Modelling Social-Economic-Climatic Feedbacks for Policy Development

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ABSTRACT
Simple models of the social-economic-climatic system offer an alternative to the standard GCM-driving scenario modelling approach, which focuses on the climate system and neglects important feedback-effects from socio-economic systems. This failure to represent the whole system is clearly problematic, because natural and socio-economic systems exhibit complex, non-linear behaviour, and each certainly affects the other. We therefore offer an alternative approach, based on explicit modelling of the feedbacks within and between components of the system. The system dynamics simulation methodology used here facilitates representation of feedback processes, time delays, and non-linearities, and encourages an understanding of the interconnections within a system that fundamentally determine its behaviour. As a working example of the system dynamics approach, our paper describes a simple climate-carbon cycle-water cycle-population closed-loop model. A set of three experiments compare a “business-as-usual” case with model modifications, including exogenous technology change, and endogenous equation and parameter changes. Analysis of the experimental results demonstrates model sensitivities and shortcomings: exponential growth patterns may indicate the necessity for additional model sectors and feedbacks, and sensitive relationships suggest the need for further study. Future work will improve the representation of socio-economic sectors of the model.

Key words: feedback; climate change; system dynamics; simulation

Introduction
According to the Intergovernmental Panel on Climate Change (IPCC), studies consistently find strong evidence for anthropogenic influences on a global climate that has changed demonstrably since pre-industrial times (IPCC, 2001a). As a society, we should be concerned about the possibly devastating consequences of such changes, since increased atmospheric greenhouse gas concentrations could result in large-scale, high-impact, non-linear, and potentially abrupt and irreversible changes in physical and biological systems (ibid.).

The current international climate change dialogue – as exemplified by publications from organizations such as the National Academies of the Sciences (NAS, 2005), the Intergovernmental Panel on Climate Change (IPCC, 2001a, b), and the United Nations Framework Convention on Climate Change (UNFCCC, 1992) – aims to clarify the science behind climate change and its effects, and to provide policy-relevant information for governments (IPCC, 2001a). Climate change modelling plays an essential role in these efforts by encouraging researchers to 1) test and improve their understanding of processes that operate within individual system components (Hartmann, 1999); 2) identify and include the feedbacks, both within and between components, that influence systemic behaviour; and 3) predict future changes in both physical and socio-economic systems at regional and even global scales. Since better understanding encourages better decision-making, modelling can also help policy-makers to enact effective policies and programs to address and to adapt to climate change.

Climate change modelling typically involves the use of climate models with driving scenarios, such as the SRES scenarios used by the IPCC (IPCC, 2000). Following this standard approach, a researcher applies projected trends (or scenarios), outputs from another model, or reanalysis data as input to a climate model. Data from the driving scenarios influences the behaviour of the climate model over time, forcing it to adapt to higher levels of carbon dioxide in the atmosphere, for example, and thus including socio-economic influences on the climate system as a set of external drivers.

Climate models used in the climate change modelling process come in at least three different forms, and their classification is based on both model resolution and purpose. General Circulation Models, or Global Climate Models (GCM), provide the most realistic and complete representation of climate – they calculate “the full three-dimensional character of the climate comprising at least the global atmosphere and the oceans” (McGuffie and Henderson-Sellers, 1997: 48). At the middle of the climate model range, Earth-System Models of Intermediate Complexity (EMIC) offer a simpler, faster, but lower-resolution modelling approach to GCMs; however, as compared with simple models, the third model type, EMICs are much more comprehensive and explicitly couple components of the Earth-system (Claussens et al., 2002). Finally, simple models have low temporal and spatial resolution, and produce zonally- or globally-averaged results for temperature, but not for other variables such as precipitation; however, they are computationally fast and their behaviour is easy to understand (Harvey et al., 1997).
General Circulation Models generally receive the most attention from the climate research community, and therefore provide the majority of climatic predictions and policy-relevant information to the policy-development community – this emphasis on complex climate models is clear in IPCC publications such as the IPCC Third Assessment Report (IPCC, 2001a). Of course, GCMs are a focal point of climate research for good reason. They can presently resolve even sub-continental variations in climate with reasonable accuracy, and despite difficulties in predicting certain local-to-regional climate characteristics like precipitation, improvements both in model resolution and in the representation of physical processes should eventually lead to models that exhibit good agreement with climate observations and that produce more reliable predictions (ibid.). However, current GCMs cannot provide the kind of fine detail necessary for regional climate, and their computational requirements mean that very few studies can be run and for very short simulated periods (Claussen et al., 2002). Model complexity also means that the results of simulations can also be very hard to evaluate – cause-and-effect relationships can be very difficult to trace (IPCC, 2001a).

In developing climate change policy, more comprehensive, less complex models therefore offer an important alternative to climate-only GCMs. EMICs will eventually include human interactions with the environment, but they are under development at present and exclude socioeconomic factors – they cannot help us to understand biophysical and socio-economic connections (Claussen et al., 2002). Therefore, simple models offer the best means of improving our understanding of the vital feedbacks that connect human activities to the global climate system and the carbon cycle. Such models can currently incorporate the sorts of socio-economic and natural feedbacks required for effective study of the social-economic-climatic system.

The rest of this paper explains our approach towards modelling the social-economic-climatic system with a simple but powerful approach, called system dynamics, that focuses on feedbacks and nonlinearities. We will first describe the research approach in comparison with other approaches, before providing a simple example of the research principles at work. Finally, we provide conclusions and discuss plans for future work.

**Our Approach**

This section describes the general GCM-driving scenario approach to modelling the social-economic-climatic system and explains its limitations. It then provides another option, using the system dynamics methodology, that focuses on the full system.

**The Problem**

Climate change will affect virtually every natural system on Earth, from water cycles, sea levels, and ocean circulation to the productivity of natural and agricultural systems, and the abundance and survival of plant and animal species. Therefore, it will influence human welfare, through changes in supply of and demand for water, food and energy, and will likely lead to a loss of life and property (IPCC, 2001b). These effects on natural and human systems mean that the climate change debate concerns the sustainability of the current socio-economic and environmental systems. The argument as to the connection is simple: because human welfare and ecological well-being are interdependent (Gibson, 2002), and the concerns of both present and future generations are equally important (WCED, 1987), failing to address climate change adequately may be disastrous for our current way of life, and will almost certainly be disastrous for our children’s.

In the real world, natural and socio-economic systems do not exist in isolation from one another. After all, it is the interaction between anthropogenic greenhouse gas emissions and natural feedbacks that drives climate change: we know that anthropogenic greenhouse gas emissions result in a net radiative forcing of 4 W m⁻² for a doubling of atmospheric carbon dioxide, which triggers a series of feedbacks within and between different climate system components. Anthropogenic emissions and natural feedbacks result, together, in a temperature increase of roughly 1.5°C to 4.5°C (IPCC, 2001a).

Despite the importance of these social-economic-climatic feedbacks, the conventional GCM-driving scenario modelling approach focuses primarily on the climate system, and does not adequately represent the socio-economic systems that affect and are affected by natural systems – the approach ignores the fact that these systems are interdependent, and indeed inextricable from one another. From a policy-making perspective, the important recognition here is that both climate change mitigation and adaptation measures depend on an interplay between natural and human systems. As the climate changes, society must adapt, and its adaptation efforts will affect the climate in turn, so that a feedback-loop results. Because this interplay between natural and socio-economic systems determines the entire system’s evolution, the representation of the corresponding feedbacks is critical to the development of appropriate climate change adaptation and mitigation strategy.

Therefore, although they have obvious value for climate research, GCMs are not the most useful model type for policy-development or for models of social-economic-climatic interconnections, because they simply cannot incorporate the important feedbacks that tie physical and socio-economic systems together (Weaver et al., 2001). From a scientific perspective, the dangers of a failure to represent the whole system should be clear. We have learned from climate models that the Earth-system functions as a whole, not as separate parts (IPCC, 2001a), and we know that the climate is a complex system (Rind, 1999), characterized by nonlinear behaviour and feedback processes. Socio-economic systems likewise exhibit complex behaviour. Yet, the most common approach to combining socio-economic and natural systems involves driving a climate model with socio-economic scenarios.

In other words, the current approach to understanding connections between natural and socio-economic systems requires their artificial separation via modelling techniques. Such an approach explicitly excludes those feedbacks critical to understanding and predicting climatic and socio-
economic behaviour. By excluding the feedbacks that operate between biophysical and socio-economic systems, we make several assumptions about the nature, predictability, and independence of these systems. According to Simonovic and Davies (2006), we assume that

1) We can capture all possible interactions between the two systems, despite their nonlinear nature;
2) We can separate human effects on the Earth from natural effects;
3) Interactions between these systems are largely irrelevant to the behaviour of each; and
4) Feedbacks between natural and socio-economic systems are external to both.

By these assumptions, the “human versus nature” dichotomy is not simply philosophical or convenient, but is in fact genuine.

**A Solution**

Despite our understanding that natural and socio-economic systems exhibit complex, nonlinear behaviour, and that each certainly affects the other – consider the otherwise-unfounded fears over rising anthropogenic CO₂ emissions – climate change researchers continue to treat each system as essentially independent. The result is a reliance on scenario-driven, feedback-free representations of future climate to provide scientifically sound projections to policy-makers, in the hope that actions based on such information, or on collections of such information, will ensure humanity’s future well-being.

We need another option, both scientifically and politically. Our research offers a *system dynamics*-based alternative to the standard approach, based on *explicit* modelling of the feedbacks within and between components of the social-economic-climatic system. System dynamics focuses on modelling systems characterized by *dynamic complexity* (Sterman, 2000) – such systems have a relatively small number of components tightly coupled through feedback loops, and their behaviour arises from the resulting feedback-rich system structure. The approach elucidates the internal structure of the system under study, allowing investigation of the actual relationships between system elements, and determination of the results of simulated decisions on such interconnections. According to system dynamics theory, “time delays, amplifications, and structural relationships between a system’s elements could be more important in determining aggregate system behaviour than the individual components themselves” (Simonovic, 2002: 253). Note that system dynamics-based models aim to improve our understanding of the connections and relationships within a system that fundamentally determine its behaviour, rather than to provide predictions of future events.

As a methodology, system dynamics is particularly well-suited to climate change modelling, since it 1) facilitates representation of feedback processes, time delays, stock and flow processes, and nonlinearities (Sterman, 2000), all of which are features of the social-economic-climatic system, and 2) allows mathematical modelling of both biophysical and socio-economic systems with equal effectiveness. System dynamics also encourages ‘big picture thinking’, making it remarkably compatible with the broad worldview of sustainability, which emphasizes a balance between economics, society, and the environment. Sustainability forms the foundation of this research and has guided the development of other, similar models: FREEmodel (Fiddaman, 2002), a climate-economy model based on the influential DICE model (Nordhaus, 1992), includes explicit consideration of sustainability, modelling the effects of resource depletion, and stressing an equitable approach to the needs of future generations.

In fact, *balance and explicit feedbacks* are the issues that really set this research apart from other current attempts to integrate science and policy, since both GCM- and EMIC-based attempts to model social-economic-climatic connections concentrate first on the physical processes of the Earth-system. This climate-first approach weights the models towards the climate and natural cycles, and makes climate policy essentially an add-on; it thus defies the inclusive, balanced perspective of sustainability. The following section provides an example of the system dynamics modelling approach in action.

**Modelling Feedback**

To be effective, a social-economic-climatic model must be simple enough to allow analysis of its behaviour and sensitivities, and identification of its major feedbacks, but also complex enough that it has value for the scientific and policy-development communities. An effective model must therefore balance simplicity and comprehensiveness with complexity and detail.

This section first describes a simple social-economic-climatic model used to investigate the connections between components of the system, and then provides the results of a series of simulation experiments designed to demonstrate the importance of feedback-effects and nonlinearities in generating model behaviour. Note that the model described below is not intended to represent the social-economic-climatic system either perfectly or completely; however, it does serve to demonstrate the importance of feedbacks and provides a working example of the overall modelling philosophy.

**Model Description**

To demonstrate the importance of feedback relationships in determining the behaviour of complex systems, our model provides a simple representation, in Figure 1, of four crucial natural and socio-economic sectors: *climate*, the *carbon cycle*, *population*, and the *water cycle*.

![Figure 1: Model Feedback Structure](image-url)
The most striking feature of the model is its representation of the social-economic-climatic system structure as a single closed-loop – each sector in Figure 1 can affect the others. All the major elements of the system are endogenous, or included explicitly, so that the dynamic behaviour of the model arises from the system structure. Good models emphasize endogenous relationships between model sectors, according to Sterman (2000: 95):

An endogenous theory generates the dynamics of a system through the interaction of the variables and agents represented in the model. By specifying how the system is structured and the rules of interaction (the decision rules in the system), you can explore how the behaviour might change if you alter the structure and the rules. In contrast, a theory relying on exogenous variables … explains the dynamics of variables you care about in terms of other variables whose behaviour you have assumed. Exogenous explanations are really no explanation at all; they simply beg the question, What caused the exogenous variables to change as they did?

In contrast to our approach, the relationship between the two sectors in the GCM-driving scenario approach is a single arrow connecting the exogenous socio-economic drivers to the GCM’s climate system. This kind of open-loop system means that, in spite of the complexity and realism of the climate model, the effects of even massive climate change in a GCM can never influence the evolution of the socio-economic system.

In Figure 1, the positive or negative polarity associated with each arrow indicates the direction of change one model component imposes on the next. Positive relationships represent change in the same direction, where an increase/decrease in one sector causes an increase/decrease in the next sector, while negative relationships mean that change occurs in the opposite direction, so that an increase/decrease in one sector causes a decrease/increase in the next sector. The figure also presents the manner in which one model component influences the next. Each arrow-connection between two model sectors bears the name of the sector element whose change causes a related change in the next model sector. For example, a change in atmospheric carbon dioxide levels, as modelled by the carbon sector, causes a change in the global surface temperature, with the magnitude of that change determined by mathematical equations within the climate sector.

In this simple representation of the social-economic-climatic system, the climate sector models the change in atmospheric and oceanic temperatures caused by the change in atmospheric concentrations of greenhouse gases, especially carbon dioxide, that result from human activities. The related carbon-cycle sector focuses on the ability of the oceans and the terrestrial biosphere to absorb anthropogenic greenhouse gases, while the population sector represents the human population growth and decline that result from changes in freshwater availability, and how population changes affect greenhouse gas emissions. Finally, the water sector models the impacts of changing global climate on the availability of freshwater for human consumption, and the corresponding effects of water surpluses and shortages on population growth.

Of course, each model component is more complicated than Figure 1 suggests, incorporating multiple variables, equations, and internal feedbacks. The climate sector of the model is an upwelling-diffusion energy-balance model (UD/EBM) based on the Box Advection-Diffusion (BAD) model of Harvey and Schneider (1985). Similar to well-known, earlier upwelling-diffusion models by Hoffert et al. (1980) and Oeschger et al. (1975), the BAD model focuses on the importance of the oceans in determining the global surface temperature response to climatic forcings, such as changes in anthropogenic greenhouse gas emissions. The model includes the important solar and terrestrial radiative energy exchanges between outer space, the atmosphere, and the oceanic surface layer; infrared and latent and sensible heat flows between the earth’s surface and the atmosphere; and diffusive and advective energy transfers within the ocean. Although simple, the temperature profile generated by the model at steady state – in other words, when external forcings are assumed to equal zero – matches that of Levitus (1982) quite well. The BAD model also generates good matches to global surface temperature changes predicted by GCMs and other complex models under climatic forcings (Harvey and Schneider, 1985).

The carbon cycle comes directly from Fiddaman (1997, 2002), and models carbon flows between the atmosphere, the terrestrial biosphere, and the oceans, focussing on atmosphere-mixed ocean layer interactions, and in carbon storage in soil, the terrestrial biosphere, and the deep oceans. The model is based on the work of Goudriaan and Kettner (1984), the IMAGE 1.0 model (Rotmans, 1990), and the upwelling-diffusion model of Oeschger et al. (1975). The remaining two parts of the model, the water cycle and population sectors from Prodanovic (2004), are relatively simple; although speculative, these components include important feedbacks to the climate and carbon cycle sectors.

**Feedback between Model Sectors**

Because this paper focuses on the importance of feedbacks between the four model sectors, we describe the connections between model parts in Figure 1, rather than listing all the equations in each individual sector. Each set of adjacent sectors is connected in the following manner: the carbon cycle and climate via atmospheric carbon dioxide levels, climate and the water sector via global surface temperature, water and population via total renewable surface water flow, and population and the carbon cycle via anthropogenic carbon dioxide emissions.

The link between the carbon cycle and the global climate takes this form:

\[ F_r = 0.006079 \times C_0 - 4 \]  

where \( F_r \) [W m\(^{-2}\)] is the net radiative forcing that results from increasing atmospheric carbon dioxide concentrations, and \( C_0 \) [Gt C] is the current atmospheric carbon dioxide concentration. The constants are the slope of the linear relation connecting current atmospheric CO\(_2\) concentrations with pre-industrial levels, and the assumed
forcing of $4 \text{ W m}^{-2}$ for a doubling of CO$_2$ concentrations. The equation results in a net forcing of $0 \text{ W m}^{-2}$ for current atmospheric CO$_2$ levels equal to pre-industrial levels, and a net forcing of $4 \text{ W m}^{-2}$ for a CO$_2$-doubling. Although the equation is simple, the net forcing values used are consistent with IPCC (2001a), and changes to the linear structure of the relationship – to an exponential increase in forcing beyond a $4 \text{ W m}^{-2}$ level for CO$_2$-doubling, for example – can be made easily.

The climate and water sectors are connected via temperature effects according to this equation from Prodanovic (2004):

$$\eta = 0.5 + T / 30$$

(2)

In this equation, $\eta$ is a dimensional factor that depends only on the global surface temperature, $T$ (°C), calculated by the climate sector. This factor, $\eta$, shows the effect of changing temperature on global water flows including evaporation, evapotranspiration, and snow- and ice-melt, as modelled in the water sector. Of course, the form of equation (2) is speculative, since the exact form of the relationship between climate change and hydrological processes is unknown, but it follows the general consensus that the intensity of hydrological processes should increase with increasing global temperatures (IPCC, 2001a). We have chosen a linear function for $\eta$, but have included other types of relationships in a sensitivity analysis, below.

The water and population sectors are linked through surface water availability according to the following equation (Prodanovic, 2004):

$$P_{gw} = 0.046166 - 9.1666 \times 10^{-4} \times Q_{tr}$$

(3)

where $P_{gw} \text{ [yr}^{-1}]$ represents the population-growth decline rate, and $Q_{tr} \text{ [10}^{-15}\text{ kg yr}^{-1}]$ is the total renewable water flow. Equation (3) models the influence of fresh water availability on population growth: abundant surface water permits increased levels of population growth, whereas limited fresh water either restricts population growth or leads to a decrease in population. Like equation (2), the form of equation (3) is speculative, but sensitivity analysis can reveal the effect of changes in either the constant values, or in the shape of the function.

Finally, the link between the population and carbon cycle sectors is based on the effect of population size on anthropogenic CO$_2$ emissions, and takes this form (Prodanovic, 2004):

$$E_C = -1.7361 + 1.8280 \times 10^{-9} \times P$$

(4)

where $P \text{ [people]}$ stands for the global population, and $E_C \text{ [Gt C yr}^{-1}]$ corresponds to total anthropogenic CO$_2$ emissions. Developed by Prodanovic (2004), equation (4) results from data-fitting world population to CO$_2$ emissions over the last 150 years. We include the effects of improving emission control technologies in the analysis section below.

Simulation and Analysis

To illustrate the general behaviour of the model, consider a base case in which population is growing at the beginning of a simulation. According to Figure 1, population growth causes an increase in carbon dioxide emissions, since a larger population uses more energy and produces more greenhouse gases. These increasing emissions accumulate in the atmosphere of the carbon cycle sector, and although the biosphere and oceans absorb some of the additional carbon, the atmospheric greenhouse gas concentrations rise above their pre-industrial levels. A correspondingly higher radiative forcing drives an increase in the global surface temperature, as modelled by the climate sector, causing the amount of water vapour present in the atmosphere to increase. The resulting intensification of the global hydrological cycle increases precipitation over land, providing additional surface water for human consumption, and allowing the global population to rise (of course, the global scale of the precipitation increase says nothing about its spatial distribution). The result of the loop, therefore, is to increase population growth and climate change above what it would have been without feedbacks. In other words, population would have grown even without the feedback loop, but not as quickly.

Simulation of this base case, over the period from 1960-2100, results in the sort of model behaviour we expect, where global population rises from approximately 3.0 billion people in 1960, to 6.13 billion people in 2000, to 13.8 billion people in 2100. These model-generated population numbers from 1960-2000 match United Nations figures (UNESA, 2004) quite closely, being roughly 45 million too high in 2000. Over the 140-year period, the other variables in the feedback loop also increase as expected: the global surface temperature rises by 1.47 °C, the total renewable water flow increases by $2.8 \times 10^{15} \text{ kg yr}^{-1}$, the atmospheric CO$_2$ concentration increases by 92 percent, and the net radiative forcing rises from 0 to 3.7 $\text{ W m}^{-2}$ by 2100.

With these initial values for a “business-as-usual” case, the question is how changing parameter values and equation forms will affect the model’s behaviour. Because we are interested here in the effects that feedbacks between sectors have on simulated values, and because most of the relationships are specified endogenously, we examine first the effects of changing exogenous variables, such as the variables associated with improving emission control technologies. Next, we investigate the effects of altering the form of equation (2), which connects the climate and water sectors, before simulating the overall system response to a reduction of the heat uptake by the oceans. In summary, the experiments involve: 1) improvement in exogenous emission control technologies, 2) change in the temperature feedback factor ($\eta$) function, and 3) elimination of diffusive and advective heat transfer parameters.

In terms of the first experiment, we know that carbon dioxide emissions result from the burning of fossil fuels, which form a large part of our global energy supply; however, new technologies can reduce the amount of emissions released per unit of fossil fuel burned. Complicated climate-economy models have been
developed that provide detailed representations of socio-economic systems and their use of fossil fuels – see for example IMAGE 2.1 (Alcamo et al., 1998), DICE (Nordhaus, 1992), RICE (Nordhaus and Boyer, 2002), and FREE (Fiddaman, 2002) among others. The approach here is far simpler, involving three options: 1) no externally-imposed change in technology as time passes and population increases, 2) an imposed slow improvement in efficiency from 1960-2100, and 3) an optimistic projection of efficiency increases over the 140-year simulation period.

Case 1 represents the base case, as provided in Prodanovic (2004), while cases 2 and 3 illustrate the effects of changes in important exogenous variables. For cases 2 and 3, emission control technologies result in reductions from 1960 levels of 0.28 and 0.30, respectively, by the year 2000, so that emissions are at 72% and 70% of their 1960s level. In the year 2040, emissions are 55% and 42% of their 1960s level, while in 2100, emissions are 50% and 15% respectively – case 2 has efficiency improvements that slow dramatically after 2040, while case 3 allows efficiency to improve almost linearly from 1960 to 2100. The results of simulations using the assumptions in cases 1 to 3, as displayed in Figure 2, are not realistic projections, and therefore should not be interpreted literally. Instead, they show how changes in one variable can cause ripple effects throughout a feedback system.

The most noticeable feature of Figure 2 is the rapid divergence of the “business-as-usual” scenario (case 1) from the other two cases.

However, while cases 1 and 2 display exponential growth, case 3 shows surface temperatures beginning to stabilize at a value of roughly 0.9°C higher than 1960 levels. Of course, exponential growth in global surface temperature of the sort in the first two cases cannot continue forever, because the drivers of the change must eventually fail – temperature increases like those in cases 1 and 2 would cause failures at some point in the social-economic-climatic system that would in turn reduce anthropogenic emissions. As formulated currently, the model cannot simulate such a failure. The third case demonstrates that the model can generate a “soft-landing” if emissions are cut dramatically; however, because emission control technologies are an exogenous variable, the model reveals nothing of the socio-economic steps necessary to bring about such a strong reduction in emissions.

For the second experiment, we demonstrate the results of alternative formulations of system feedbacks on model behaviour by changing the form of equation (2), above, which connects the climate and water sectors of the model. Two nonlinear functions, high and low, were tested in addition to the normal linear function in equation (2), and the form of all three functions is given in Figure 3. Here, the high function yields higher results for the value of \( \eta \), while the low function gives lower values, as the names suggest. All three functions begin at \( \eta = 0.5 \) for \( T = 0°C \), then diverge from that point before converging again at \( \eta = 1.5 \) for a surface temperature of 30°C.

![Figure 3: Functions for Temperature Feedback factor, \( \eta \)](image)

The results of simulations for high, normal, and low formulations of the temperature feedback factor illustrate considerable model sensitivity to the equation formulation. Whereas the emissions control technology experiments yielded almost no population change (the difference was less than 200 million people in 2100) between the three scenarios despite increases in surface temperature, changes in the formulation of equation (2) have a strong effect on all model variables, including population. See Figure 4, below, for the effects of the temperature feedback factor on global population. Not illustrated is the effect of \( \eta \) values on surface temperature, which also depend closely on the formulation of equation (2): the normal case shows a temperature increase from 15.9°C in 1960 to 18.8°C at 2100, while the high and low cases increase to final values of 21.2°C and 17.9°C, respectively.

As in experiment 1, these simulation results are not realistic projections, and should not be interpreted as such. However, they do highlight model sensitivities and therefore areas of interest for future study. In addition to demonstrating the ripple effects of feedbacks, they reveal how model behaviour can depend very strongly on one equation, which is the purpose of sensitivity analysis: to
expose the model parameters, equations, and general assumptions that affect model behaviour most. Note, however, that the functions shown in Figure 3 assign very different η values for the same temperature. For example, at the initial temperature of 15.9°C, η equals 1.28, 1.03, and 0.78 for high, normal, and low cases, respectively, giving differences of 24% upwards and downwards from the normal case.

Unlike experiment 2, where the model proved very sensitive to changes in η, the population change that stems from the elimination of oceanic thermal inertia is very small, ranging from a population increase of 80 million people in 2100 for case 1, to an increase of only 20 million people for case 3. Clearly, the model is not very sensitive to the magnitude of the surface temperature change, and the reason has to do with the population-water supply connection: even for large changes in surface temperature, the total renewable flow value changes very little. For example, for the 2.6% surface temperature increase from case 1 to case 1, no ocean, the renewable flow changes by only 1.4%, and the changes for the other two cases are even smaller. According to this version of the model, then, we should focus our attention on improving the representation of the water and population sectors, because likely changes in the physical sectors of the model exert little influence on the socio-economic elements of the system.

Conclusions and Future Work

The traditional GCM approach ignores the fact that the social-economic-climatic system functions as a whole, involving multiple, nonlinear feedbacks between interdependent system components. From a technical and policy-development perspective, the conventional approach has other failings that stem from the high resolution of the climate component. High model resolution results in two real disadvantages: excessive detail makes sorting the causes and effects of model behaviour difficult; high resolution is also computationally very expensive, and therefore slow (Weaver et al., 2001; Harvey et al., 1997).

Note however that, despite the above arguments, the standard approach has certain advantages, including the capacity to simulate the effects of various socio-economic policy directions on the physical environment. Such directions include those given in the IPCC (2000) Special Report on Emission Scenarios, which provides high economic- and technological-growth coupled to low population-growth scenarios (A1), heterogeneous development scenarios (A2), and more environmentally sound scenarios (B1 and B2). Furthermore, the resolution and accuracy of GCMs offers a means of verifying the biophysical results of simpler models. However, researchers must recognize that the connection between socio-economics and the climate system runs one way only by this approach – the effects of climate change on human systems simply cannot be determined, despite views to the contrary.

By excluding feedbacks we make dangerous assumptions about the nature, predictability, and independence of the highly complex and nonlinear social-economic-climatic system. This point is relatively clear. However, what we fail to recognize is that these assumptions affect the
structure and function of the models we rely on in planning for climate change. In other words, in neglecting socio-economic and natural feedbacks, we may greatly restrict our ability to develop appropriate climate change mitigation and adaptation strategies. Climate change poses real dangers for our current way of life, so while further research may show these kinds of assumptions to be correct, we must determine their validity before staking our future on them.

An alternative to the standard GCM-driving scenario modelling approach is therefore necessary. Good governance requires useful and reliable science for decision-making, since the effects of poor planning could be disastrous. Instead of imposing a human versus nature dichotomy on the system, researchers must investigate the real connections between the social, economic, and natural elements of the entire system. We must plan well, and good planning requires understanding and foresight. We cannot base important policy decisions on an incomplete and inaccurate description of such a highly complex and unpredictable system.

Therefore, instead of assuming that we can both separate human from natural feedbacks and predict all the important interactions of nonlinear systems, we model the entire social-economic-climatic system in a simplified fashion. The result is, of course, a simple model. However, in spite of its simplicity, this kind of model has many useful characteristics. Following the system dynamics methodology, such models represent all of the important elements of the system endogenously, allowing investigation of the effects of feedbacks within and between system sectors, and of changes in system behaviour that result from altered model structure and rules. They also permit the identification of unforeseen connections between seemingly separate systems. Finally, policy-makers require clear messages about the social and economic behaviours that provide the most benefit or cause the most damage to society. Simple models can run multiple scenarios over a short time span, illustrating the results of policy choices quickly. They can therefore assist governments and other decision-makers, through a greater understanding of nonlinearities and feedbacks, to design better policies for mitigating and adapting to climatic change.

This paper has described a relatively simple, closed-loop version of the social-economic-climatic system (see Figure 1), and neither the model’s form nor its results are intended to represent the full system completely or accurately. Instead, the purpose was to demonstrate the importance of feedbacks to system behaviour and to display the overall modelling philosophy in action. The four sectors of the model – climate, carbon cycle, population, and water cycle – illustrate the types of interdependences that exist in real-world systems. Note that although we emphasize the connections between sectors rather than within each sector, feedbacks govern the behaviour of the entire model, regardless of their location.

The experiments described in the simulation and analysis section compare the results of a “business-as-usual” base case with a set of model variations, which include exogenous technology change, and endogenous equation and parameter changes. The emission control technologies experiment revealed that changes in exogenous variables could cause elements of the system to behave in very different fashions, from large divergences in final variable values to entirely different system behaviour modes (exponential increase for cases 1 and 2 versus goal-seeking behaviour for case 3). The same experiment also demonstrated the dependence of model behaviour on structure. For example, the exponential growth of cases 1 and 2 would not be sustainable in the real-world, but the model incorporated none of the feedback loops in the natural or socio-economic systems that could balance the positive feedback. The second experiment, involving changes to the temperature feedback factor, \( \eta \), function, illustrated the behaviour of the model to changes in a high-sensitivity component. Sensitive elements like equation (2) warrant further study, especially since the real-world nature of the population-water connection is unclear. However, while experiment 2 revealed the sensitivity of the model to this equation, and therefore the necessity to investigate this inter-sectoral connection in greater detail, it did not say anything about the realism of the connection. Finally, the third experiment, which explored the effects of changes to one sector of the model, demonstrated that a model is not generally sensitive to changes in every parameter. Based on the results of this experiment, we should improve the representation of the water and population sectors, rather than focussing on the natural sectors of the model.

Therefore, in terms of future work, the full model will include many more sectors than the four used in this paper. We are building on the RICE (Nordhaus and Boyer, 2000) and FREE (Fiddaman, 2002) climate-economy models – and on the IMAGE 2.1 (Alcamo et al., 1998) model, to a lesser extent – by providing improved representations of the physical processes involved in the climate system and carbon cycle, and including the socio-economic sectors and activities that govern interactions with natural systems, especially those that influence or control anthropogenic emissions.

The resulting model will combine climate and carbon- and water-cycle models with socio-economic models that incorporate aspects of economics, energy, policy, carbon emissions, land-use change, population, and social welfare (Fiddaman, 2002; Nordhaus and Boyer, 2000) – see Figure 6 below. The inclusion of so many different sectors, and their interdependence, makes a multi-disciplinary approach necessary. Beyond the simple necessity of such an approach, however, are the advantages it offers over a traditional single-disciplinary approach: sharing, new knowledge, completeness, and accuracy. A multi-disciplinary approach allows the sharing of expertise and methodology between different academic disciplines, helping established disciplines to push their boundaries and grow. It can help to build new knowledge and new disciplines, because, as Peckerar (2004) observes, recent history shows that the greatest scientific progress has occurred at the interfaces between classical scientific disciplines. Finally, in modelling social-economic-climatic interactions properly, there is no other alternative than to include such disciplines as economics, political science, the natural sciences and engineering. To do otherwise would render the model incomplete and
Inaccurate, and useless to both science and policy development.

In summary, simple models cannot provide the fine detail necessary for local- to regional-level studies, and most cannot even simulate variables such as rainfall. However, such models can include the vital feedbacks that connect human activities to the global climate, and can therefore present important processes as feedbacks to other processes, rather than resorting to driving-fields. They also allow multiple simulations in a short time, easy comprehension of model behaviour, and simple sensitivity analysis. In essence, when choosing between coupled GCM-driving scenario and simple models, one must decide whether to sacrifice resolution for completeness, or whether to sacrifice completeness for resolution. Since anthropogenic effects form one of the largest uncertainties faced by climate change modelling efforts, it makes sense to include them in our models. Engineers should be concerned about climate change, because although they deal primarily with natural variables, social need and general well-being form the overall context of their work.

Figure 6: Interconnections between Model Sectors

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