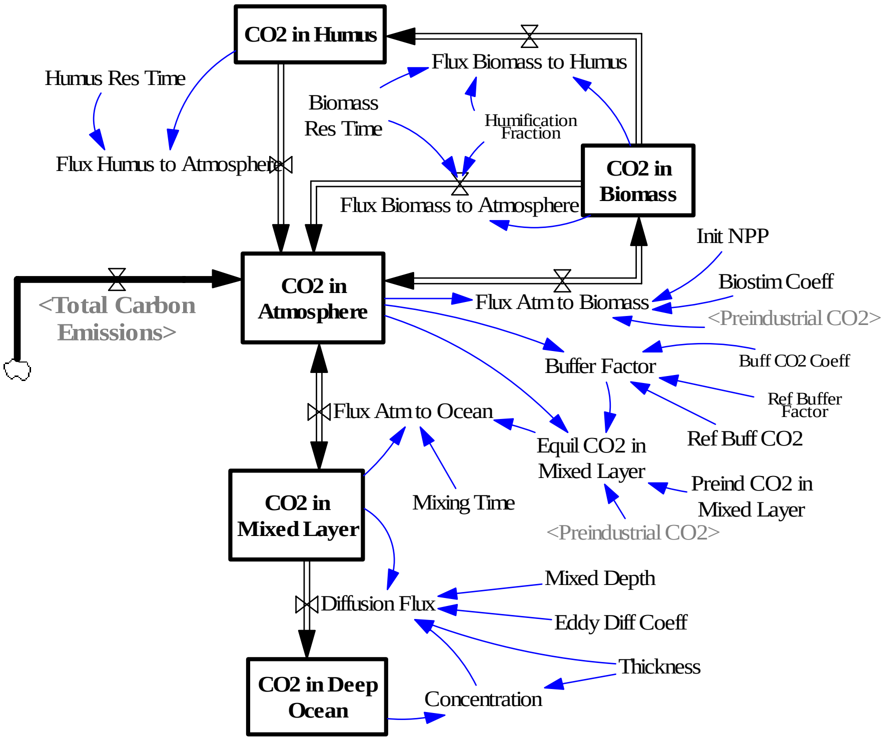

Figure 7. Representation of the carbon cycle in the model by Fiddaman (2002).

The anthropogenic emissions are highlighted by the bold flow in each diagram. These emissions add to the stock of CO2 in the atmosphere. Both models simulate the exchange of

CO2 between the atmosphere and the terrestrial system. Richardson represented the terrestrial system with a single stock; Fiddaman used two stocks. Both models simulate the exchange between the atmosphere and the ocean system. Richardson used two stocks, one for the CO2 dissolved in the ocean and a second stock for the carbon taken up by the ocean biomass. Fiddaman used one stock for CO2 in the upper layer (where the mixing takes place) and a second stock for CO2 in the deep ocean.

Figures 6 and 7 show a similarity in the size of a carbon cycle portion of each model. Using the number of state variables as a measure of model size, the diagrams show that 5 or 6 stocks were judged sufficient to meet the modeler's purpose. This decision puts the system dynamics models in the same size category as the "simple" climate models[4] described by the IPCC (1997, p. 26). The carbon cycle portions of each model were selected for comparison in this paper, but both models include more variables than shown. Figure 6 is one of three views in Richardson's model; Figure 7 is one of around thirty views in the Fiddaman model. The difference is size arises from differences in the purpose of the models.

Richardson's purpose was to arrive at a better understanding of the key uncertainties in the climate system. He elected to construct a quite compact model to serve this purpose. The entire model fits on three views of the Vensim software.[5] Figure 6 shows the carbon cycle view. A second view is used to represent the heat stored in the earth, the average temperature and the effect of temperature on the ice - water cycle. And a third view is used to keep track of atmospheric concentration of other greenhouse gasses and the aerosols. Richardson (2007) used the model to isolate the research questions in most need of resolution. He found the key uncertainty to involve the relative importance of the water vapor feedbacks. This finding matches the finding in the most recent assessment by the IPCC (2007, p. 9). They concluded that resolving the relative importance of the water vapor feedbacks was one of the highest priority research areas.[6]

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[4] The IPCC 1997, p. 26) describes the carbon cycle commonly used in "simple models" as comprised of 8 stocks. The common approach is to assign one stock to carbon in the atmosphere and a second stock to carbon in the ocean. Six stocks are used to represent carbon stored in different types of vegetation, their detritus, in the mobile soil and in the resistant soil. However, if the ocean portion is to be treated in more detail (p. 28), a variation in the simplest approach is to distinguish between the upper layer and the deep ocean and between the northern and southern hemisphere. The inclusion of four stocks would allow for a simulation of polar sinking and upwelling in each hemisphere.

[5] Vensim models are comprised of multiple "views," and many modelers use different views to separate conceptually different parts of the model. Often a single view will contain variables that can be displayed in a clear fashion on a single screen, as shown in Figures 6 and 7. The three views in Richardson's model follow this practice. The intent was to explore sensitivity of climate projections with a "pocket" model, i.e., a sufficiently compact model that one could think of it as fitting in your pocket.

[6] The water vapor effects are crucial because they involve a combination of stabilizing and destabilizing feedbacks. For example, with warmer temperatures, there is more water vapor in the atmosphere and there could be greater short wave reflection. On the other hand, more water vapor could lead to an increase in long wave absorption, still more warming and still more water vapor in the air. The IPCC concluded that judging the strength of the feedback effects is a key factor influencing climate sensitivity.

Fiddaman's model is much larger, around 30 views in total. He elected to build a larger model because his purpose was to simulate the climate system within a larger system that includes growth in human population, growth in the economy, and changes in the production of energy. Fiddaman's focus was on policy making, and the model allowed for simulation of energy taxes, carbon taxes and carbon permits. The model was organized conceptually as nine interacting sectors[7] with a high degree of coupling between the energy, economic and the climate sectors. Fiddaman focused on policy making, especially the challenge "to take aggressive action without causing extreme short-run economic disruptions and the ensuring political backlash. He concluded that carbon taxes are a more suitable policy than carbon permits. His view on carbon taxes is shared by many economists, but the politics of policy making in the US and Europe favor the adoption of carbon permits, as explained in Appendix A.

Future Directions for System Dynamics Models of Climate Change

The two models were selected to illustrate directions for future contributions of system dynamics modeling. The models were constructed with quite different purposes, but they would be viewed as quite similar by scientists outside the system dynamics community. Indeed, both models would fit clearly in the category of simple[8] models in the classification by Claussen (2000). She describes climate models as belonging to three groups (simple, intermediate and comprehensive) depending on the degree of complexity.

These categories differ in their emphasis on number of processes, the detailed treatment of the processes and the extent of integration among the different processes. These three dimensions are shown in Figure 8 with "integration" as the prominent dimension. Achieving integration among the atmospheric, terrestrial and ocean systems is the point of emphasis in the simple models. Claussen (2000) and the IPCC (1977) do not refer to system dynamics climate models, but readers will appreciate that the two examples described here fit cleanly in the simple category.

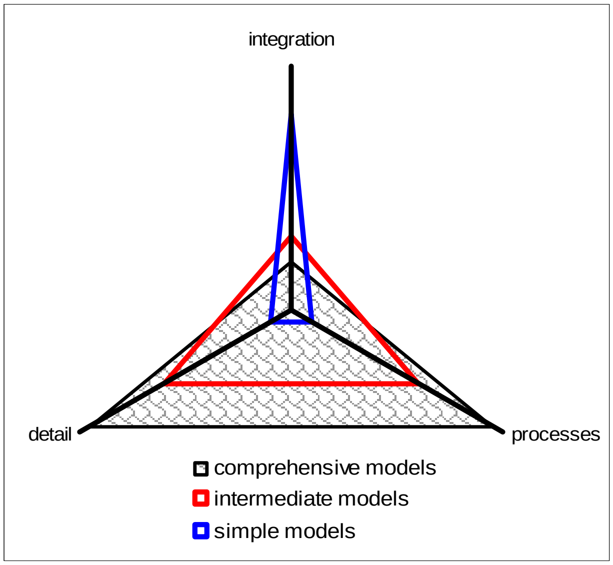

Figure 8. Classification of climate models.

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[7] Three sectors are used for population, the economy and energy. An additional three sectors are assigned to CO2 emissions, the carbon cycle and the climate. Two sectors are used to keep track of results, one for impacts of the climate changes and a second to perform welfare calculations. The model is designed to simulate a wide variety of policies, and a ninth sector is assigned to policy considerations.

[8] The term "simple" is sometimes used in a derogatory fashion, perhaps to convey the idea that a model is simplistic and therefore not useful. This is not the intent of Claussen (2000) and the IPCC (1977). These comparisons make it clear that simple models have a useful role to play.

Their emphasis is on simulating feedback loops that create a tightly coupled picture of the climate system. Climate scientists recognize the importance of closing these loops. Using Claussen's terminology, one would say that such models have achieved a high degree of "integration." However, this is achieved by limiting the number of processes and the degree of detail in representing each of the processes. The "comprehensive" models, on the other hand, strive to include as many processes as possible and to simulate them with tremendous detail (often with a high degree of spatial resolution). However, this highly detailed treatment is computationally difficult, and the scientists are forced to work with decoupled models that lack the degree of "integration" needed in sensitivity studies or in policy analysis.

In looking to future directions, some readers might view the next challenge as moving the system dynamics models from the "simple" to the "intermediate" category. By adding more processes and more detailed treatment of each process, the models might gain greater credibility and deliver new insights. However, I believe a move in this direction would entail a loss of feedback coupling between the sectors, and the new group of models would loose their ability to provide an "integrated" treatment of the climatic system.

In my view, the best line of improvement is to retain the emphasis on providing an integrated treatment of the climate system. New models might expand along the "processes" dimension (in Fig. 8), but such expansion should not be achieved by sacrificing the degree of integration. My personal view is that system dynamics modelers should not aim for highly detailed treatments of each process, for that direction would almost certainly lead to less integration and to difficulties in simulation time and in interpretation.

The Richardson and Fiddaman examples provide role models for other system dynamicists interested in either the science or the policymaking of climate change. Richardson's example deals with the science of climate change, and it reveals that a relatively simple model can lead to improved understanding of the key uncertainties. Readers who elect to conduct similar modeling studies will find that climate scientists appreciate the value of a feedback approach. Although few of the climate modelers use the familiar system dynamics simulation packages, almost all of the scientists "speak the same language" as system dynamicists when they talk about the system. This is a productive area for further applications, especially for those in educational positions who would strive for new ways to structure models for maximum communication, learning and discovery.

Fiddaman's example shows the usefulness of integrating climate, the economy and the energy system in a single model. Carbon policy is shaped by a combination of political and economic factors, and professional economists make important contributions to the policy discussion. Readers who elect to follow Fiddaman's example will probably discover that the economists do not necessarily "speak the same language" as system dynamicists. For example, many economists might acknowledge the feedback effects simulated by Fiddaman, but few would attempt to represent them in a single, integrated model of the climate/economic/energy system. This difference in thinking (and modeling) creates an important need for additional simulation studies of the climate/economic/energy system.

Future Directions for Carbon Policy Simulations

System dynamics has been put to good use in the study of carbon policy. Examples of previous studies and ideas for future directions are summarized in the appendices.

Appendix A. Carbon Policy and System Dynamics

Policymakers are considering a variety of targets, regulations and incentives to reduce CO2 and other GHG emissions. Figure A-1 summarizes some of the targets for emission reductions that have been adopted or proposed around the world. In many cases, the targets are specified relative to a country's emissions in the year 1990. So, for ease of comparison, the 100 on the vertical axis denotes emissions in the year 1990. Emissions have been growing at around 1.4%/year. The upward curve shows the future emissions if this trend continues: emissions would double by 2040 and double again by 2090. The graph shows great differences in the stringency of the targets. Some call for holding emissions constant; others call for dramatic reductions over time. Some targets apply to the next two decades; many extend to the year 2050; and some extend to the year 2100. However, when compared to the upward trend, all targets require major reductions in emissions.

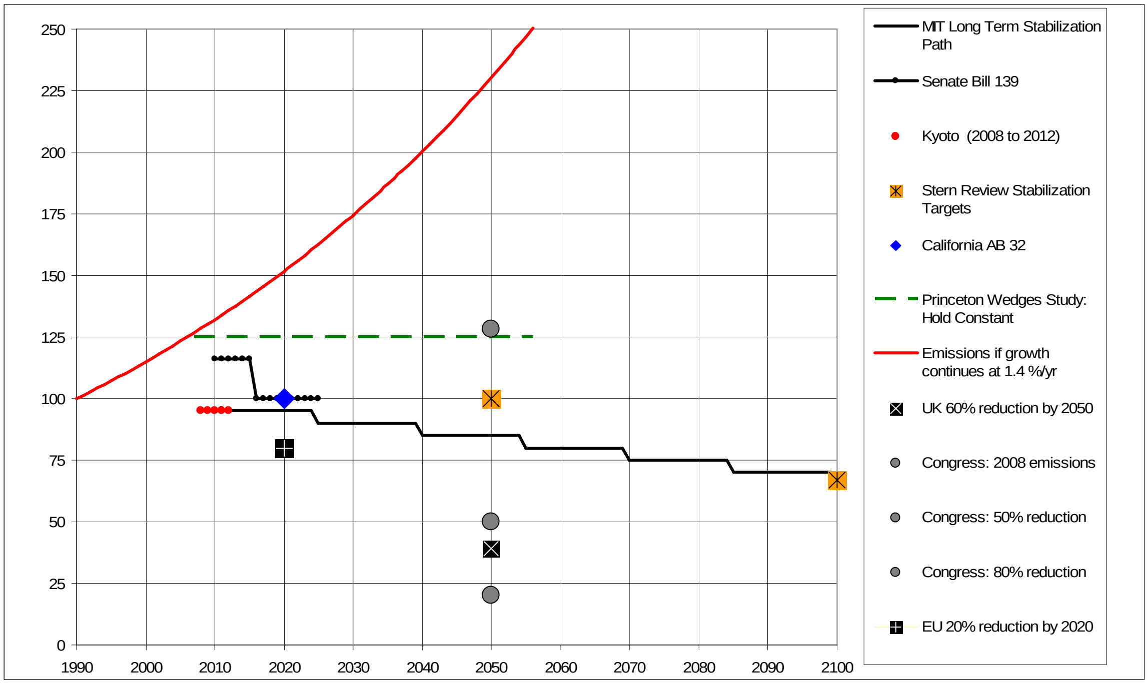

Figure A-1. Comparison of goals for emission reductions.

The targets from the Kyoto treaty are probably the best known. The treaty became effective in February of 2005 and called for the Annex I countries to reduce emissions, on average, by 5% below 1990 emissions by the year 2008 and to maintain this limit through 2012. The Kyoto Protocol allows for a range of emission reductions (i.e., some countries will aim for reductions greater than 5%), and it allows countries to purchase reductions achieved elsewhere (i.e., through a clean development mechanism, CDM). The extension of the Kyoto protocol beyond 2012 is the subject of ongoing discussions.

The solid line in Figure A-1 from 2010 to 2050 represents the stabilization path used in the MIT study described previously (Webster 2003). The limit on emissions was imposed in modeling calculations designed to stabilize atmospheric CO2 at 550 ppmv or lower. The scenario assumed that the Kyoto emissions caps are adopted by all countries by 2010. The caps would be extended and then further lowered by 5% every 15 years. By the end of the century, the emissions would be 35% below the value in 1990.

Appendix B discusses Senate Bill 139, The Climate Stewardship Act of 2003. Figure A-1 shows the S139 targets over the interval from 2010 to 2016. The bill called for an initial cap on emissions from 2010 to 2016. The cap would be reduced to a more challenging level in 2016, when the goal was to limit emissions to no more than the emissions from 1990. The S139 cap extends to the year 2025, the time period for the study described in the next appendix.

All of the proposed targets would require major reductions in CO2 emissions relative to the emissions in a business as usual scenario. But the proposals differ widely in the extent of the emissions reductions. The wide differences arise from different judgments about the severity of climate impacts and about the cost of reducing emissions. It can also arise from different judgments about political feasibility.

Achieving these reductions will require a combination of regulations and incentives. Incentives are viewed as crucial in order to “put a price on carbon.” This may be done with a carbon tax or a carbon market, as explained by Ford (2008). With certainty in the costs of emission reduction, either a carbon market or a carbon tax could be designed to deliver the requested reductions in emissions over time. And both the tax and the market could be designed to put the same price on carbon over time. However, with great uncertainty in the costs of emissions reductions, most economists favor the carbon tax. They argue that it makes more sense to guarantee the cost than to guarantee that emissions do not exceed a particular target, especially when the possible targets can vary so widely, as shown in Figure A-1. These arguments are compelling, but political factors in the USA and in Europe tend to favor the use of carbon markets. Indeed, all of the proposals currently under consideration in the US congress (and in the states) call for cap-and-trade in carbon allowances. And in Europe, the members of the European Union are in the initial test stage of the ETS, the Emissions Trading Scheme.

The main questions facing policy makers in the next few years concern the design of carbon markets and the expansion of market coverage across all sectors of the economy and across all nations. Depending on the experiences with markets, future policy makers may be concerned about the design and adoption of carbon taxes as an alternative method of putting a price on carbon.

System dynamics modeling can contribute to the design of carbon markets. And it can aid the learning as nations gain experience with cap and trade. Learning from market experiences is difficult, and many will draw different conclusions from the recent experiences (Ford 2008). System dynamics can be particularly useful in helping policy makers to anticipate the volatility of carbon market prices and to test the effectiveness of various proposals to limit the volatility. A prominent example is Fiddaman’s (2002) demonstration that a carbon price could soar to almost $1,000 per metric ton of carbon shortly after the opening of a market. System dynamics can also shed light on alternative ways to spread carbon markets across many countries through the design of the allowance allocation schemes that meet multiple goals (ie, efficiency, sustainability and fairness). An example is the experimetnal analysis of the “contraction and convergence” allocation proposal explained in a paper at this conference by Saysel (2007).

The usefulness of system dynamics has also been demonstrated in studies of volatility in energy markets. One example involves the volatility of electricity prices in the western USA following restructuring of the regulatory rules (sometimes called “deregulation”). Another example involves the volatility in prices for Tradeable Green Certificates (TGCs) to encourage the investment in renewable electricity generation. System dynamics is especially helpful in learning about market design when we employ a combination of classroom simulation and computer simulation. An example of the combined approach is explained in a paper on TGCs at this conference by Bier (2007).

Appendix B. Study of the Power System in the Western USA and Canada

The electric power industry accounts for an important share of CO2 emissions, due in large part to emissions from coal-fired power plants. The power sector has great flexibility to use different primary sources of energy to generate electricity, and there is plenty of room for fuel switching, both in the short run and in the long run. This sector has a long history of regulation, so it is a natural place to introduce carbon policies (i.e., regulations and cap-and-trade). A previous conference paper by Ford (2006) describes a system dynamics study which shows that the power sector would lead the way in reducing CO2 emissions when the USA puts a price on carbon. This appendix summarizes the study and concludes with the methodological aspects of the simulations that proved most useful for analysis of carbon policy impacts.

Figure B-1 shows the opening view of a model to simulate electricity generation, transmission and consumption with a particular interest in CO2 emissions. The opening view serves as a starting point for navigating through the many views. The model was designed for simulation studies of a wide variety of scenarios. For example, natural gas prices may remain high, or they could return to values predicted by previous studies of S139. Load growth might remain at low values, or we could see a return to more rapid growth. The transmission system could remain at approximately current capacity, or there might be major expansions to link the coastal load centers with coal and wind resources in the eastern areas of the WECC.

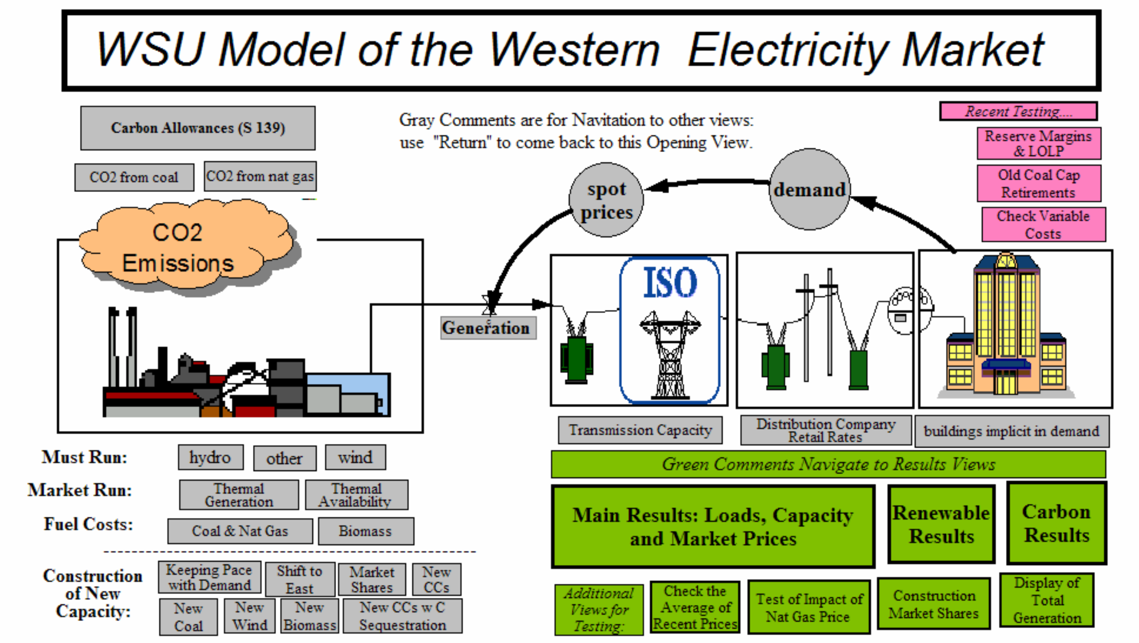

Figure B-1. Opening view of the model.

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Figure B-2 Map of WECC, the Western Electricity Co-ordinating Council. The utilities in the four areas report data on loads and resources to the WECC.

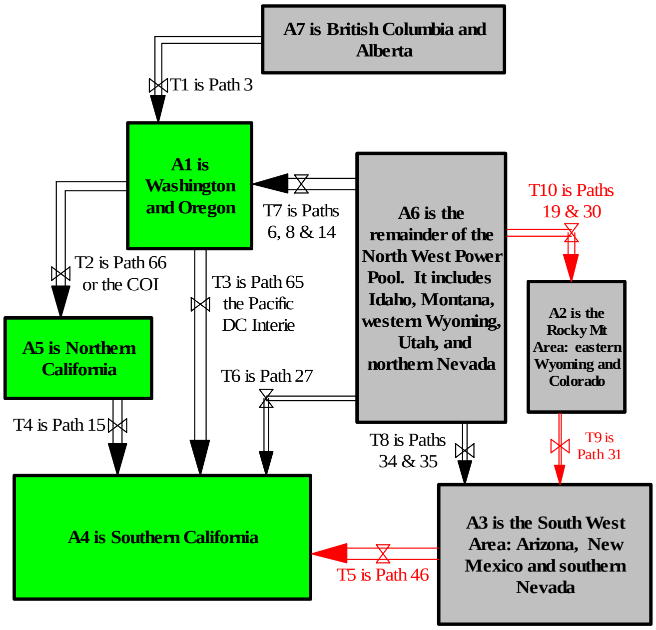

Figure B-3. Areas and transmission corridors for simulation.

Figure B-2 shows the study area, and Figure B-3 shows the simulated transmission corridors that connect the loads and resources. Simulating power flows and spot prices in a transmission network is not amenable to the standard system dynamics tools (i.e., stocks, flows, and information feedback). For our purposes, it was better to simulate the spot prices using engineering methods, as explained by Ford (2006, Appendix F) Senate Bill 139 was the focus of the study. We wished to learn to learn if the western system could achieve the large reductions in CO2 emissions that were projected for the nation as a whole. CO2 emissions in a business as usual scenario are shown in Figure B-4. The total emissions vary during the different seasons of each year. (They peak in the summer when there is less hydro generation and a much greater dependence on fossil fuels.) The growing carbon emissions are caused by a combination of increased emissions from coal plants and from gas-fired combined cycle plants.

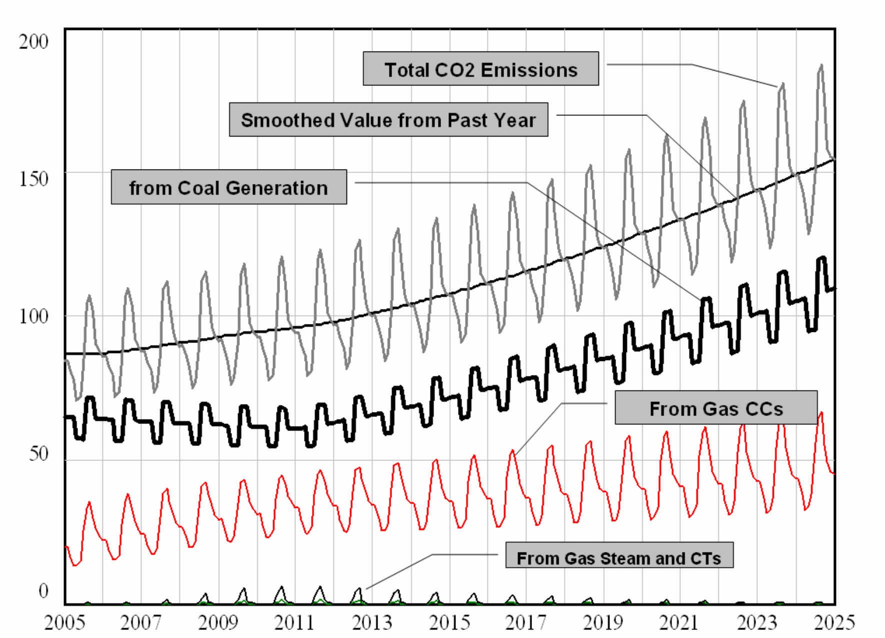

Figure B-4. CO2 emissions in a business as usual scenario.

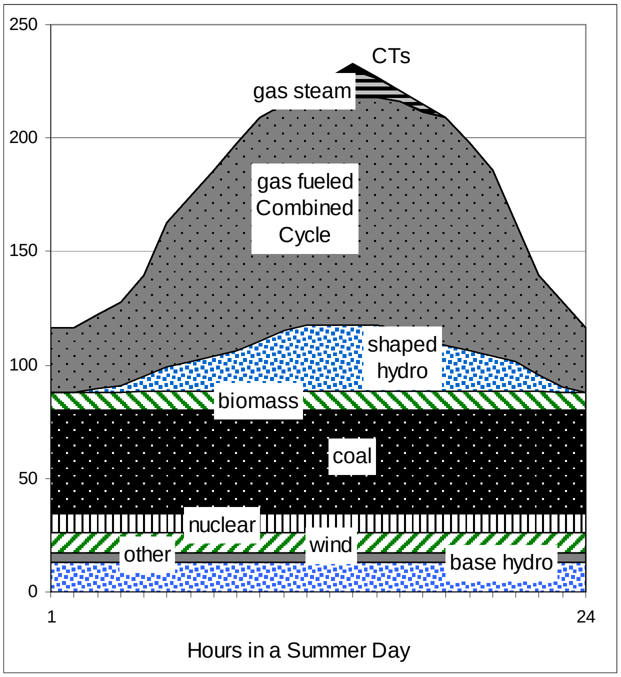

Figure B-5A. Generation for a peak summer day in 2024 in the reference case.

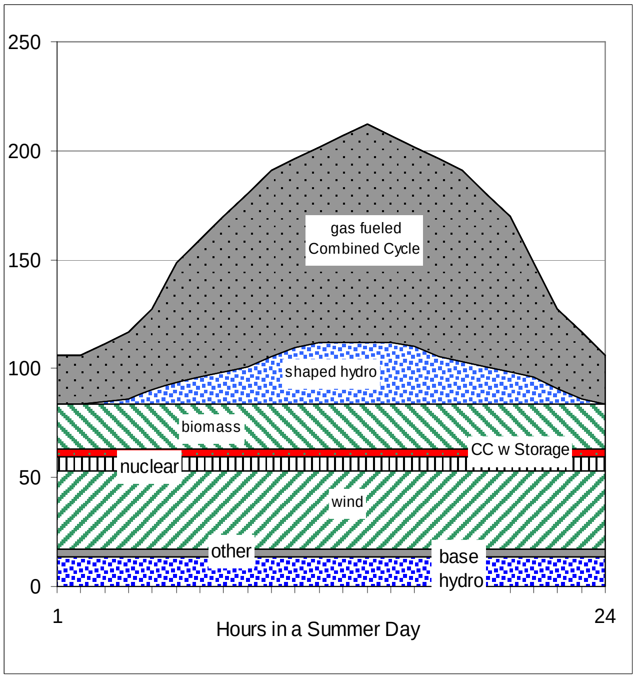

Figure B-5B. Generation for a peak summer day in 2024 in the S139 case.

Simulations with the carbon prices expected under S139 indicate that the emissions could be reduced by around 75% by the end of the simulation. Insight on this dramatic reduction is gained by comparing the daily dispatch of generators in a typical summer day at the end of the simulations, as in Figure B-5. The side by side comparison makes is easy to visualize the change in the WECC system. A comparison of the peak loads shows that the demand for electricity would be reduced. The reduction in the WECC simulation was 9%, due entirely to the consumers' reaction to higher retail electric prices in the S139 simulation.

The most dramatic difference in the daily dispatch is the complete elimination of coal-fired generation. Coal-fired units are shown to operate in a base load mode in Figure B-5A. They provide around 28% of the annual generation, but they account for around two/thirds of the CO2 emissions in the western system. The carbon prices from S139 make investment in new coal-fired capacity unprofitable at the very start of the market in the year 2010. As the carbon prices increase over time, it becomes economical for utilities to cut back on coal-fired generation and compensate with increased generation from gas-fired combined cycle capacity. With the gas prices used in the WECC study, the fuel switching would push the coal units into the difficult position of operating fewer and fewer hours in a day. Eventually this short duration operation is no longer feasible, and coal generation is eliminated completely. Further details on the WECC study are provided by Ford (2006). To conclude this paper, it is worth highlighting two important methodological features that allowed the WECC modeling to deliver important insights on the CO2 reductions that could emerge when the USA puts a price on carbon.

One feature is the inclusion of hour by hour results for a typical day in each month of the year. This is accomplished within a long term model that extends 20 years into the future. The long time horizon is needed to see the changes in generating capacity after new technologies come on line. The hourly results are needed to simulate the phase out of coal-fired plants in the daily dispatch. This combination of short-run/long-run dynamics has been accomplished in previous models of the western power system by simulating with an extremely short DT (needed to provide accuracy in spot prices). However, a short DT can lead to long simulation times and the loss of the quick, responsive simulations for interactive exploration of results. Rapid simulations were achieved in the WECC model by setting DT to one month and representing the daily load profiles and generation results with a subscript assigned to the 24 hours of a day.

The second important methodological feature in the WECC study is the use of engineering methods to simulate the power flows over an electricity network (like the one shown in Figure B-3). This was accomplished through algebraic methods to find the OPF (optimal power flows) over the grid. We used a DC OPF, where the term DC means that the calculations ignore the reactive power. The standard form of the DC OPF is explained in the text by Wood (*Power Generation, Operation and Control*, 1996, John Wiley). The implementation of the DC OPF within the system dynamics model is explained by Ford (2006).

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