Improving Understanding of Climate Change Dynamics Using Interactive Simulations

by

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Abstract

Global climate change is one of the most complex problems that human kind will face during the 21st century. Long delays in changing greenhouse gas emissions and in the response of the climate to anthropogenic forcing mean action to limit the risks of "dangerous interference with the climate system" must begin now, before further impacts of climate change are observed. However, research shows even well educated adults do not understand the time delays and other basic stock and flow dynamics of the climate, resulting in widespread belief that action to limit emissions can be delayed. Poor intuitive understanding of the dynamic structure of climate change has important consequences for building public support for mitigation policies. We introduce an interactive simulation designed to improve people's understanding of climate change dynamics and influence their attitude towards mitigation action. We report results of an experiment using the simulator in an interactive workshop with highly educated adults. Results show a positive shift in participant opinion about the urgency of emissions reductions and improved performance on tasks involving stocks and flows in the context of climate change.

Thesis Supervisor: John D. Sterman

Tile: Jay W. Forrester Professor of Management, Director, MIT System Dynamics Group

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To my shooting star,
she shines above to guide me
and within to inspire me.

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Acknowledgements

My time at MIT was a tremendous experience. I look back at the past two years and realize how much I have learned and grown. I met people from around the globe that brought exotic spices to my life. I actually got to explore new corners of the world too. I was exposed to high tech everything and shared the enthusiasm of many engineers trying to make the world a better place.

From all the buzzwords and management fads I heard in these years, one is probably going to stick with me: *sustainability*. We are growing in a way and at a pace we cannot sustain. The planet will not hold for much longer. John Sterman (a.k.a. Dr. Doom) was instrumental in this reflection. Naturally drawn to System Dynamics because of my holistic approach to understanding the world, I tried to convince John to let me join his class during my first semester at MIT. I did not get into the class then, but I got an RA appointment with him.

For the next two years we worked on a simulation to help people understand the dynamics of climate change. I got my share of System Dynamics in the process and developed a simulation that captures our reflections during that time. I want to thank John for supporting my research, for his personal consistency and the passion with which he teaches. Through John, I met Drew Jones from the Sustainability Institute. Drew was a constant source of energy, enthusiasm and one of the most charismatic advocates for sustainable development I have ever met.

Coming to MIT was an adventure in itself. I want to acknowledge all who stood by me in this decision and took the interest to stay in touch. Particularly, my family has always been a fundamental source of love and encouragement. I also want to thank the Fulbright Program for introducing me to the U.S. culture and for their continued support.

Finally, my experience at MIT would not have been the same without Faaiza. Her curious and honest pursuit of knowledge pushed my boundaries from the beginning. Our long and profound conversations shaped my view of the world. Her contributions to my work are fundamental. In her, I found a research partner, a close friend and a life accomplice.

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I. Introduction

Global climate change is one of the most complex problems that human kind will face during the 21st century. Its impact on the world economy is unquestionable. Its effects on our daily lives are already noticeable. Collective action on a large scale across nations remains the biggest challenge because climate change spans national boundaries and has long-term implications (Stern, 2007). Action to limit the risks of "dangerous interference with the climate system" must begin now, before further impacts of climate change materialize. To increase public support for international agreements people need to understand the basic dynamics of climate change and realize how critical it is to support prompt mitigation action.

In democratic governments, a broad public understanding of a problem is an important step towards building political support for public policy. Public policy depends on public opinion because public opinion is a key component of the socio-political context within which policy makers operate. For critical public policy issues such as climate change, only strong public support will compel governments to take significant action. Further, to mitigate or adapt to global warming, billions of individuals will need to change their behavior. Everyday, each one of us makes individual choices that have enormous collective impact on the Earth's climate (Leiserowitz, 2007).

Public opinion towards support for collective action needs to start by recognizing and understanding the problem of climate change. Inappropriate conceptualization of climate change and lack of knowledge of effective responses can obstruct social response (Kempton, 1993). However, awareness is a necessary but insufficient condition to motivate an individual or collective response. An individual's initial concern (that results from acknowledging the existence of climate change, its human causes, and risks to human welfare) has to first grow into a sense of urgency (Moser and Dilling, 2004). As people start to internalize the problem they can begin to move from awareness to engagement and finally advocacy of the issue.

Various studies have shown that public opinion towards dealing with global warming seems to be gaining momentum worldwide. However, they also indicate that current perceptions of the risks of climate change are not yet enough to support mitigation policies. In his report for the United Nations Development Programme, Leiserowitz (2007) assesses international public opinion, perception, and understanding of climate change over the last decade. Many public opinion surveys show that most people in developed countries are aware of climate change and express some degree of concern. However, concern doesn't necessarily make an issue national priority. When compared to more pressing problems such as war, poverty or unemployment it appears that climate change remains a relatively low priority globally.

Low public support for mitigation policies may arise from misconceptions of climate dynamics rather than uncertainty about the impact of climate change. Misconceptions of climate dynamics are associated with a weak intuitive understanding of the concept of accumulation (Sterman and Booth Sweeney, 2007). The principle of accumulation refers to the ability to determine the level of a resource or stock, such as greenhouse gas (GHG) concentration in the atmosphere, when the rate of change in the stock level varies as determined by the difference between its inflow and its outflow (GHG emissions released into the atmosphere minus the amount removed by natural processes).

Booth Sweeney and Sterman (2000) carried out an experiment based on the principle of accumulation with graduate students at the Massachusetts Institute of Technology. They used the analogy of a bathtub to illustrate how the difference between the inflow and outflow would accumulate or drain water in the bathtub. The experiment was designed to test the participants' ability to infer the level of a stock (the water in the bathtub) after analyzing graphs of the inflow and outflow (water coming in and out of the bathtub). Although the patterns were simple, fewer than half of the students responded correctly. This is evidence that problems with a stock and flow structure are unintuitive and difficult to solve (Cronin and Gonzalez, 2007; Cronin et al., 2008).

The researchers in the previous study attributed the majority of the erroneous responses to the use of a pattern matching heuristic. In this mode of operation, participants would follow the trajectory of the system's output when asked to project future values of the system's input. Other research groups have replicated some of these results while working with similar demographics (Atkins et al., 2002; Pala and Vennix, 2005).

Sterman and Booth Sweeney (2002) extended their bathtub experiment to assess people's intuitive understanding of climate change. Results revealed that participants followed the same pattern matching heuristic. The vast majority of the subjects expected to stabilize atmospheric GHG concentrations by leveling GHG emissions while the net inflow remained positive. In the context of the bathtub analogy, this is equivalent to saying that the bathtub will never overflow even if there is more water flowing in than draining out.

Erroneous judgments that result from using pattern matching to assess the dynamics of the climate have important public policy implications. Currently, GHG emissions are roughly double the rate at which they are removed from the atmosphere by natural processes (IPCC, 2007a). Atmospheric GHG concentrations will continue to rise even if emissions fall, until emissions fall to the removal rate. Underestimating the magnitude of GHG emissions reduction needed to stabilize atmospheric GHG concentrations can result in support of policies that delay mitigation action (Sterman and Booth Sweeney, 2007).

The current study was motivated by the lack of intuitive understanding of the dynamic structure of climate change and its implications for building public support for mitigation policies. We devised an experiment to test if we could improve people's understanding of climate change dynamics and influence their attitude towards support of mitigation action.

The experiment was built around an interactive simulation and conducted with a group of educated adults with a strong technical background. We used the simulation to raise awareness of climate change and help participants reflect on the consequences of delaying mitigation action. In the rest of the paper we describe the simulation we used and the experiment conducted. We also discuss results showing a positive shift in participant opinion about the urgency of emissions reductions and improved performance on tasks involving stocks and flows in the context of climate change.

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II. Method

Addressing climate change is a shared responsibility. However, there is an inherent challenge in collective action. People are likely to avoid contributions to the public commons if they face significant private costs (Olson, 1965). In the case of the environment, private costs do not reflect most of the negative externalities that result from burning fossil fuels. Mitigation policies are likely to affect private costs in the future (e.g. with a carbon tax) aggravating the problem. Efforts towards collective action should be based on promoting a collective understanding of the problem we face as human kind. This work introduces a learning tool that can contribute to the shared understanding of the dynamics of climate change.

The first objective of our interactive simulation is to improve understanding of climate change dynamics. We have learned from prior work that people struggle when making decisions in the presence of dynamic complexity[1]. Sterman and Booth Sweeney (2007) concluded that subjects involved in their experiment failed to respond correctly because of the prevalence of a pattern matching heuristic. The idea that people often use dynamically deficient mental models to guide their decisions is also referred to as *misperceptions of feedback* (Sterman, 2000). It represents the notion that people fail to appreciate time delays between cause and effect, do not understand the relation between stocks and flows, and are insensitive to non-linearities that could abruptly affect the outcome of an evolving system.

Misperceptions of feedback are persistent. Cronin et al. (2008) evaluated subjects under different test conditions and observed sustained poor performance across problems with stock and flow structures. To help users cope with misperceptions of feedback in our simulation, we use an explicit analogy that communicates the underlying structure of the system.

[1] There are other dimensions of complexity in climate change. For example, combinatorial complexity arises from the number of variables involved in the assessment of climate change. This study focuses on the dynamic complexity of the problem, i.e. complexity that emerges from the interactions of agents over time, which does not necessarily depend on the combinatorial complexity of a system (Sterman, 2000).

The second objective of this study is to test if people's attitude towards climate change action can be affected by their experience with the simulation. To evaluate participant's attitudes, we put together a survey with questions about climate change and administered it before and after the experiment. Questions were extracted from previous global surveys (Chicago Council, 2007; Leiserowitz, 2006; Leiserowitz, 2007) to benchmark our sample group against the general population.

In the next sections we describe the simulation and the experiment conducted. The simulation description is divided in three parts: first, we introduce the climate-economy model in which the simulation is based; second, we present design principles that guided the development of the simulation; and third, we describe the user interface. After describing the simulation, we present the details of the experiment and describe both the learning and experiment protocols.

II.1 Climate-Economy Model

Our simulation is based on a climate-economy model that enables exploration of climate change dynamics under different scenarios. The climate-economy model is built on the FREE (Feedback-Rich Energy Economy model) model developed by Fiddaman (Fiddaman, 1997).

The model is divided into three subsystems: the world economy, the carbon cycle and the climate. Figure 1 describes the high level structure of the model.

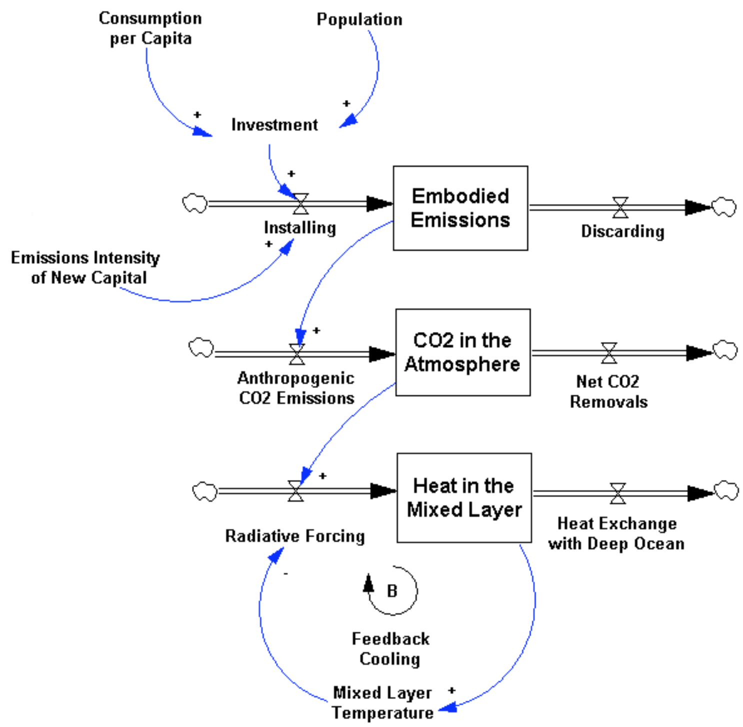


Figure 1. Climate-economy model high level stocks and flows diagram. The climate-economy model is divided into three subsystems: (1) the world economy, which drives CO_2 emissions; (2) the carbon cycle that represents the natural processes by which CO_2 accumulates in the atmosphere; and (3) the climate, which models the greenhouse effect that results in global warming.

The world economy drives *CO_2 emissions* as determined by *population* growth, economic output, and the state of technology. Figure 2 presents the IPAT heuristic (Impact = Population x Affluence x Technology) often used to describe this relationship (Ehrlich and Holdren, 1971; IPCC, 2000). As *CO_2 emissions* are released into the atmosphere, some dissolves in the oceans or is taken up by biomass, and the rest accumulates. The presence of carbon dioxide in the atmosphere alters *radiative forcing*, which affects the amount of heat retained by the atmosphere. The accumulation of heat increases *global mean temperature* impacting the climate. The rest of this section presents an overview of each subsystem. The appendix provides a description of the complete model.

$$CO_2\ Emissions = Population * \frac{Income}{per\ capita} * CO_2\ Intensity\ of\ the\ Economy$$

$$\frac{tons\ of\ Carbon}{year} = people * \frac{dollars/people}{year} * \frac{tons\ of\ Carbon}{dollar}$$

Figure 2. IPAT Equation. In our model, *CO_2 emissions* as determined by *population* growth, affluence, and the state of technology. World population is currently 6.65 billion. According to the median United Nations projection, it will reach about 9 billion by 2050, then stabilize (United Nations, 2004). *Income per capita* (Gross World Product per capita, in real terms), has been growing at an average compound rate of about 1.3% per year since 1980 (Energy Information Administration, 2008). We assume that this rate continues through 2100. The *CO_2 intensity of the economy* is determined by how much energy is needed to produce a dollar of economic output and the efficiency of energy-consuming *capital* stocks.

The world economy subsystem accumulates the *capital* stock, i.e. the stock of cars, homes, factories and power plants in the system. The *capital* stock increases with *investments* and decreases with *depreciation*. The *investment rate* is determined by consumption while depreciation is associated with the *average life of capital*. As affluence increases and *population* grows, *consumption per capita* drives *investment* and accumulates more *capital* in the world economy.

As the economy grows, more energy-consuming capital is installed. The *CO_2 intensity of the economy* (how many tons of carbon are released into the atmosphere per real dollar of economic activity) depends on the energy efficiency of installed capital, the fuel mix, and technologies such as carbon capture and sequestration. Technological progress can reduce the *CO_2 intensity of new capital*, but developing new technologies and replacing existing capital takes time. The average life of power plants, vehicles, buildings and other infrastructure is on the order of decades. Although some retrofits of old capital are possible, significant reduction of the *CO_2 intensity of the economy* can only come from reducing our fossil fuel dependence.

The second subsystem is a depiction of the carbon cycle, which models how carbon is exchanged between the atmosphere and the natural sinks represented by the biosphere and the oceans. Natural sinks absorb a fraction of the carbon dioxide released into the environment, while the rest remains in the atmosphere unless it is captured by artificial means such as *carbon sequestration* mechanisms. However, carbon dioxide stored in natural sinks is eventually released back into the atmosphere through processes such as respiration and deforestation: bacteria, fungi, and other organisms consume carbon in soils and release carbon dioxide and methane to the atmosphere; wildfire releases carbon in terrestrial biomass; the oceans release carbon dioxide back to the atmosphere as marine bacteria process phytoplankton and as carbon saturated water outgases carbon dioxide. The flux of carbon dioxide removed by natural sinks less the flux of carbon dioxide released back into the atmosphere is referred to as *net removal*. Currently, *net removal* is about half of total *anthropogenic* CO_2 *emissions* (IPCC, 2007b).

The last subsystem models the impact of carbon dioxide on the climate. Greenhouse gases contribute to *radiative forcing*, which is the net change in irradiance at the tropopause due to a change in an external driver of climate change such as carbon dioxide (IPCC, 2007a). More carbon dioxide in the atmosphere results in a stronger greenhouse effect that traps more heat between the atmosphere and the earth. Although some heat is radiated to space or absorbed by the oceans, the net result has increased *global surface temperature* 0.74 degrees Celsius over the last 100 years (IPCC, 2007a). This is the process we refer to as *global warming*.

The time horizon of our model is between 1900 and 2100. We used historical data to calibrate the model and project its effects till the end of the 21st century (Etheridge et al., 1998; Hansen et al., 2007; Keeling and Whorf, 2005; Marland et al., 2007). A limitation of our current formulation is that it omits the devastating effects that climate change can bring to the world economy. Severe climatic events like hurricanes, droughts or sea level rise could create economic disruption, which would only make the case for immediate mitigation action stronger.

II.2 Learning Tool

Simulation Design

We previously discussed the difficulty people experience when dealing with dynamic complexity. People generally adopt an event-based, open loop view of causality, which makes inferences about a system's structure difficult when observations of cause and effect are distant in time and space (Sterman, 2000). Simulations can reveal even the distant effects of our decisions, closing the learning loop and thus enabling learning.

With feedback in place, users can adjust their decisions to align the state of a system with their goals. Reacting to feedback can improve results but does not necessary lead to learning. For learning to take place it is necessary to reflect on how decisions are made so we can revise our mental models. However, people are more likely to accept evidence that is consistent with their current beliefs and, unless results are largely inconsistent, are unlikely to challenge their mental models (Morecroft and Sterman, 1994). To facilitate learning in our simulation, we reveal the underlying structure of the system and provide users with tools for experimentation.

Simulations present users with a representation of the real world that can help them change their understanding of that world (Papert, 1980). As people mostly trust their own views of the world as a basis for their decisions, it is important to place them at the center of the learning process and provide them opportunities to challenge their mental models. Learning is accelerated as users input their own assumptions and receive feedback on the consequences. (Morecroft and Sterman, 1994)

As a result, we created an interactive simulation where people could explore the challenges of climate change, question their assumptions and observe the long-term impacts of their decisions. We constrained the behavior of the system to the accepted physical science while maintaining a streamlined user experience. Simulation scenarios were built to illustrate the interaction between key climate change variables and are not intended to be precise forecasts.

Simulation Interface

We chose a web-based platform for the simulation. The Internet offers straightforward scalability and allows us to reach a broader audience. For the interface itself we used Adobe® Flash®, because it provided the flexibility and graphics capability to create a rich user experience. Additionally, it solved most of the cross-browser compatibility issues because it runs on a multi-platform browser plug-in already available in most computers.

Several prototypes were built and tested with our intended audience before the final experiment was conducted.

The simulation is arranged into six modules presented to the user sequentially: background information, initial Stock and Flow (SF) Challenge, First Experiment: "bathtub dynamics", Second Experiment: "time delays in the economy", final SF Challenge and simulation debrief (Figure 3). The rest of this section describes each module in more detail.

Figure 3. Simulation modules. The simulation presents the user with six different modules in a sequence. First, we set the context of the simulation and introduce a SF Challenge to test the user's intuitive understanding of climate change dynamics. Two experiments follow where the user is able to explore aspects of climate change and the effects of time delays in the system. A final SF Challenge is used to test for learning, before we provide the experience debrief.

In the first module, we presented subjects with a brief non-technical summary of climate change extracted from the IPCC's Fourth Assessment Report [AR4] Summary for Policymakers [SPM] (IPCC, 2007a). The text provides a background for the experience as well as introduces the concepts of *atmospheric CO_2 concentration*[2], anthropogenic *CO_2 emissions* and removal of carbon dioxide from the atmosphere by natural processes. We also provide a graphic display for the historical trend of anthropogenic *CO_2 emissions* and introduce the relationship it has with *atmospheric CO_2 concentration* and increasing *global mean temperature*.

The initial Stock and Flow (SF) Challenge is designed to test the user's intuitive understanding of climate change dynamics (Figure 4). We pose a question to the user based on the experiment conducted by Sterman and Booth Sweeney (2007). It presents a stabilization scenario for future *atmospheric CO_2 concentration* in which *atmospheric CO_2 concentration* stabilizes at 420 ppm by the year 2100 (Figure 4a). It also provides graphs of

[2] Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas (GHG). In 2004, it accounted for 76.7% of total GHG emissions. Total GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. In that same period, annual emissions of carbon dioxide grew by about 80% (IPCC, 2007a).

past anthropogenic *CO_2 emissions* and *net removal* (Figure 4b). The user is asked to infer the path for anthropogenic *CO_2 emissions* required to stabilize *atmospheric CO_2 concentration* at 420 parts per million (ppm) by 2100, assuming that *net removal* remains constant in the future at about 5 gigatons of carbon per year (GtC/yr). As a reference, we present the business as usual emissions projection according to the IPCC A2 ASF SRES scenario (IPCC, 2007a). Users drag the red arrow (Figure 4c) with the mouse to select their choice of path for *CO_2 emissions*. We capture users' responses.

Note that *net removal* is dependent on the level of *atmospheric CO_2 concentration* and it will not stay constant in reality. However, the purpose of this first experiment is to assess the extent to which people understand the stock and flow relationship between *atmospheric CO_2 concentration* and the flows of *CO_2 emissions* and *net removal*. For this purpose, the simple assumption that *net removal* remains approximately constant is appropriate. In the Sterman and Booth Sweeney (2007) experiment, subjects were asked to draw their best estimate of future *net removal* and many drew trajectories that were roughly constant near current rates. The scenarios after this first experiment relax the assumption of constant *net removal* by modeling it endogenously (see below).

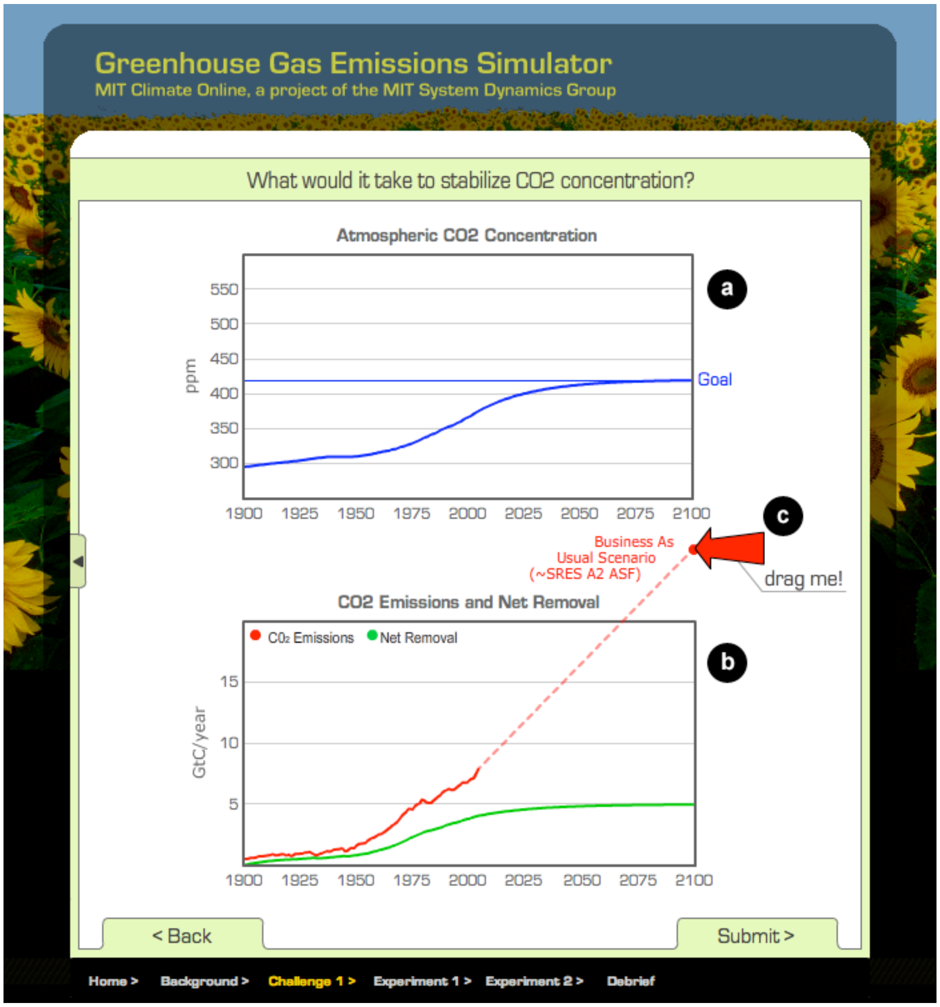


Figure 4. Initial SF Challenge. The initial Stock and Flow (SF) Challenge is designed to test the user's intuitive understanding of climate change dynamics. It presents a stabilization scenario for future atmospheric *CO_2 concentration* by the year 2100 (a). It also provides the historical trend of anthropogenic *CO_2 emissions* and *net removal* (b). The user is asked to infer the path for anthropogenic *CO_2 emissions* by 2100, assuming that *net removal* remains constant in the future at about 5 GtC/yr.

The first experiment is designed to explore the relationship between *CO_2 emissions* and *net removal* required to achieve the stabilization scenario presented in the first SF Challenge (Figure 5). We provide the user with a graphical reference to the desired path for *atmospheric CO_2 concentration* from 2000 to 2100 (Figure 5a). We include an empty graph canvas below the first one (Figure 5b), where the user can see the path for *CO_2 emissions* and *net removal* once the simulation starts. As the simulation runs, the integration of *CO_2 emissions* minus *net removal* is plotted against the reference for *atmospheric CO_2 concentration.*

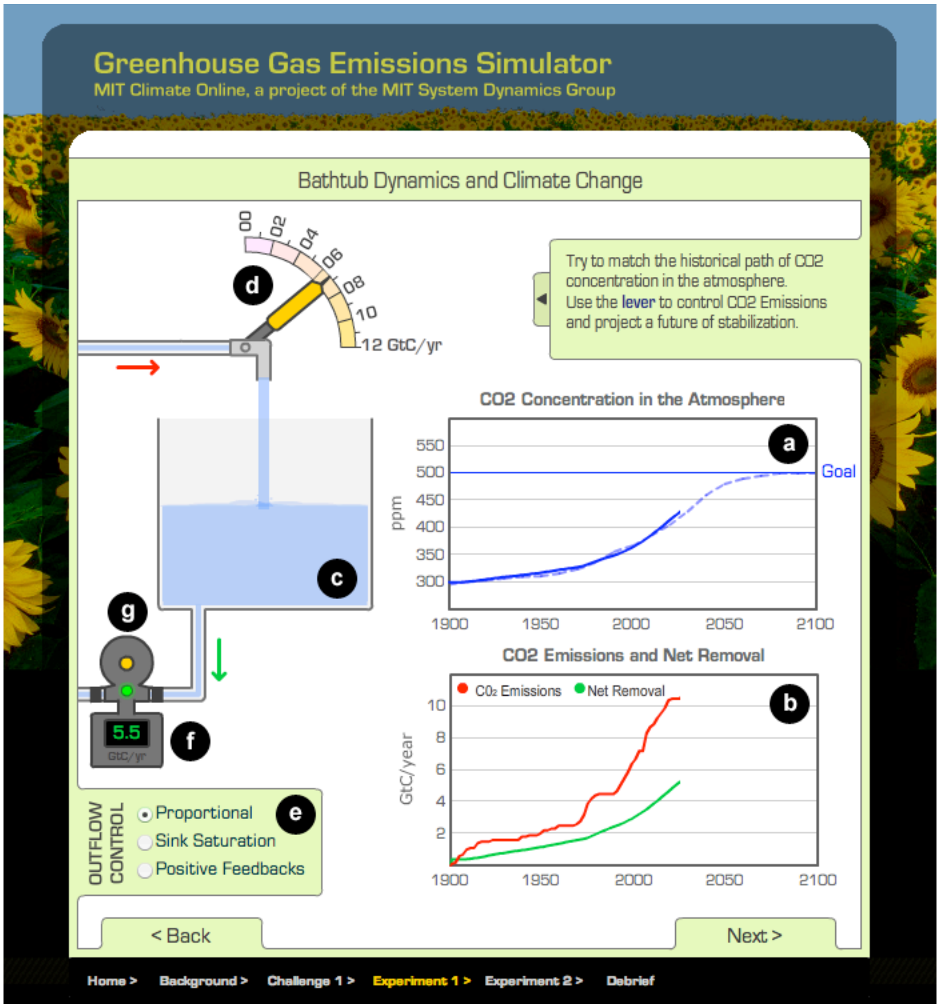


Figure 5. First Experiment: *Bathtub Dynamics*. This experiment is designed to explore the relationship between *CO_2 emissions* and *net removal* that is required to achieve a stabilization scenario. (a) provides a reference to the desired path for *atmospheric CO_2 concentration* from 2000 to 2100. A second graph (b) enables the user to see the path for *CO_2 emissions* and *net removal* once the simulation starts. As the simulation runs, the integration of *CO_2 emissions* minus *net removal* is plotted against the reference for *atmospheric CO_2 concentration*. Next to the graphs (c), water flows into a bathtub and accumulates like *atmospheric CO_2 concentration*. We included the animation to provide an explicit reference to the underlying stocks and flows structure of the system.

We include a bathtub animation to make an explicit reference to the underlying stock and flow structure of the system (Figure 5c). The level of water in the bathtub is analogous to *atmospheric CO_2 concentration*. *CO_2 emissions* are represented by the flow of water going into the bathtub. The drain represents the *net removal* of carbon dioxide from the atmosphere. With the use of the mouse, the user controls a lever placed on the inflow pipe and determines the rate at which water will flow into the bathtub (Figure 5d). Controlling the water inflow is equivalent to controlling *CO_2 emissions*. The challenge in this experiment is to control *CO_2 emissions* to replicate the path for *atmospheric CO_2 concentration* stabilization.

To make things more interesting, the path for *net removal* is determined by the simulator according to three different settings: *proportional*, *sink saturation* and *positive feedbacks*:

a. In the *proportional* setting, the flow of carbon dioxide extracted from the atmosphere is proportional to its concentration. As *atmospheric CO_2 concentration* accumulates, *net removal* increases because more carbon dioxide is taken up by the biomass and dissolved into the oceans. The assumption of proportional removal is common in many simplistic carbon cycle models such as the DICE and RICE models of the economics of climate change (Nordhaus, 1994; Nordhaus and Boyer, 2000). Sterman and Booth Sweeney (2007) show that many subjects in their experiment believe such carbon dioxide fertilization will cause *net removal* to rise with rising *atmospheric CO_2 concentration*.

b. In the *sink saturation* setting, the response is the same as in the *proportional* case, except that the ability of biomass and the oceans to absorb additional carbon dioxide is gradually reduced as these carbon sinks saturate. Using climate-carbon cycle models, the IPCC projects that future climate change would reduce the efficiency of the Earth system to absorb anthropogenic carbon dioxide (IPCC, 2007b). For example, the rate at which carbon dioxide is dissolved into the oceans depends on the difference in the partial pressure of carbon dioxide (pCO_2) between the atmosphere and the ocean surface. As the ocean takes up more carbon dioxide from the atmosphere, pCO_2 rises, reducing future uptake. Recent studies suggest that the oceans may be already decreasing their ability to absorb carbon dioxide from the atmosphere (Le Quéré et al., 2007; Schuster and Watson, 2007).

c. In the *positive feedbacks* setting, the ability of natural sinks to absorb additional carbon dioxide declines even more rapidly than in the *sink saturation* case. As *global mean temperatures* increases, more of the carbon dioxide stored in soils and standing forests is released into the atmosphere through enhanced microbial respiration, increased incidence of wildfire, and other positive (reinforcing) feedbacks. For example, as the ocean warms, carbon dioxide dissolved into the ocean's surface layer becomes less soluble, its partial pressure increases and ocean uptake is reduced still more; thawing permafrost makes large stocks of previously frozen and sequestered organic carbon bioavailable for respiration by bacteria, fungi, etc.; warming reduces snow pack and lengthens the fire season, increasing carbon dioxide release from wildfire (IPCC, 2007b).

Users choose their preferred assumption by clicking on the appropriate option on the lower left panel (Figure 5e).

To illustrate the fact that the simulator controls *net removal*, the outflow pipe has an electronic flow control instead of a lever (Figure 5f). We have also included an electric pump that controls the flow of water through the drain. The pump is placed to emphasize that the outflow of water is dependent on the pump throughput, which is set by the user's assumption about the carbon cycle, and is not proportional to the water pressure in the bathtub (Figure 5g).

The second experiment is designed to illustrate the effects of time delays present in the system, as well as to bring the discussion closer to a policy debate. The basic setting is similar to that of the first experiment. It has the illustration of the bathtub on one side and the graphs for *atmospheric CO_2 concentration* on the other (Figure 6). It also presents a panel in the bottom left to control the different settings for *net removal* (Figure 6d). The main difference in this view is that the inflow pipe lever has been replaced by an electronic flow control (Figure 6c). The user is no longer in control of *CO_2 emissions*. Instead, *CO_2 emissions* are the result of the interactions amongst *world population*, *income per capita* and *CO_2 intensity of the economy*, as described by the IPAT equation (Figure 2). To access the control panel for this experiment, we added a drawer that can be pulled out by clicking on the small arrow on the left side (Figure 6e).

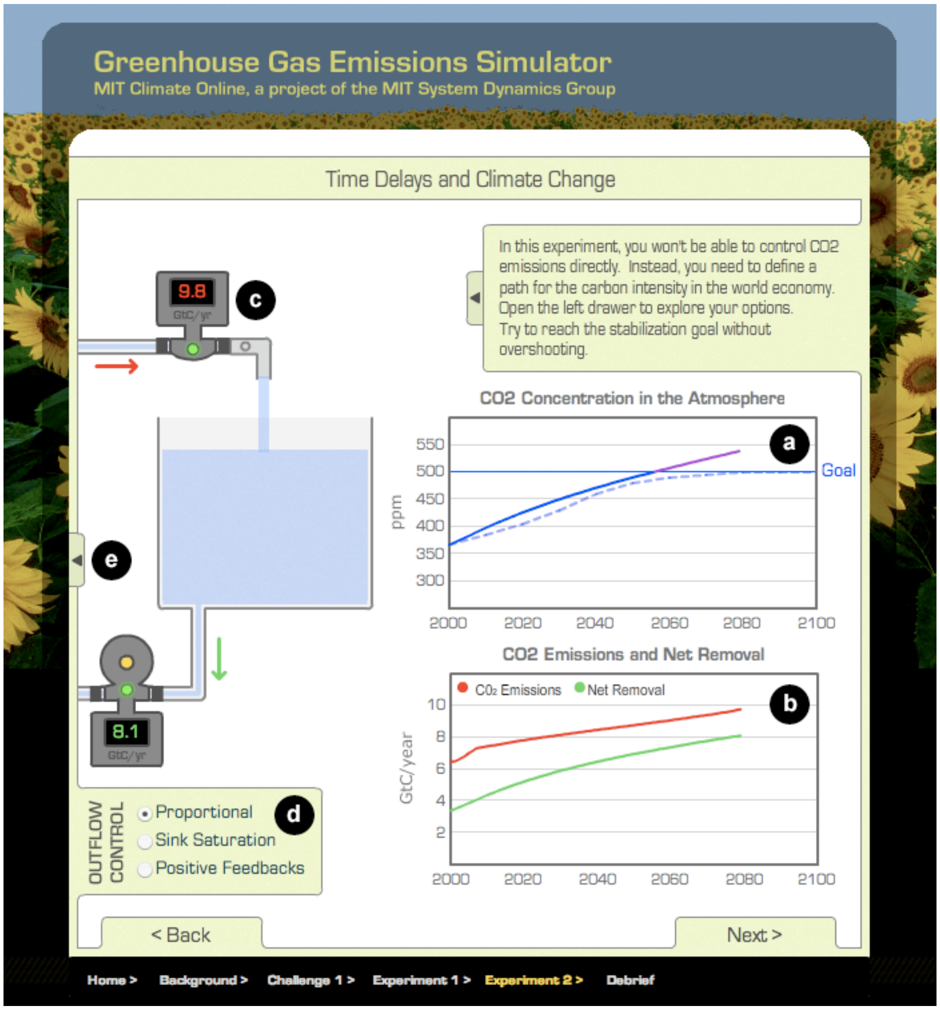


Figure 6. Second Experiment: *Time delays in the economy.* This experiment is designed to illustrate the effects of time delays present in the system, as well as to bring the discussion closer to a policy debate. In this experiment, *CO_2 emissions* result from the interaction amongst *world population*, *income per capita* and *CO_2 intensity of the economy*, and are no longer controlled directly by the user. By pressing (e), users have access to the control panel, which is displayed in Figure 7.

The drawer contains three additional graphs for the variables in the IPAT equation (Figure 7c, Figure 7d, Figure 7e).

a. *World population* at the beginning of 2008 was approximately 6.65 billion. According to the medium fertility United Nations projection, it will continue growing to reach about 9 billion by 2050, then stabilize (United Nations, 2004).

b. *Income per capita* (Gross World Product per capita, in real terms), has been growing at an average compound rate of about 1.3% per year since 1980

(Energy Information Administration, 2008). We assume that this rate continues through 2100.

c. The *CO_2 intensity of the economy* is determined by how much carbon dioxide is emitted for each dollar of economic output, and depends, in turn, on the energy efficiency of existing plant and equipment and the mix of fuels needed to power those capital stocks.

In this experiment, we ask the user to determine the desired level of *CO_2 intensity of the economy* to replicate the path for *atmospheric CO_2 concentration* stabilization presented in Figure 7a. To achieve this objective, the user needs to drag the small blue arrow at the right of the lower graph with the mouse (Figure 7f). As the simulation runs, all visible graphs are plotted simultaneously.

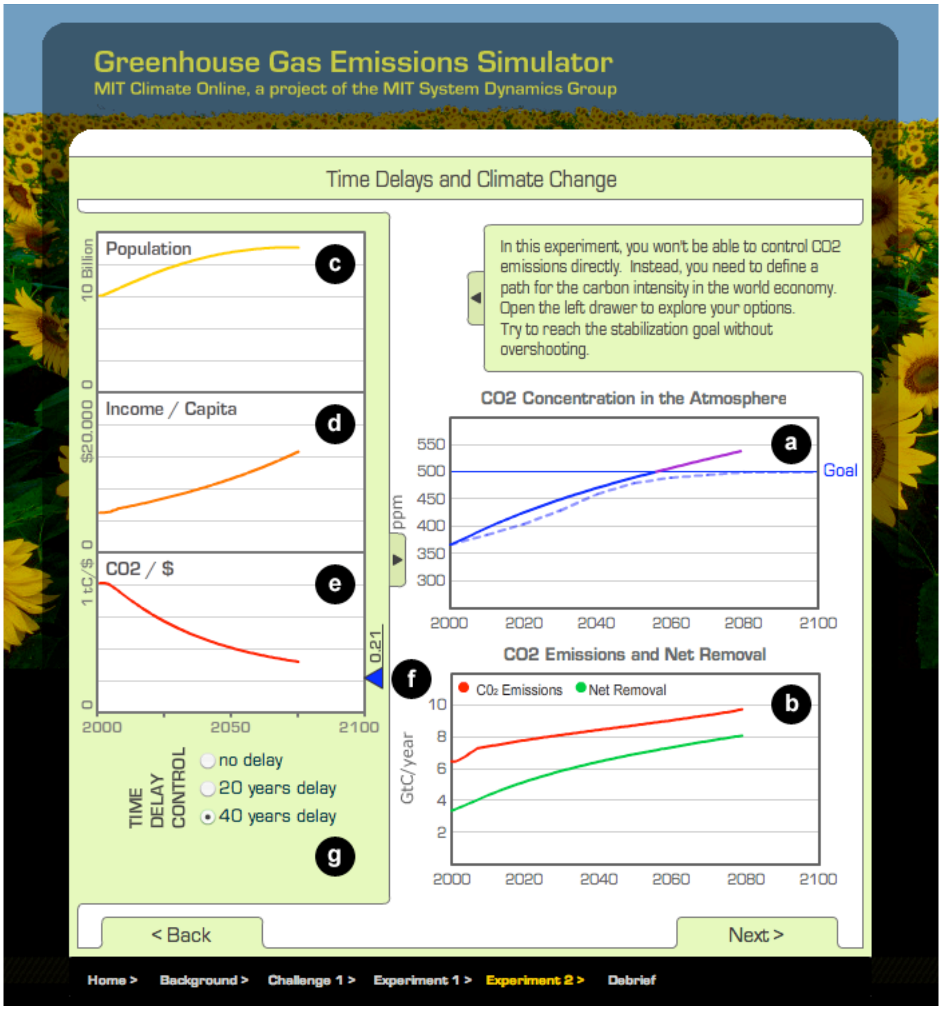


Figure 7. Second Experiment: *Control panel*. Opening the drawer provides access to three additional graphs for the variables in the IPAT equation: (c) *World population, (d) Income per capita, and (e) CO_2 intensity of the economy*. In this experiment, we ask the user to determine the desired level of *CO_2 intensity of the economy* to replicate the path for *atmospheric CO_2 concentration* stabilization presented in (a). To achieve this objective, the user drags the small blue arrow at the right of the lower graph (f). As the simulation runs, all visible graphs are plotted simultaneously.

The *CO_2 intensity of the economy* cannot adjust immediately to policy and economic conditions as it depends on the characteristics of existing plant and equipment, settlement and trade patterns, and other attributes of the economy that change only slowly. To capture the adjustment delay, we model the *CO_2 intensity of the economy* by smoothing the desired level indicated by the user with a first-order exponential delay (Figure 8). The user can choose the time constant from the panel in the bottom (Figure 7g). Three options are available: no time delay, 20 years and 40 years. The second and third options represent two estimates of the time it takes to develop new technologies and turn over and replace existing power plants, vehicles, buildings and other infrastructure. By varying the time constant, users can explore the effects of time delays in their decision.

$$i_t = i_{t-1} + dt * \frac{(I_t - i_{t-1})}{T}$$

i_t : actual CO_2 intensity of the economy at time t
i_{t-1} : actual CO_2 intensity of the economy at time (t - 1)
dt : time interval (one year in this case)
I_t : desired CO_2 intensity of the economy at time t
T : time constant (average delay between desired and actual output)

Figure 8. First order exponential delay in the response of i(t) to I(t). Increasing the time constant results in a longer time to reap the benefits of reducing the *CO_2 intensity of the economy* with new technologies or faster *capital* stocks turn over.

After the experiments, the user is tested one more time with the final SF Challenge[3]. The objective of this module is to evaluate if users can apply the concepts introduced by the experiments. The final SF Challenge is very similar in presentation to the initial SF Challenge (Figure 9). The main difference is that the target scenario is not of stabilization but of reduction. The *atmospheric CO_2 concentration* target for 2100 is now 340 ppm, below current levels. Additionally, the projection of *net removal* follows a hypothetical trajectory according to the scenario of *sink saturation* introduced in the first experiment. To choose the path for *CO_2 emissions*, users drag the red arrow to specify the end point of the trajectory (Figure 9c). Another difference with the initial SF Challenge is that we included two handles that can be used to define the desired trajectory with more precision (Figure 9d). Dragging the handles (red dots) inside the graph canvas allows users to refine their answer by shaping the *CO_2 emissions* path to 2100. Finally, we collect users' responses for comparison with their answers on the initial SF Challenge.

[3] At the time of the workshop, the online version of the final SF Challenge was not available. Participants were given a paper version instead (Figure 14). The paper version stated the same problem but allowed users complete freedom to indicate their preferred trajectories for *CO_2 emissions* and *net removal*.

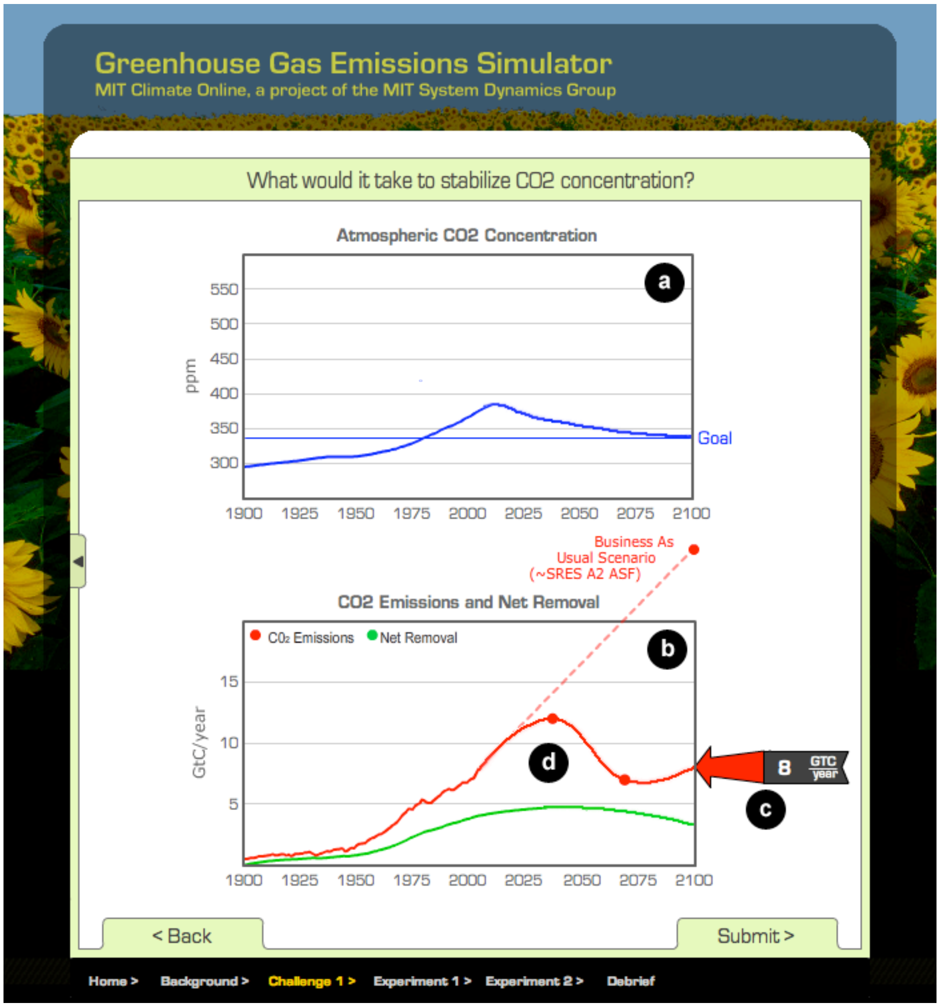


Figure 9. Final SF Challenge. The final Stock and Flow (SF) Challenge is designed to evaluate if users can apply the concepts introduced by the simulation. In this case, the target scenario is not of stabilization but of reduction. The target for *atmospheric* CO_2 *concentration* by 2100 is 340 ppm, below current levels. The projection of *net removal* follows a hypothetical trajectory according to the scenario of sink saturation introduced in the first experiment. To choose the path for CO_2 *emissions*, users drag the red arrow to specify the end point of the trajectory (c). An important difference with the first SF Challenge is that users can now draw a precise trajectory by dragging the red dots inside the graph canvas to shape the curve (d).

The final module in the experiment is a short debrief of the experience and presents the key takeaways of the simulation[4].

[4] In the case of the experiment presented in this study, we discussed key takeaways with participants at the end of the workshop without using the simulation debrief.

II.3 Experiment

Learning Protocol

The simulation design was based on several key concepts of system dynamics applied to climate change such as the concept of dynamic complexity, stocks and flows and the effects of time delays in a system's behavior. To guide the design process, we created a learning protocol that summarizes the concepts we embedded in the simulation:

Table 1. Design guide for the simulation. We built the simulation around several key concepts of systems dynamics applied to climate change and used this table as a reference for the overarching questions, contents and lessons for each module in the simulation.

	Question	Content	Lesson
Introduction	*What is this simulation about?*	*Title page and invitation to participate. Background on climate change based on IPCC AR4 SPM report. Links to references and climate related sites.*	
Initial SF Challenge	*What does it take to stabilize atmospheric CO_2 concentration?*	*A common misconception is that, to stabilize atmospheric CO_2 concentration, it is enough to level CO_2 emissions at current levels. We ask participants to project a path for CO_2 emissions that can stabilize atmospheric CO_2 concentration given a future of constant net removal.*	▪ *To stabilize the concentration of CO_2 in the atmosphere, CO_2 emissions must equal net removal.*
First Experiment	*How much do we need to cut CO_2 emissions?*	*To appreciate the magnitude of the challenge imposed by climate change, we ask users to match the historical trajectory of CO_2 emissions and project its future path under a stabilization scenario. We provide different trajectories for net removal.*	▪ *The magnitude of the cut on CO_2 emissions required to stabilize atmospheric CO_2 concentration is important (reduction of 50-80% from current levels by 2050)* ▪ *Net removal is not constant. In fact, it depends on the level of CO_2 concentration in the atmosphere. Carbon sinks can saturate and abruptly diminish nature's ability to remove CO_2 from the atmosphere.*

Second Experiment	*Why can't we just wait and see?*	*In this experiment, users are asked to control CO_2 emissions indirectly by determining the value for CO_2 emissions intensity. Additionally, users can choose amongst three possible time constants that delay the progress towards its desired state.*	▪ *Delaying mitigation action has important implications because solving the problem in the future would require considerably more effort. Acting now, even if just as insurance, is imperative.* ▪ *Technology is only part of the solution. CO_2 emissions in the economy also depend on other variables such as population growth and consumption.* ▪ *Living in a sustainable world will require a change in behavior of billions of human beings.*
Final SF Challenge	*What would it take to reduce atmospheric CO_2 concentration?*	*As a way to measure if participants learned from the experience, we ask them to project a path for CO_2 emissions that can reduce atmospheric CO_2 concentration given a future o net removal determined by carbon sink saturation.*	▪ *Reducing atmospheric CO_2 concentrations requires that emissions fall below net removal. In a scenario that includes future saturation of carbon sinks, the effort to mitigate climate change increases. Immediate action would help to avoid a lock-in scenario.*
Debrief	*What did I learn with the simulation?*	*We provide a brief summary page with some of the lessons that can be extracted from the experience with the simulator.*	▪ *Previous lessons recapitulated and summarized.*

Experiment Protocol

We conducted the experiment with MBA students at the MIT Sloan School of Management, who participated voluntarily[5] in a workshop for which they received credit towards degree requirements. We did not offer any financial or other incentives to take part in the experiment.

The experiment was designed to test the effectiveness of our interactive simulation. We wanted to test if: (1) people interacting with the simulation learn about the dynamics of climate change, and (2) people's attitude was more supportive of mitigation action after the experiment. To answer the first question, we created problem sets based on Stock and Flow concepts (SF Challenges) and we presented them to participants at the beginning and at the end of the experiment. Similarly, we administered an opinion survey before and after

[5] Before conducting the experiment, we took the necessary steps to comply with the ethical and legal guidelines for conducting studies involving human subjects. These guidelines are set by federal mandate and enforced at MIT by the Committee On the Use of Humans as Experimental Subjects (COUHES). They are designed to ensure that participants understand what they are being asked to do, that participation is voluntary, and that the published results exclude any personal identifying information.

the interaction with the simulation to answer the second question. The experiment flow is presented in Figure 10.

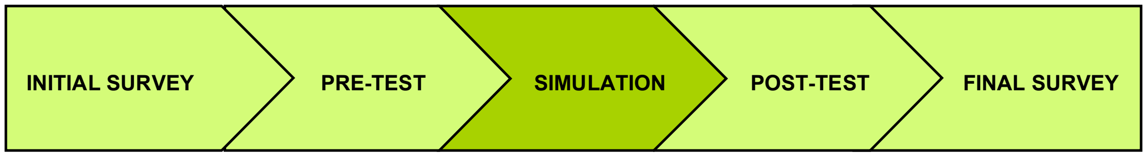


Figure 10. Experiment flow. The experiment was designed to test the effectiveness of our interactive simulation on two levels: (1) learning about the dynamics of climate change, and (2) shifting people's attitude towards climate change action. To test the impact on learning, we included pre-test and post-test SF Challenges. To detect shifts in attitudes towards climate change action, we conducted a survey at the beginning and at the end of the workshop.

We administered an opinion survey to evaluate participants' prior attitude towards climate change action. A total of thirteen survey questions were extracted from previous global surveys to benchmark our sample group against the general population (Chicago Council, 2007; Leiserowitz, 2006; Leiserowitz, 2007). Questions included stating your views about climate change, prioritizing national issues, and expressing support to different mitigation policies and international agreements, amongst others. Questions were administered in random order to lessen the order/response bias. We also included ten demographic questions (e.g. gender, age, country, field of study, etc) to create control variables for our posterior analysis. A total of 57 participants answered this first survey with an average response time of 6 minutes and 26 seconds. Sample results are shown in the results section (Table 4) and the complete survey is included in the appendix.

We administered a series of pre-test Stock and Flow (SF) Challenges with problems based on the principle of accumulation before the simulation. Participants were divided into three subgroups to isolate the effect of a given pre-test on the post-test. Each group was given two problems to solve according to their respective treatment (Table 2). Participants completed the pre-test tasks in no more than ten minutes.

Table 2. Stock and Flow Challenges used in the experiment. The sample was divided into three subgroups: Each subgroup was given a different treatment during the pre-test.

	Pre-test SF Challenges		Post-test SF Challenges		
Treatment	**1**	**2**	**1**	**2**	**3**
A	*Department Store*	*Stabilization Scenario*	*340ppm Scenario*	*Department Store*	*Ice Cover*
B	*Ice Cover*	*Stabilization Scenario*	*340ppm Scenario*	*Department Store*	*Ice Cover*
C	*IPCC Reading*	*Stabilization Scenario*	*340ppm Scenario*	*Department Store*	*Ice Cover*

Subgroup A was given a graph of people entering and leaving a department store during a thirty-minute period (Figure 11). They were asked to calculate the number of people inside the department store for that interval and sketch its evolution over time as a line graph. This task was previously used in Cronin et al. (2008) with a different population of students from the MIT Sloan School of Management, enabling us to compare performances against this demographically similar group.

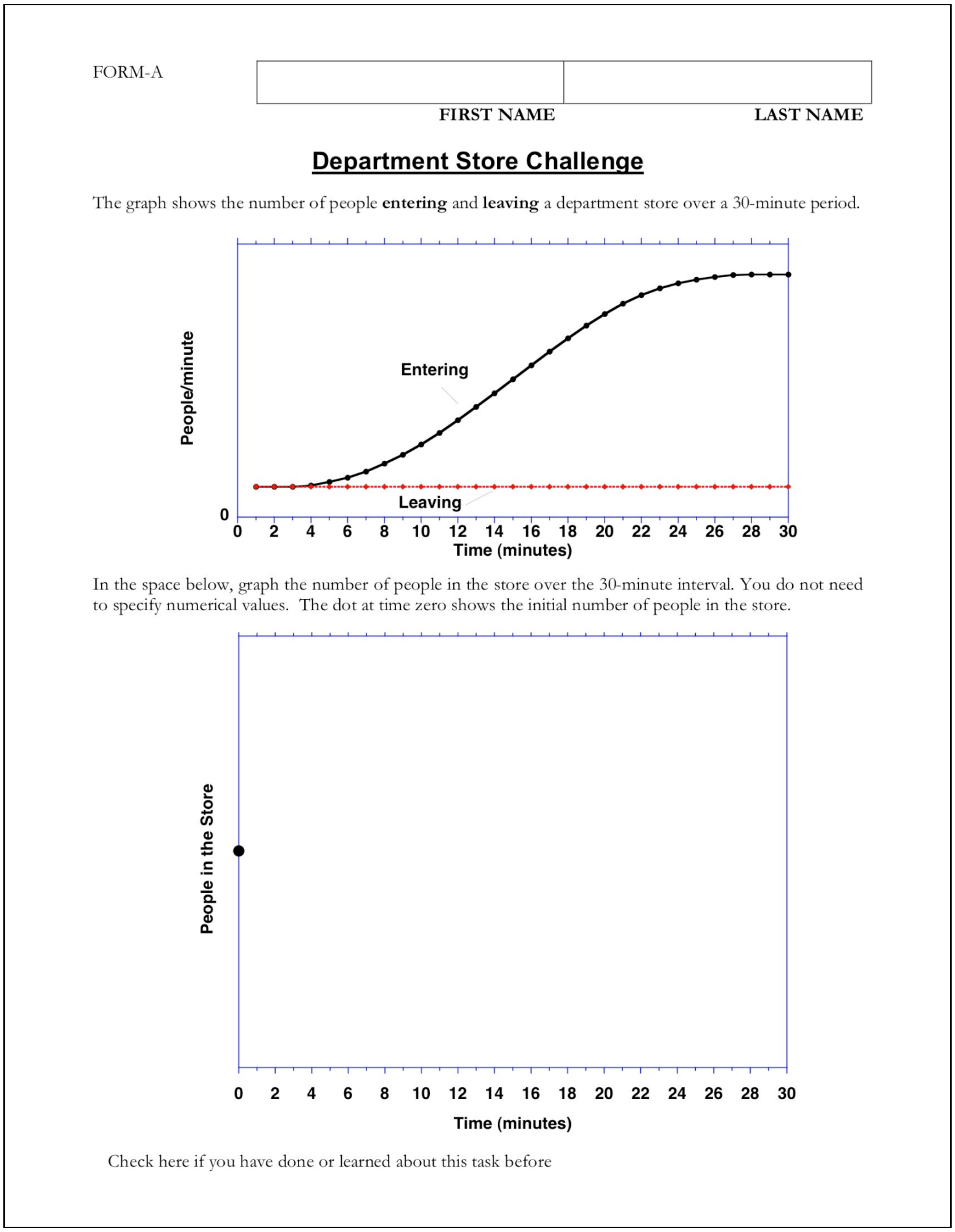
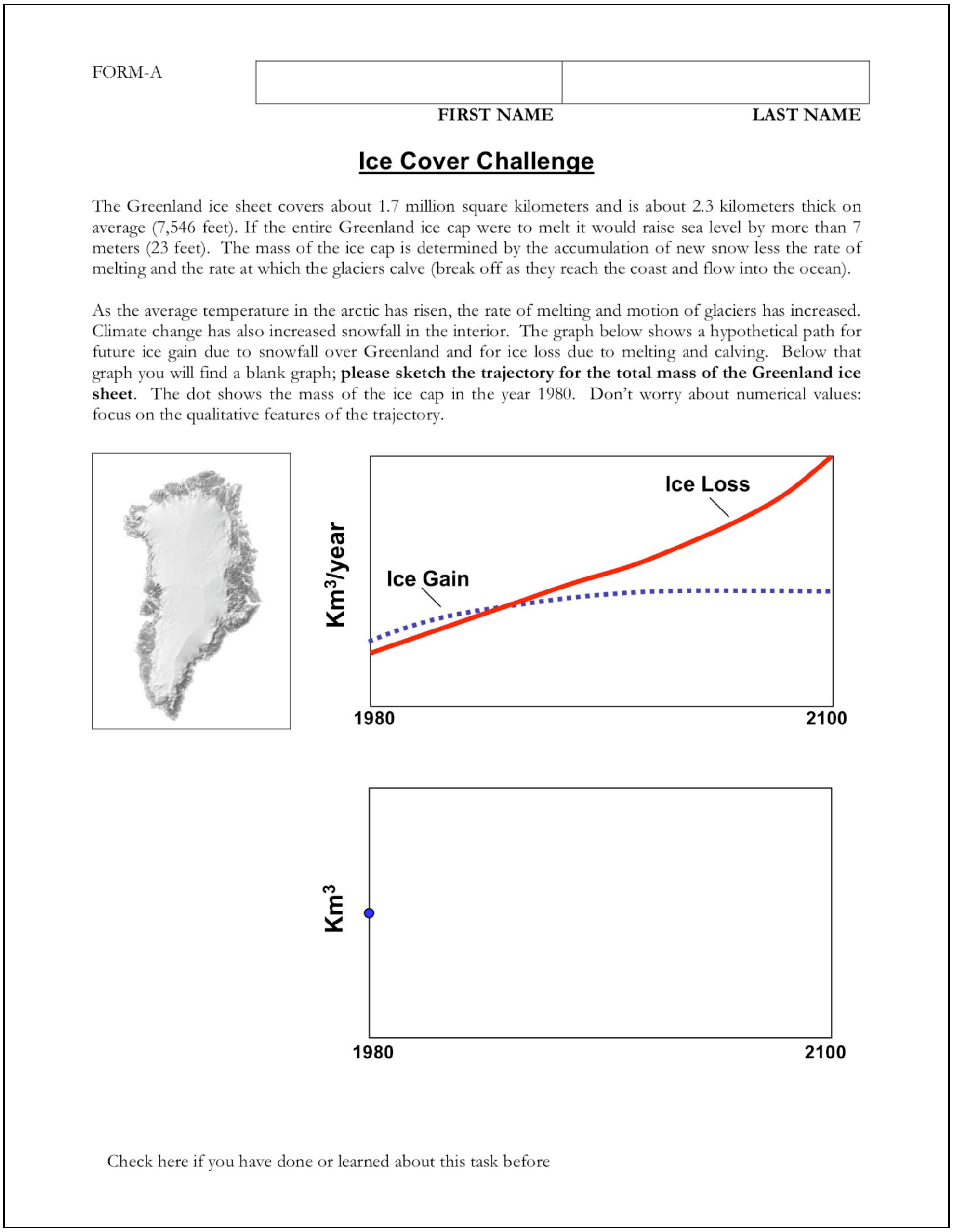


Figure 11. Department Store SF Challenge. The Department Store SF Challenge was administered to Subgroup A in the pre-test and to all participants in the post-test. Participants were asked to calculate the number of people inside a department store for a 30-minute interval and sketch its evolution over time as a line graph.

Subgroup B received a brief description of the Greenland ice sheet and a graph showing a hypothetical path for future ice gain due to snowfall and for ice loss due to melting and calving of glaciers as they flow into the sea (Figure 12). They were asked to sketch the trajectory for the total mass of the Greenland ice sheet based on the previous information.



FORM-A

FIRST NAME LAST NAME

Ice Cover Challenge

The Greenland ice sheet covers about 1.7 million square kilometers and is about 2.3 kilometers thick on average (7,546 feet). If the entire Greenland ice cap were to melt it would raise sea level by more than 7 meters (23 feet). The mass of the ice cap is determined by the accumulation of new snow less the rate of melting and the rate at which the glaciers calve (break off as they reach the coast and flow into the ocean).

As the average temperature in the arctic has risen, the rate of melting and motion of glaciers has increased. Climate change has also increased snowfall in the interior. The graph below shows a hypothetical path for future ice gain due to snowfall over Greenland and for ice loss due to melting and calving. Below that graph you will find a blank graph; **please sketch the trajectory for the total mass of the Greenland ice sheet**. The dot shows the mass of the ice cap in the year 1980. Don't worry about numerical values: focus on the qualitative features of the trajectory.

Check here if you have done or learned about this task before

Figure 12. Ice Cover SF Challenge. The Ice Cover SF Challenge was administered to Subgroup B in the pre-test and to all participants in the post-test. Participants were asked to sketch the trajectory for the total mass of the Greenland ice sheet based on the hypothetical path for future ice gain due to snowfall and for ice loss due to melting and calving of glaciers as they flow into the sea.

Subgroup C did not receive a SF Challenge. Instead, they were asked to read an excerpt of the IPCC Fourth Assessment Report (AR4). The text presented basic definitions of *atmospheric* CO_2 *accumulation*, CO_2 *emissions* and *global mean temperature*, as well as graphs showing their historical trajectories (Figure 13).

FORM-C

FIRST NAME	LAST NAME

In 2007, the Intergovernmental Panel on Climate Change (IPCC), a scientific panel organized by the United Nations, published its 4th assessment report. The panel states "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." The panel concludes "Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." The following text is drawn from from the *Summary for Policymakers* of the IPCC's 3rd and 4th assessment reports.

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values. Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas. The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use, with land use change providing another significant but smaller contribution. Annual fossil carbon dioxide emissions increased to about 7.2 GtC (billion metric tons per year of carbon equivalent) in 2000–2005. Carbon dioxide emissions associated with land-use change are estimated to be 1.6 GtC per year over the 1990s, although these estimates have a large uncertainty. Figure 1 shows total anthropogenic carbon emissions since 1900.

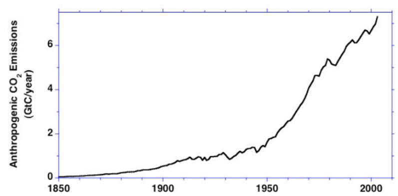


Figure 1: Anthropogenic CO_2 Emissions from 1900 to 2005 (billion tons of Carbon per year (GtC/yr).

Natural processes gradually remove CO_2 from the atmosphere (for example, as it is used by plant life and dissolves in the ocean). Currently, the net removal of atmospheric CO_2 by natural processes is about half of the anthropogenic CO_2 emissions. As a result, the global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 [384 ppm in 2007] (Figure 2). The atmospheric concentration of carbon dioxide today exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores.

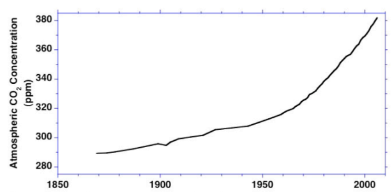


Figure 2: Concentration of CO_2 in the atmosphere, parts per million.

Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing, which is used to compare how a range of human and natural factors drive warming or cooling influences on global climate. Positive forcing tends to warm the surface while negative forcing tends to cool it. Figure 3 shows that global average surface temperatures have risen over the past century.

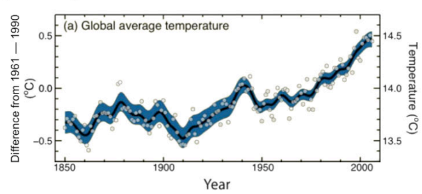


Figure 3: Average global temperature, °C.

Check here if you have done or learned about this task before

Figure 13. IPCC AR4 Excerpt. The IPCC AR4 Excerpt was administered to Subgroup C during the pre-test, instead of a SF Challenge. The text presented basic definitions of *atmospheric* CO_2 *accumulation*, CO_2 *emissions* and *global mean temperature*, as well as graphs showing their historical trajectories.

All three subgroups were then asked to answer a question in the context of climate change (Figure 4). Participants were shown historic *atmospheric* CO_2 *concentrations* and a future scenario in which the concentration of carbon dioxide stabilizes by the year 2100 at about 420 parts per million (ppm). Participants were asked to sketch a trajectory for anthropogenic CO_2 *emissions* that would stabilize *atmospheric* CO_2 *concentrations*.

After the pre-test was completed, we introduced participants to the simulation environment. In the first experience, they explored the relationship between *CO_2 emissions* and *net removal* required to stabilize *atmospheric CO_2 concentration* by 2100. The second experiment illustrates the drivers of *CO_2 emissions* and enables participants to explore the effect of delaying climate change mitigation action. For more details on the simulations, please refer to section II.2 where we describe the learning tool.

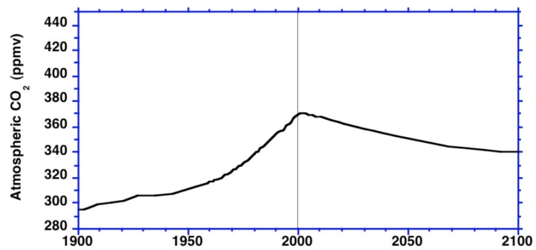
After participants interacted with the simulation, we conducted post-test Stock and Flow (SF) Challenges as presented in Table 2. The first post-test SF Challenge is a variation of the *Stabilization Scenario SF Challenge* conducted in the pre-test. The second and third post-test SF Challenges were presented in the pre-test to subgroups A and B, respectively. Every participant was asked to respond all three post-test SF Challenges, and were given sufficient time to do so (about ten minutes).

FORM-A

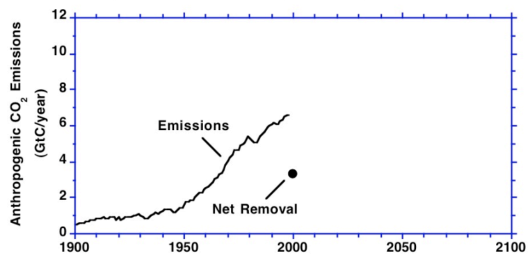
FIRST NAME	LAST NAME

340ppm Scenario Challenge

Consider a scenario in which the concentration of CO_2 in the atmosphere gradually falls to 340 ppm, about 8% lower than the level in 2000, then stabilizes by the year 2100, as shown here:



1. The graph below shows anthropogenic CO_2 emissions from 1900-2000, and current net removal of CO2 from the atmosphere by natural processes. Sketch:
   a. Your estimate of likely future net CO_2 removal, given the scenario above.
   b. Your estimate of likely future anthropogenic CO_2 emissions, given the scenario above.



2. Assuming CO_2 concentrations follow the scenario above, the average global temperature would most likely:
   - Continue to rise through the year 2100.
   - Continue to rise, then stabilize by the year 2100.
   - Rise for a few more years, then peak, gradually fall and stabilize above current levels.
   - Stabilize now at current levels.
   - Rise for a few more years, then peak, gradually fall and stabilize below current levels.
   - Rise for a few more years, then peak and continue to fall through the year 2100.
   - Immediately drop, then stabilize by the year 2100 below current levels.

3. Why? Explain your choices (briefly):

Check here if you have done or learned about this task before

Figure 14. 340-ppm SF Challenge. The 340-ppm SF Challenge was administered to all participants in the post-test. Participants were asked to estimate future trajectories of *CO_2 emissions* and *net removal*, given a scenario for *atmospheric CO_2 concentration* that gradually falls to 340 ppm and stabilizes by the year 2100.

The first post-test SF Challenge is similar to the *Stabilization Scenario SF Challenge* conducted as a pre-test. Participants were shown a graph of historical *anthropogenic CO_2 emissions* and current *net removal* of carbon dioxide by natural processes (Figure 14). They were asked to estimate future trajectories for both variables under a scenario of *atmospheric CO_2 concentration* falling gradually to 340 ppm and stabilizing by the year 2100. This task was previously used by Sterman and Booth Sweeney (2007) with a group of students from the MIT Sloan School of Management. In the results section, we compare our results with the outcomes from that study.

The second and third post-test SF Challenges are the *Department Store* and *Ice Cover* SF Challenges. These problems were administered to Subgroups A and B during the pre-test. Both problems have a similar level of difficulty compared to the *Stabilization Scenario SF Challenge* but they are situated in different contexts. The *Department Store SF Challenge* is not at all associated with climate change. The *Ice Cover SF Challenge* is related to climate change and was briefly introduced during the workshop. A total of 51 participants completed all pre-test and post-test SF Challenges.

After participants completed all post-test SF Challenges, they completed the initial opinion survey once more. The final survey omitted the demographics section of the previous questionnaire but repeated all questions concerning climate change. Questions were administered in random order to lessen the order/response bias. A total of 54 participants completed the final survey with an average response time of 3 minutes and 45 seconds.

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III. Results

In this section we describe the subject group that participated in the experiment. Then, we present participants' attitude towards climate change action by analyzing the survey results. We compare initial and final survey responses to establish that there was a positive change in attitude towards climate change action after participating in the experiment. Finally, we present the results of the SF Challenges used to test participants' ability to solve problems based on the principle of accumulation. We compare these results with prior experiences to assess participants' learning. Our results show that participants did better on SF Challenges in the context of climate change than in SF Challenges situated on different contexts.

III.1 Demographics

We conducted the experiment with a group of 57 well-educated adults with above average technical training and an average of 5 years of work experience. A total of 54 participants (95%) completed the initial and final surveys and 51 (90%) responded all SF Challenges. Almost all participants (96%) were enrolled as MBA students at MIT Sloan School of Management and voluntarily chose to participate in a three-hour workshop about climate change, for which they received credit towards their degree. The median age was 28 years (σ = 3.7, range 22-48) and 81% were male. Half of the group (52%) had strong mathematics training with a degree in science, technology, engineering, or mathematics (STEM); 35% had a degree in the social sciences, primarily economics; 9% had a degree in business/finance and 4% in humanities. Half of the group (48%) spoke English as their first language and 65% were citizens of OECD[6] countries. Almost all participants (98%) had at least one year of work experience with a median of 5 years (σ = 2.9, range 0-20).

[6] Convention on the Organization for Economic Co-operation and Development (OECD)

Since most were first year students, few had taken a course in system dynamics.[7] Table 3 summarizes the sample group demographics.

Table 3. Sample group demographics.

	Subgroup	N	%
Gender	*Male*	*44*	*81*
	Female	*10*	*19*
Program	*MBA*	*52*	*96*
	Other	*2*	*4*
Native Language	*English*	*26*	*48*
	Other	*28*	*52*
Country	*U.S.*	*23*	*43*
	Other OECD	*12*	*22*
	Rest of the world	*19*	*35*
Highest Prior Degree	*BA / BS*	*37*	*69*
	Master / PhD	*17*	*31*
Field of Study	*STEM*	*28*	*52*
	Social Sciences	*19*	*35*
	Business/Finance	*5*	*9*
	Humanities	*2*	*4*
Age	*Median: 28 years*		
	Std. Dev: 3.7 years		
	Range: (22,48)		
Years of Work Experience	*Median: 5 years*		
	Std. Dev: 2.9 years		
	Range: (0, 20)		

III.2 Change in attitude towards climate change action

We conducted an initial survey to assess participants' attitude towards climate change action prior to their participation in our workshop. The first question in the survey addressed participant's view on climate change. We asked: *"Which comes closest to your view on climate change?"* and offered three statements with language expressing different degrees of urgency. Figure 15 compares workshop participants' responses to those of a global survey conducted in 2006 by the Chicago Council on Global Affairs and

[7] As part of their first year experience, MBA students at the MIT Sloan School of Management play the Beer Distribution Game. The Beer Distribution Game is a simulation game created by the MIT System Dynamics Group in the early 1960's to demonstrate a number of key principles of supply chain management. Almost all participants had played the Beer Distribution Game (94%), although very few (9%) had taken a formal class on system dynamics prior to their involvement in our experiment.

WorldPublicOpinion.org[8]. Results show that participants of our workshop were more concerned about climate change prior to the experiment than the general population. These results are not surprising because participants self-selected to attend a workshop about climate change.

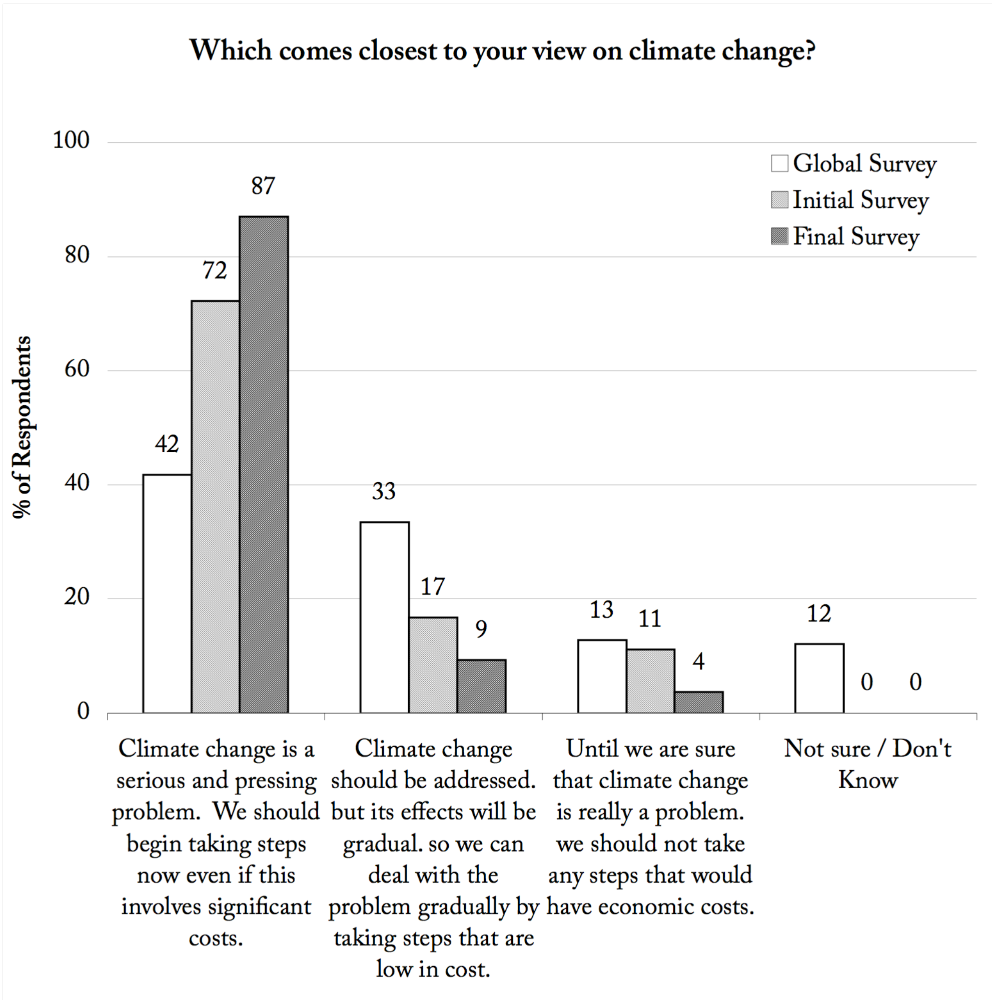

Figure 15. Views on Climate Change. Participants in our study were more supportive of climate change action compared to the respondents of a global survey (Chicago Council, 2007). Participants express even more support for climate change action after going through the workshop. People saying that immediate Climate Change Action is necessary increased from 72% to 87%, a marginally significant change according to the Pearson's Chi-square test ($\chi^2(1) = 3.653, p = 0.056$).

[8] The Chicago Council on Global Affairs and WorldPublicOpinion.org conducted a global survey in 13 countries during 2006. Although the poll found a widespread agreement on climate change being a pressing problem, the majority was divided over whether climate change is urgent enough to take immediate action regardless of cost or whether moderate efforts will suffice (Chicago Council, 2007).

Participants appear even more supportive of climate change action after going through the workshop. The group had shown concern and a sense of urgency towards climate change in the first survey. However, responses to the final survey showed a marginally significant increase in people saying that immediate climate change action was necessary even if it involved significant costs (Pearson's Chi-Square Test[9]: $\chi^2(1) = 3.653, p = 0.056$).

Workshop participants were then asked: *"Greenhouse gas emissions from richer countries have had the most impact on the Earth's climate, however, emissions are growing more quickly in poorer countries with large populations. As a result, there is a debate about when these poorer countries should join richer countries in taking significant action to reduce human impacts on climate. Do you think these poorer countries should…?"*. Figure 16 compares workshop participants' responses to those of a global survey conducted in 1998 by GlobeScan[10]. In their initial responses, more than half of participants in our study supported the idea that poorer countries should "*Be required to take significant action only after richer countries lead with action*". In contrast, the global survey reported most answers supporting the notion that poorer countries should "*Be required to take significant action immediately along with richer countries"*. Responses in the final survey shifted towards the latter response significantly ($\chi^2(1) = 7.567, p = 0.006$), which corresponds to a greater sense of urgency at the end of the workshop.

[9] The Pearson's Chi-Square statistic can be used to test the hypothesis of no association of paired observations on two variables of categorical data. A chi-square probability of .05 or less is commonly interpreted as justification for rejecting the null hypothesis that the row variable is unrelated (i.e. only randomly related) to the column variable (Garson, 2008). Statistical results reported in this study were calculated using SPSS™ predictive analytics software package v16.0.

[10] GlobeScan conducted a global public opinion survey on climate change in 1998. The survey included responses from 30 countries around the world (Leiserowitz, 2007).

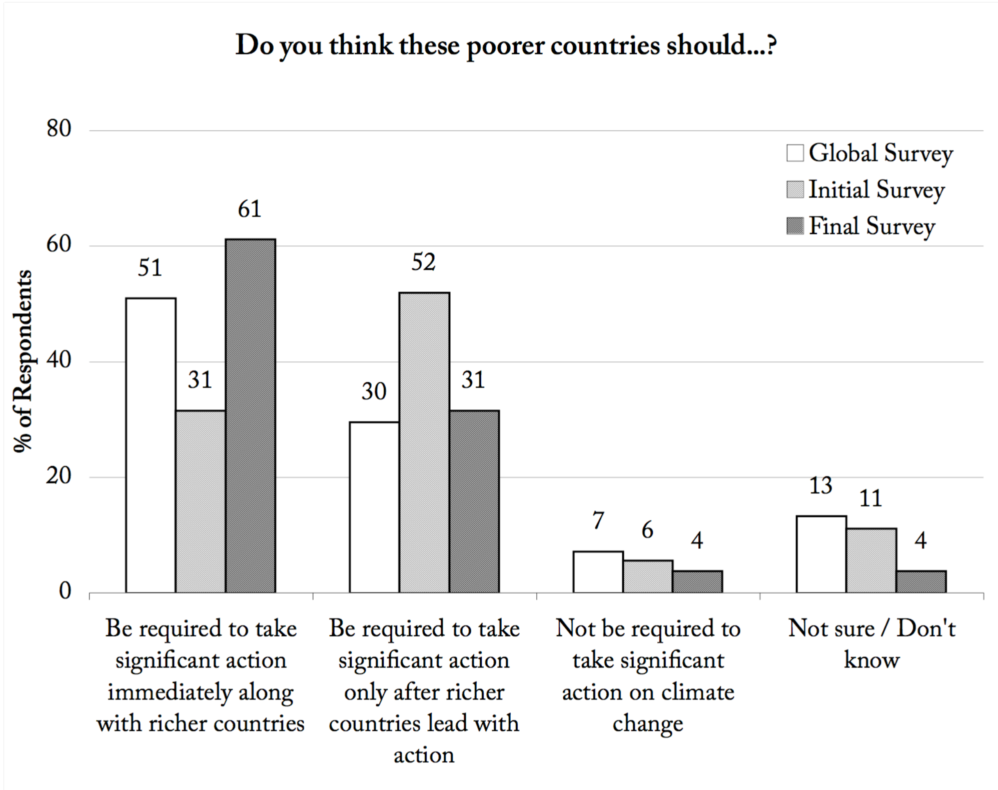

Figure 16. Poorer countries taking significant action along with richer countries. Participants in our study started with a lower sense of urgency compared to the respondents of a global survey (Leiserowitz, 2007). At the end of the workshop, participants had shifted their support for more immediate action in poorer countries regardless of richer countries' initiative. A change from 31% to 61% of support for immediate action is statistically significant according to the Pearson's Chi-square test ($\chi^2(1) = 7.567, p = 0.006$).

We also assessed participant's support for specific mitigation policies. We asked them to express their support for a list of potential mitigation policies that included government regulation, carbon taxes, subsidies for renewable energy, and a market-based carbon trading system, amongst others. Figure 17 compares workshop participants' responses to those of a study in the United States conducted in 2003[11]. Support for most mitigation policies was over 80% and, in almost all cases, was stronger than what the U.S. study reported. Tax-based policies received the least support amongst all policy proposals. At the end of the workshop, participants had increased their support for even the initially less-desirable tax-

[11] Leiserowitz (2006) reports an in-depth study conducted in the United States in 2003. The study was designed to measure public support for specific policy proposals to mitigate climate change. Results are from Americans that have heard about global warming (92%) with n = 568 to 575.

based policies. In the case of the gasoline tax, support shifted from 44% to 67%, a large and statistically significant difference ($\chi^2(1) = 5.400$, $p = 0.02$).

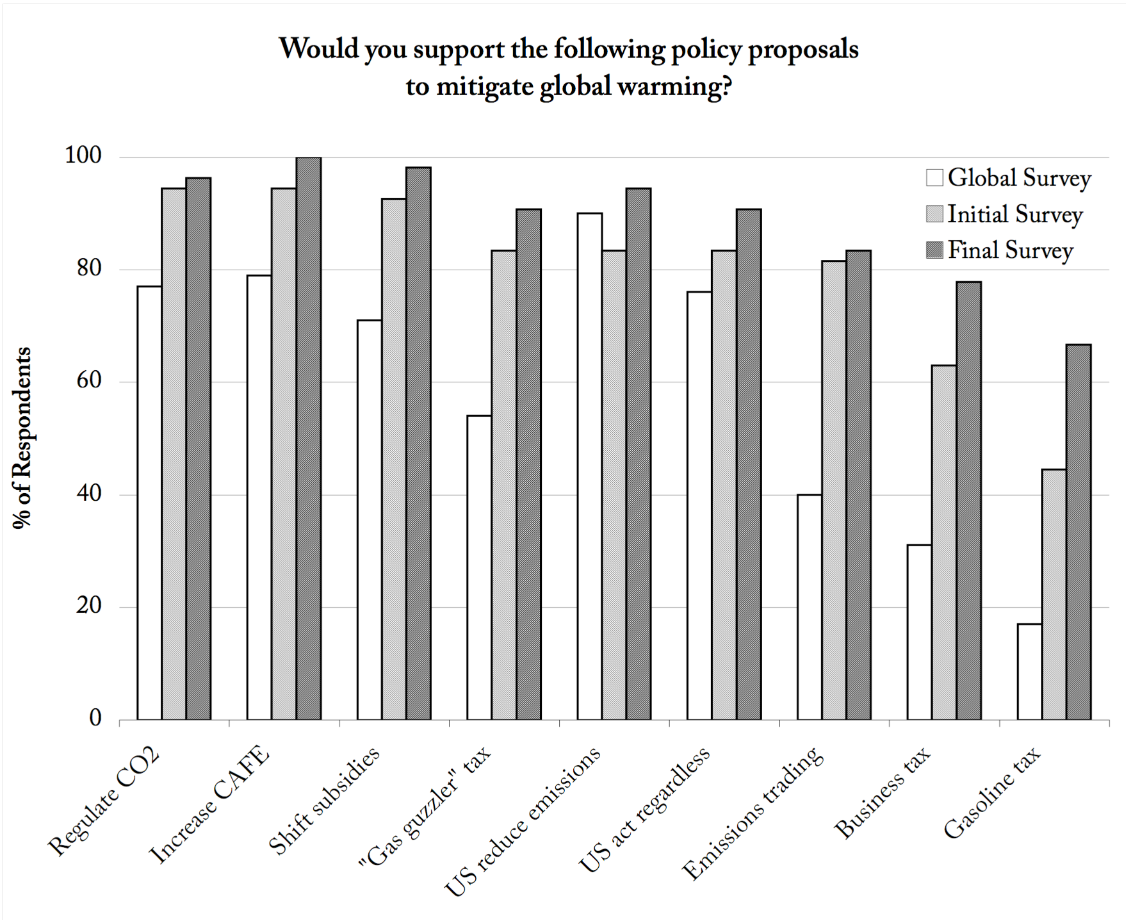

Figure 17. Support for mitigation policies. Participants in our study expressed more support towards almost all mitigation policies compared to the respondents of an U.S. study (Leiserowitz, 2006). At the end of the workshop, participants had increased their support for even the initially less-desirable tax-based policies. In the case of the gasoline tax, support shifted from 44% to 67%, which is a statistically significant change according to the Pearson's Chi-square test ($\chi^2(1) = 5.400$, $p = 0.02$).

Even when participants express concern about climate change and appear supportive of mitigation policies, climate change may not be considered to be a high priority compared to other national issues. We asked participants in our study: *"Here are some national issues now being discussed in Washington. Which do you think should be the top priority for Congress and the President?"*. Responses from the initial and final surveys are presented in Figure 18 along with results from a U.S. study adapted from Leiserowitz (2007). Workshop participants gave global warming a high priority amongst other pressing national issues and a much higher priority compared to the U.S. study. Global warming was initially ranked third, only after the Economy and Education. In the final survey, Global warming was the top priority.

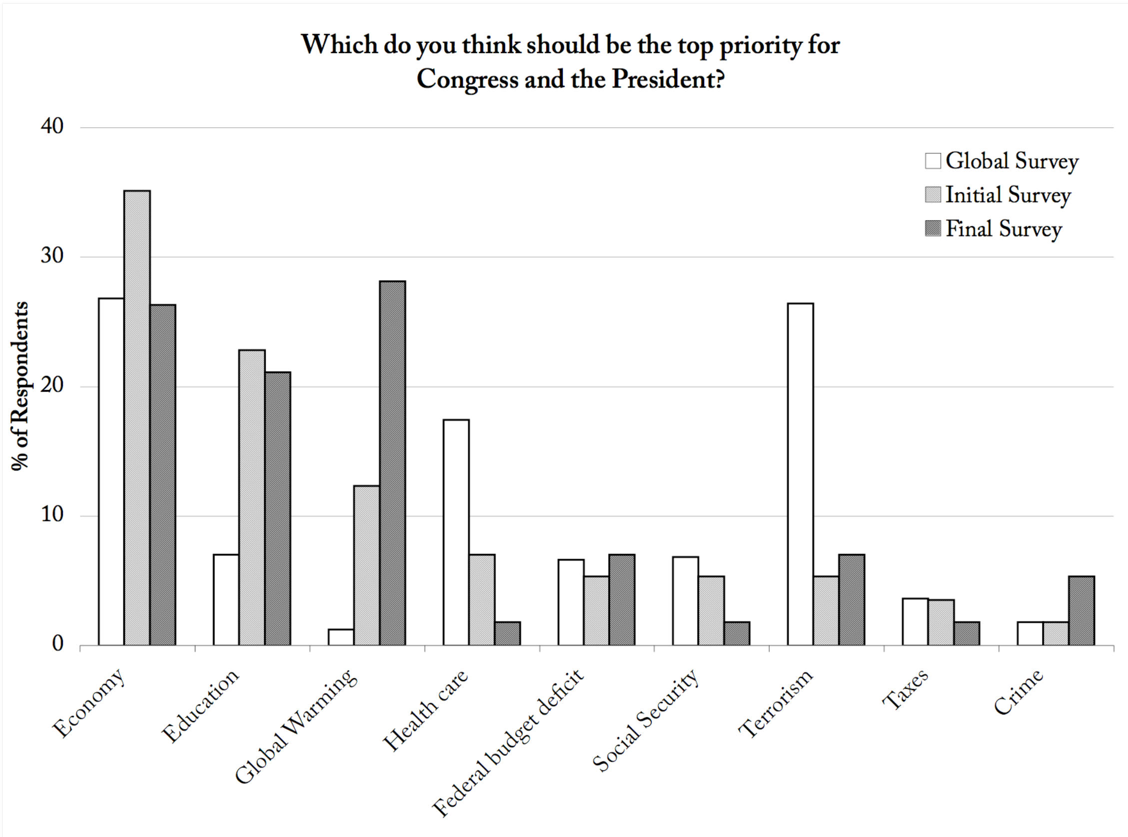

Figure 18. Top priority amongst national issues. Participants in our study expressed similar priorities amongst national issues compared to the respondents of a 2003 U.S. study (Leiserowitz, 2007). The Economy, Education and Global Warming where the three top priorities amongst pressing national issues. Global warming moved from the third position to the top priority after the workshop, although the positional change was not statistically significant according to the Pearson's Chi-Square test ($\chi^2(2) = 4.173$, $p = 0.124$). Global warming received more attention in our study, an expected result since participants were involved in a climate change workshop. The 2003 U.S. study was conducted closer to the terrorist attack of 9/11, hence the prominence of Terrorism in those results.

Table 4. Survey results. The following results represent a sample of the complete survey conducted in our experiment (Initial and Final surveys). We compare participants' responses with that of global surveys (Chicago Council, 2007; Leiserowitz, 2006; Leiserowitz, 2007). For the complete survey results, please refer to the appendix.

Q1. Which comes closest to your view on climate change?	**Survey**		
	Global	**Initial**	**Final**
Until we are sure that climate change is really a problem, we should not take any steps that would have economic costs.	*42*	*72*	*87*
Climate change should be addressed, but its effects will be gradual, so we can deal with the problem gradually by taking steps that are low in cost.	*33*	*17*	*9*
Climate change is a serious and pressing problem. We should begin taking steps now even if this involves significant costs.	*13*	*11*	*4*
Not Sure / Don't Know	*12*	*0*	*0*
	100	***100***	***100***

Q2. Greenhouse gas emissions from richer countries have had the most impact on the Earth's climate, however, emissions are growing more quickly in poorer countries with large populations. As a result, there is a debate about when these poorer countries should join richer countries in taking significant action to reduce human impacts on climate. Do you think these poorer countries should...?

	Survey		
	Global	**Initial**	**Final**
Be required to take significant action immediately along with richer countries	*51*	*31*	*61*
Be required to take significant action only after richer countries lead with action	*30*	*52*	*31*
Not be required to take significant action on climate change	*7*	*6*	*4*
Not sure / Don't know	*13*	*11*	*4*
	101	***100***	***100***

Q3. Would you support the following policy proposals to mitigate global warming?	**Survey**		
	Global	**Initial**	**Final**
Tax based on a vehicle's fuel economy ("Gas guzzler" tax)	*77*	*94*	*96*
A tax on energy used by businesses	*79*	*94*	*100*
Government regulation of carbon dioxide as a pollutant	*71*	*93*	*98*
Increase in vehicle fuel economy standards (CAFE)	*54*	*83*	*91*
Market-based emissions trading system	*90*	*83*	*94*
Mandatory reductions in US greenhouse gas emissions	*76*	*83*	*91*
Shift in subsidies from the fossil fuel industry to the renewable energy industry	*40*	*81*	*83*
Mandatory reductions in US greenhouse gas emissions regardless of what other developed or less-developed countries do	*31*	*63*	*78*
Gasoline tax (60 cents/gallon)	*17*	*44*	*67*

Q4. Here are some national issues now being discussed in Washington. Which do you think should be the top priority for Congress and the President?	**Survey**		
	Global	**Initial**	**Final**
Crime	*27*	*35*	*26*
Economy	*7*	*23*	*21*
Education	*1*	*12*	*28*
Federal budget deficit	*17*	*7*	*2*
Global Warming	*7*	*5*	*7*
Health care	*7*	*5*	*2*
Medicare	*26*	*5*	*7*
Social Security	*4*	*4*	*2*
Taxes	*2*	*2*	*5*
	98	***98***	***100***

III.3 Learning about accumulation

We conducted pre-test and post-test SF Challenges to assess participants' ability to solve basic dynamic problems involving the principle of accumulation. Results were consistent with prior studies in the sense that participants had difficulties answering SF Challenges correctly. In the context of climate change, results show that people learned about the principle of accumulation. Performance did not improve in SF Challenges that were similar in complexity but differ in context.

We asked participants to solve Stock and Flow (SF) Challenges, before and after they interacted with the simulation, to test if they had learned about the dynamics of climate change. All participants where asked to answer two SF Challenges in the context of climate change. Before the simulation experience, they were given the *Stabilization Scenario SF Challenge* (Figure 4). After they interacted with our simulation, we used the *340-ppm Scenario SF Challenge* (Figure 14) to determine how they applied the concepts embedded in the simulation. Additionally, we gave participants other SF Challenges not related to climate change according to the treatments presented in Table 2. Participants where given one of three different SF Challenges before the *Stabilization Scenario SF Challenge* and two SF Challenges after they completed the *340-ppm Scenario SF Challenge*. The objective of the additional SF Challenges was to test if participants were able to transfer stock and flow concepts to different contexts.

Overall performance in the *Stabilization Scenario SF Challenge* was poor, with 62% of participants violating mass balance requirements. From the erroneous responses, 87% believe that *atmospheric CO_2 concentration* can be stabilized by 2100 while *CO_2 emissions* released to the atmosphere exceed *net removal*. Further, deviations from the equilibrium condition (*CO_2 emissions* = 5 GtC/year by 2100) are large, averaging 6.2 GtC/year. Table 5 summarizes the responses to the *Stabilization Scenario SF Challenge*.

Table 5. Performance in the *Stabilization Scenario SF Challenge*. Overall performance in the *Stabilization Scenario SF Challenge* was poor, with the majority of participants believing that *atmospheric CO_2 concentration* can be stabilized by 2100 while *CO_2 emissions* released to the atmosphere exceed *net removal*. A response is consistent with the equilibrium condition if *CO_2 emissions* minus *net removal* (E_{net}) in 2100 equal 5 GtC/year (eq). A response is otherwise classified as incorrect and the mean deviation from equilibrium (E_{net} – eq) is reported in an additional column.

	Correct		Incorrect					
	E_{net} = eq		E_{net} < eq			E_{net} > eq		
SF Challenge	**N**	**%**	**N**	**%**	**dif.**	**N**	**%**	**dif.**
Stabilization	*19*	*38*	*4*	*8*	*2.5*	*27*	*54*	*6.2*

Misunderstanding of the stock and flow structure, leading to errors in *CO_2 emissions*' projection, is consistent with prior experiences. Table 6 compares the experiment results with those of the Sterman and Booth Sweeney (2007) study. Participants in both experiments performed poorly in the *Stabilization Scenario SF Challenge*, with over 60% of participants answering incorrectly.

Table 6. Performance in the *Stabilization Scenario SF Challenge* across studies. Participants involved in our study did not perform significantly better on this SF Challenge than participants in the Sterman and Booth-Sweeney (2007) study ($\chi^2(1) = 1.407, p = 0.236$)

	Stabilization Scenario SF Challenge			
	Correct		Incorrect	
Simulation	**N**	**%**	**N**	**%**
Yes	*19*	*38*	*31*	*62*
No	*9*	*26*	*26*	*74*
	28	*33*	*57*	*67*

Different treatments did not affect performance on the *Stabilization Scenario SF Challenge* conducted during the pre-test. Table 7 shows participants' responses to the *Stabilization Scenario SF Challenge* according to different treatments. The hypothesis that responses to the *Stabilization Scenario SF Challenge* are unrelated to treatment cannot be rejected ($\chi^2(2) = 0.540, p = 0.763$).

Table 7. Performance in the *Stabilization Scenario SF Challenge* across treatments. Treatments did not affect performance in this SF Challenge (*$\chi^2(2) = 0.540$, $p = 0.763$*)

	Stabilization Scenario SF Challenge			
	Correct		Incorrect	
Treatment	N	%	N	%
A	*7*	*39*	*11*	*61*
B	*7*	*44*	*9*	*56*
C	*5*	*31*	*11*	*69*
	19	***38***	***31***	***62***

We compared the responses to the *Stabilization Scenario SF Challenge* (pre-test) and the *340-ppm Scenario SF Challenge* (post-test) to determine if the experience with the simulation was conducive to learning about the dynamics of climate change. Performance in the post-test did not improve compared to the pre-test. The number of participants answering correctly in the post-test did not change significantly (*$\chi^2(1) = 0.240$ $p = 0.624$*). This could be explained by the fact that the *340-ppm Scenario SF Challenge* is less intuitive than the *Stabilization Scenario SF Challenge* or simply because participants did not learn to deal with the underlying stock and flow structure of the problem. Table 8 compares the results of the pre-test and post-test.

Table 8. Performance in the pre-test *Stabilization Scenario SF Challenge* compared to the post-test *340-ppm Scenario SF Challenge*. Participants did not improve significantly in the post-test after being exposed to the simulation (*$\chi^2(1) = 0.240$ $p = 0.624$*)

	Performance			
	Correct		Incorrect	
SF Challenge	N	%	N	%
Stabilization	*19*	*38*	*31*	*62*
340-ppm	*17*	*33*	*34*	*67*
	36	***36***	***65***	***64***

A limitation in the design of our study is that we were unable to isolate the influence of the simulation on the post-test SF Challenges. We did not have a control group without exposure to the simulation but we have similar studies to compare our results. In Sterman and Booth-Sweeney (2007), the researchers ran the same SF Challenge with a group of participants with similar demographics[12]. Participants in that study were not exposed to

[12] Sterman and Booth-Sweeney (2007) conducted the same *340-ppm Scenario SF Challenge* with a group of graduate students at MIT Sloan School of Management. Subjects were primarily MBA students (63%) and graduate students from other programs (35%); average age was 30 (σ = 5, range 20-56); 75% were trained in

any learning tool before answering the SF Challenge. Table 9 compares the results of participants in both studies.

Table 9. Performance in the *340-ppm Scenario SF Challenge* across studies. Participants involved in our study performed significantly better on this SF Challenge than participants in the Sterman and Booth-Sweeney (2007) study (Fisher's Exact Test, *p = 0.006*)

	Stabilization Scenario SF Challenge			
	Correct		Incorrect	
Simulation	N	%	N	%
Yes	*17*	*33*	*34*	*67*
No	*2*	*6*	*30*	*94*
	19	***23***	***64***	***77***

Participants in our study performed significantly better on the *340-ppm Scenario SF Challenge* compared to participants in the Sterman and Booth-Sweeney (2007) study that were not exposed to our simulation (*Fisher's Exact Test*[13], $p = 0.006$). The improved results can be considered indicative of the simulation being a positive influence in participants' performance on the post-test SF-Challenge.

III.4 Importance of understanding stocks and flows

Stocks and flows are present in many aspects of everyday life: from our bank account to water accumulating in a bathtub. We can solve some of these problems by converging to the solution through trial and error (correcting the amount of water in the tub by closing the faucet once it reaches the desired level). When cause and effect are distant in time and space the ability to use outcome feedback to control the level of the stock is undermined. Trial and error becomes impossible, and our ability to learn diminishes. In such cases, people are forced to rely on mental simulation of how changes in the flows affect the stock.

Given the relevance of the principle of accumulation, we decided to test if it improved performance in the SF Challenges. We identified the group of participants in our study

STEM and most others were trained in economics and other social sciences; and 30% held prior advanced degrees.

[13] Fisher's Exact Test is statistical test used to determine the significance of association between variables in small samples of categorical data (cell count < 5). In the results reported in this study, the p-value corresponds to the two-tail probability of Fisher's Exact Test for a two-by-two contingency table (Garson, 2008). Statistical results were calculated using SPSS™ predictive analytics software package v16.0.

that responded correctly to the *Stabilization Scenario SF Challenge* in the pre-test and analyzed their performance across post-tests. Participants that answered correctly the pre-test SF Challenge performed better than the rest in the post-test *340-ppm Scenario SF Challenge* ($\chi^2(1) = 4.741$, $p = 0.029$) as shown in Table 10.

Table 10. Performance of participants that responded correctly to the pre-test *Stabilization Scenario SF Challenge* compared to their responses to the post-test *340-ppm Scenario SF Challenge.* Participants that answered correctly the pre-test SF Challenge, answered correctly the post-test *340-ppm Scenario SF Challenge.* Vice-versa, participants that answered incorrectly the pre-test SF Challenge were likely to fail in the post-test *340-ppm Scenario SF Challenge* ($\chi^2(1) = 4.741$, p = 0.029).

Stabilization Scenario SF Challenge	340-ppm Scenario SF Challenge: Correct N	Correct %	Incorrect N	Incorrect %
Correct	*10*	*53*	*9*	*47*
Incorrect	*7*	*23*	*24*	*77*
	17	***34***	***33***	***66***

Participants who answered correctly the pre-test SF Challenge did not show a significant improvement in performance in the other post-tests (SF Challenges situated in different contexts). Table 11 shows the results that yield $\chi^2(1) = 2.771$ ($p = 0.096$) for the *Department Store SF Challenge* and $\chi^2(1) = 1.556$ ($p = 0.212$) for the *Ice Cover SF Challenge*. Understanding the principle of accumulation is an important skill but it may be difficult to translate between different contexts. The next section explores this problem in more detail.

Table 11. Performance of participants that responded correctly to the pre-test *Stabilization Scenario SF Challenge* compared to their responses to post-tests situated in different contexts. The hypothesis that performance in the pre-test SF Challenge is not associated to the performance in the Department Store and Ice Cover SF Challenges cannot be rejected: $\chi^2(1) = 2.771$ ($p = 0.096$) and $\chi^2(1) = 1.556$ ($p = 0.212$) respectively.

Stabilization Scenario SF Challenge	Department Store Scenario SF Challenge: Correct N	Correct %	Incorrect N	Incorrect %
Correct	*7*	*37*	*12*	*63*
Incorrect	*5*	*26*	*26*	*84*
	12	***24***	***38***	***76***

Stabilization Scenario SF Challenge	Ice Cover Scenario SF Challenge: Correct N	Correct %	Incorrect N	Incorrect %
Correct	*10*	*53*	*9*	*47*
Incorrect	*10*	*34*	*19*	*66*
	20	***42***	***28***	***58***

III.5 Translating stock and flow concepts to different contexts

People have difficulty applying the principles of accumulation even in settings where the presence of accumulation is obvious (Cronin et al., 2008). This situation could be aggravated if participants are not able to detect the stock and flow structure of SF Challenges situated in a different context than climate change.

To test if translating stock and flow concepts to different contexts is hard, we compared participants' performance in the pre-test *Stabilization Scenario SF Challenge* to the post-tests *Department Store* and *Ice Cover SF Challenges* (Table 12). The hypothesis of no association between the different SF Challenges and performance cannot be rejected ($\chi^2(2) = 3.532$, $p = 0.171$).

Table 12. Performance in the pre-test *Stabilization Scenario SF Challenge* compared to the post-tests *Department Store* and *Ice Cover SF Challenges.* Performance is not associated to the SF Challenges ($\chi^2(2) = 3.532$, $p = 0.171$).

	Performance			
	Correct		Incorrect	
SF Challenge	N	%	N	%
Stabilization	*19*	*38*	*31*	*62*
Department Store	*13*	*25*	*38*	*75*
Ice Cover	*21*	*43*	*28*	*57*
	53	*35*	*97*	*65*

Cronin et al. (2008) ran the *Department Store SF Challenge* with a group of participants with similar demographics[14]. Participants in the Cronin et al. (2008) study were not exposed to any learning tool before answering the SF Challenge. Table 13 compares the results of participants across studies and shows that performance was low in both cases. Even if stock and flow concepts are important to solve climate change SF Challenges, translating this knowledge to a different context appears to be difficult.

[14] (Cronin et al., 2008) conducted the same Department Store SF Challenge with a group of MBA students at MIT Sloan School of Management. Participants were demographically similar to the ones involved in our study: average age was 28 (range 20-44); 71% were male; 54% were trained in STEM and 37% were trained in economics or other social sciences; and 29% held prior advanced degrees.

Table 13. Performance in the *Department Store SF Challenge* across studies. Participants involved in our study did not perform significantly better on this SF Challenge than participants in the Cronin et al. (2008) study ($\chi^2(1) = 0.272, p = 0.602$).

	Department Store SF Challenge			
	Correct		Incorrect	
Simulation	N	%	N	%
Yes	*13*	*25*	*38*	*75*
No	*7*	*21*	*27*	*79*
	20	***24***	***65***	***76***

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IV. Discussion

We presented an interactive simulation designed to improve people's understanding of climate change dynamics and influence their attitudes towards mitigation action. The simulation was built on several key concepts of system dynamics applied to climate change: the concept of dynamic complexity, stocks and flows and the effects of time delays in a system's behavior. Additionally, we took into account common misconceptions about climate change, lessons from other simulation environments and typical responses to problems of dynamic complexity.

We conducted an experiment designed to test the effectiveness of our interactive simulation on two levels: (1) learning about the dynamics of climate change, and (2) shifting people's attitude towards climate change action.

To test the impact of our interactive simulation on learning about the dynamics of climate change, we presented participants with Stock and Flow (SF) Challenges. Results showed that participants had difficulty answering SF Challenges correctly, which is consistent with prior studies (Cronin et al., 2008; Sterman and Booth Sweeney, 2007). If participants had been given more individual time with the simulation, perhaps they would have improved their understanding of the underlying stock and flow structure. However, it is possible that the pattern matching behavior will prevail since it has proven to be a robust phenomenon (Cronin et al., 2008). Moreover, the experimental setting is far more informative and focused on climate change that what most people would come across in their everyday experience. Under those circumstances, the cognitive burden of understanding the problem coupled with small incentives to take individual action may result in insufficient time or effort to explore the problem. As a result, people may resort to a "wait and see" approach under the assumption than corrective action can be postponed.

A design limitation in our workshop made it impossible to isolate the influence of the simulation on participants' performance in the SF Challenges. We did not have a control group without exposure to the simulation. As an alternative, we compared our results to previous studies involving subjects of similar demographics. Caution must be applied in interpreting the comparisons: although the SF Challenges were exactly the same, and the participants were drawn from the same or similar populations of graduate students, it is possible that unmeasured differences in subject pool or context account for the differences.

When compared to previous studies, our interactive simulation appears to have a positive effect on people learning about the principle of accumulation. Workshop participants showed similar performance on the pre-test *Stabilization Scenario SF Challenge* and better performance on the post-test *340 ppm Scenario SF Challenge*. This can be interpreted as people learning about the principle of accumulation after their interaction with the simulation. However, performance did not improve in SF Challenges that were similar in complexity but differed in context. When compared to results from another study, workshop participants showed similar performance on the *Department Store SF Challenge* before and after the simulation. Transferring stock and flows concepts across contexts proved to be hard. However, this particular workshop was about climate change and we did not cover system dynamics concepts, such as stocks and flows, in detail.

To detect shifts in attitude towards climate change action, we administered a survey at the beginning and at the end of the workshop. By comparing the results of both surveys, we detected an improvement in attitude towards climate change action. However, the role of the simulation in shifting participants' attitudes is confounded with the workshop experience itself. Participants may feel inclined to support climate change due to social desirability thus introducing a response bias in their answers (Garson, 2008). Further, the group self-selected to participate in a climate change workshop. Their attitude prior to coming to the workshop was more inclined towards climate change action than responses in global surveys. Nevertheless, a significant shift in attitude was detected with the survey conducted at the end of the experiment.

A change in attitude towards climate change action is an important step towards support for mitigation policies. The effort to reduce greenhouse gas (GHG) emissions to stabilize atmospheric GHG concentration is not only a technical challenge: it requires a change in behavior of billions of human beings. If people are unable to understand the rationale behind mitigation policies, they will be unwilling to generate the political support to implement them (Morgan et al., 2002). In consequence, the lack of intuitive understanding of the dynamic structure of climate change can have important consequences on building support for mitigation policies in the public opinion (Sterman and Booth Sweeney, 2007).

Communicating the physical science is difficult because climate related processes are complex and the language used to describe them is highly technical (e.g. *radiative forcing*, *gigatons of carbon*, etc). People can easily feel overwhelmed by the amount of information and rely on simple heuristics, such as pattern matching, to assess the problem. To help communicate the essence of the challenge imposed by climate change we used a simple analogy to depict the basic dynamics governing global warming and created a learning environment around it. We hope that participants take the idea of water flowing into a bathtub and use it to inform their exploration of complex issues such as climate change. In our experiment, we worked with people that are likely to be in leadership roles in the future and could effectively support and promote climate change mitigation action.

A three-hour workshop may be a short and mild treatment to successfully change someone's mental models. By making our learning tool publicly available on the Internet, we expect that more people will have a chance to challenge their mental models and learn about climate change dynamics, stocks and flows and their implications towards mitigation action. Public exposure will also allow us improve the interface of our interactive simulation and enhance its performance as a learning tool.

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VI. Appendix

VI.1 Survey Results

Sample Group Demographics

Statistics	Age	Years of work experience
Mean	28.69	5.19
Median	28.00	5.00
Mode	28	5
Std. Deviation	3.736	2.89
Minimum	22	0
Maximum	48	20

Age	Frequency	Percent
22	1	2%
25	3	6%
26	9	17%
27	7	13%
28	12	22%
29	8	15%
30	5	9%
31	4	7%
33	2	4%
36	1	2%
37	1	2%
48	1	2%
Total	**54**	**100%**

Gender	Frequency	Percent
F	10	19%
M	44	81%
Total	**54**	**100%**

English is my first language	Frequency	Percent
No	28	52%
Yes	26	48%
Total	**54**	**100%**

Country of origin	Frequency	Percent
Argentina	1	2%
Brazil	1	2%
Bulgaria	1	2%
Colombia	1	2%
Czech Republic	1	2%
France	2	4%
India	6	11%
Israel	2	4%
Italy	1	2%
Japan	1	2%
Lebanon	1	2%
Mexico	3	6%
China	1	2%
Russia	1	2%
Saudi Arabia	1	2%
South Korea	1	2%
Spain	1	2%
Taiwan	1	2%
Turkey	1	2%
UK	1	2%
USA	23	43%
Venezuela	2	4%
Total	**54**	**100%**
U.S.	23	43%
OTHER OECD	12	22%
NON-OECD	19	35%

School and Program	Frequency	Percent
1st Year MBA	44	81%
2nd Year MBA	8	15%
Other	2	4%
Total	**54**	**100%**

Highest previous degree	Frequency	Percent
BA	15	28%
BS	22	41%
Masters	14	26%
PhD	3	6%
Total	**54**	**100%**
College degree (BA, BS)	37	69%
Graduate Degree (Master, PhD)	17	31%

Main field of study	Frequency	Percent
Business/Finance	5	9%
Economics	14	26%
Engineering	24	44%
Humanities	1	2%
Law	1	2%
Mathematics	1	2%
Other social science	4	7%
Political Science	1	2%
Science	3	6%
Total	**54**	**100%**
STEM	28	52%
Social Sciences (Economics, Political Science, Law, Other)	19	35%
Business/Finance	5	9%
Humanities (Law)	2	4%

Years of work experience	Frequency	Percent
0	1	2%
1	1	2%
2	3	6%
3	8	15%
4	10	19%
5	11	20%
6	8	15%
7	7	13%
8	1	2%
9	1	2%
10	2	4%
20	1	2%
Total	**54**	**100%**

Beer Distribution Game	Frequency	Percent
No	3	6%
Yes	51	94%
Total	**54**	**100%**

Class on System Dynamics	Frequency	Percent
No	49	91%
Yes	5	9%
Total	**54**	**100%**

Climate Change Questions

Which comes closest to your view on climate change?	Initial		Final	
	N	%	N	%
Climate change is a serious and pressing problem. We should begin taking steps now even if this involves significant costs.	39	72%	47	87%
Climate change should be addressed. but its effects will be gradual, so we can deal with the problem gradually by taking steps that are low in cost.	9	17%	5	9%
Until we are sure that climate change is really a problem. we should not take any steps that would have economic costs.	6	11%	2	4%
Total	**54**	**100%**	**54**	**100%**

Do you believe that the earth is getting warmer mostly because of human activity such as burning fossil fuels, OR mostly because of natural patterns in the earth's environment?	Initial		Final	
	N	%	N	%
Mostly because of human activity such as burning fossil fuels	44	81%	48	89%
Mostly because of natural patterns in the earth's environment	10	19%	6	11%
Total	**54**	**100%**	**54**	**100%**

Would you support the following policy proposals to mitigate global warming?	Initial		Final	
	N (yes)	%	N (yes)	%
Government regulation of carbon dioxide as a pollutant	51	94%	52	96%
Increase in vehicle fuel economy standards (CAFE)	51	94%	54	100%
Shift in subsidies to the renewable energy industry	50	93%	53	98%
Tax based on a vehicle's fuel economy ("Gas guzzler" tax)	45	83%	49	91%
Mandatory reductions in US greenhouse gas emissions	45	83%	51	94%
Mandatory reductions in US greenhouse gas emissions regardless	45	83%	49	91%
Market-based emissions trading system	44	81%	45	83%
A tax on energy used by businesses	34	63%	42	78%
Gasoline tax (60 cents/gallon)	24	44%	36	67%

Have you done any of the following things because you are concerned about global warming?	Initial		Final	
	N (yes)	%	N (yes)	%
Used energy-efficiency as a selection criterion when buying	40	74%	37	69%
Talked to family, friends, or colleagues	38	70%	39	72%
Used alternative forms of transportation	37	69%	36	67%
Planted a tree	20	37%	20	37%
Joined, donated money to, or volunteered with an organization	18	33%	16	30%
Installed insulation or weatherized your home or apartment	11	20%	10	19%
Made your views on global warming clear to politicians	10	19%	9	17%
Purchased energy from an alternative source	8	15%	8	15%
Bought a carbon offset to mitigate your own greenhouse gas emissions	3	6%	6	11%

How often do you discuss global warming with your family and friends	Initial		Final	
	N	%	N	%
1. Rarely discuss	8	15%	8	15%
2	6	11%	7	13%
3	20	37%	19	35%
4	15	28%	14	26%
5. Often Discuss	5	9%	6	11%
Total	**54**	**100%**	**54**	**100%**

Would be willing to pay 10% more for household electricity to have it supplied by solar energy, wind power, or some other renewable source?	Initial		Final	
	N	%	N	%
1. Strongly disagree	9	17%	4	7%
2	5	9%	4	7%
3	8	15%	4	7%
4	9	17%	10	19%
5. Strongly agree	23	43%	32	59%
Total	**54**	**100%**	**54**	**100%**

Greenhouse gas emissions from richer countries have had the most impact on the Earth's climate, however, emissions are growing more quickly in poorer countries with large populations. As a result, there is a debate about when these poorer countries should join richer countries in taking significant action to reduce human impacts on climate. Do you think these poorer countries should...?	**Initial**		**Final**	
	N	**%**	**N**	**%**
Be required to take significant action immediately along with richer countries	17	31%	33	61%
Be required to take significant action only after richer countries lead with actior	28	52%	17	31%
Not be required to take significant action on climate change	3	6%	2	4%
Not sure / Don't know	6	11%	2	4%
Total	**54**	**100%**	**54**	**100%**

If the developed countries are willing to provide substantial aid, do you think the less-developed countries should make a commitment to limit their greenhouse gas emissions?	**Initial**		**Final**	
	N	**%**	**N**	**%**
No. should not make a commitment	5	9%	2	4%
Not sure / Don't know	11	20%	1	2%
Yes. should make a commitment	38	70%	51	94%
Total	**54**	**100%**	**54**	**100%**

The Kyoto Protocol commits signatories to reducing their greenhouse gas emissions slightly below the 1990 levels by 2012, when it expires. However, large emitters, including China, India and the United States, are not parties to the agreement. In December 2007, representatives of the world's governments met in Bali to negotiate a new international agreement to follow the expiration of Kyoto. They were not able to reach an agreement other than to continue negotiations. Which one of the following statements best reflects your view of this?	**Initial**		**Final**	
	N	**%**	**N**	**%**
There are good reasons for the negotiations taking this long	8	15%	3	6%
This isn't good enough; national governments should take the problem and the negotiations more seriously and quickly reach a binding agreement	31	57%	31	57%
The situation is not acceptable; the United Nations should be given the power to impose legally-binding actions on national governments to protect the Earth's climate	10	19%	18	33%
No agreement is necessary; let nations choose their policy individually	2	4%	1	2%
No agreement is necessary; global warming is not a serious problem	0	0%	0	0%
Not sure/don't know	3	6%	1	2%
Total	**54**	**100%**	**54**	**100%**

Here are some national issues now being discussed in Washington.
Which do you think should be the top priority for Congress and the President?
Please rank them from most important (1) to least important (10)

Initial Survey

Priority	Crime	Economy	Education	Federal budget deficit	Global Warming	Health care	Medicare	Social Security	Taxes	Terrorism
1	1	20	13	3	7	4	1	3	2	3
2	1	9	5	7	12	10	4	5	0	2
3	4	4	13	11	6	8	4	2	1	4
4	4	5	4	5	3	10	6	7	5	7
5	7	4	3	8	7	3	4	6	10	7
6	7	1	4	3	3	6	8	5	3	4
7	3	1	2	7	4	3	9	9	7	4
8	5	1	3	4	4	4	10	7	8	9
9	6	2	2	3	4	2	7	8	9	7
10	16	7	5	3	4	4	1	2	9	7
Total	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**

Mean	7.09	3.69	4.13	4.93	4.63	4.63	6.09	5.89	6.98	6.28
Median	7.50	2.00	3.00	5.00	4.00	4.00	6.50	6.00	7.00	6.50
Mode	**10**	**1**	**1**[a]	**3**	**2**	**2**[a]	**8**	**7**	**5**	**8**
Perc. 25	5.00	1.00	1.75	3.00	2.00	2.00	4.00	4.00	5.00	4.00
Perc. 50	7.50	2.00	3.00	5.00	4.00	4.00	6.50	6.00	7.00	6.50
Perc. 75	10.00	5.00	6.00	7.00	7.00	6.25	8.00	8.00	9.00	9.00

a. Multiple modes exist. The smallest value is shown

Final Survey

Priority	Crime	Economy	Education	Federal budget deficit	Global Warming	Health care	Medicare	Social Security	Taxes	Terrorism
1	3	15	12	4	16	1	0	1	1	4
2	0	10	9	4	12	13	6	5	1	2
3	1	5	9	6	5	13	7	4	3	4
4	4	7	8	4	1	7	4	5	4	8
5	5	3	4	10	5	1	4	7	7	6
6	9	2	0	5	3	5	7	4	5	7
7	4	1	1	8	2	5	6	9	6	3
8	6	1	4	6	4	1	9	13	11	3
9	5	3	2	3	1	3	10	5	10	8
10	17	7	5	4	5	5	1	1	6	9
Total	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**

Mean	7.26	4.02	4.00	5.50	3.83	4.61	6.02	6.00	6.91	6.13
Median	8.00	3.00	3.00	5.00	2.00	3.50	6.00	7.00	7.50	6.00
Mode	**10**	**1**	**1**	**5**	**1**	**2**[a]	**9**	**8**	**8**	**10**
Perc. 25	5.75	1.00	2.00	3.00	1.00	2.00	3.75	4.00	5.00	4.00
Perc. 50	8.00	3.00	3.00	5.00	2.00	3.50	6.00	7.00	7.50	6.00
Perc. 75	10.00	6.00	5.00	7.25	6.00	7.00	8.00	8.00	9.00	9.00

a. Multiple modes exist. The smallest value is shown

VI.2 SF Challenge Results

Aggregate results

Treatment	Answer	PRETEST		POSTEST		
		Department Store	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
A	CORRECT	4	7	4	4	7
	INCORRECT	14	11	14	14	11
	N/A	0	0	0	0	0
	TOTAL	18	18	18	18	18

Treatment	Answer	PRETEST		POSTEST		
		Ice Cover	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
B	CORRECT	4	7	5	4	6
	INCORRECT	12	9	11	12	9
	N/A	0	0	0	0	1
	TOTAL	16	16	16	16	16

Treatment	Answer	PRETEST		POSTEST		
		IPCC Reading	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
C	CORRECT	0	5	8	5	8
	INCORRECT	0	11	9	12	8
	N/A	17	1	0	0	1
	TOTAL	17	17	17	17	17

Treatment	Answer	PRETEST		POSTEST		
			Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
ALL	CORRECT	N/A	19	17	13	21
	INCORRECT	N/A	31	34	38	28
	N/A	N/A	1	0	0	2
	TOTAL		51	51	51	51

Treatment	Answer	PRETEST		POSTEST		
		Department Store	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
A	CORRECT	22%	39%	22%	22%	39%
	INCORRECT	78%	61%	78%	78%	61%
	BASE	18	18	18	18	18

Treatment	Answer	PRETEST		POSTEST		
		Ice Cover	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
B	CORRECT	25%	44%	31%	25%	40%
	INCORRECT	75%	56%	69%	75%	60%
	BASE	16	16	16	16	15

Treatment	Answer	PRETEST		POSTEST		
		IPCC Reading	Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
C	CORRECT	0%	31%	47%	29%	50%
	INCORRECT	0%	69%	53%	71%	50%
	BASE	17	16	17	17	16

Treatment	Answer	PRETEST		POSTEST		
			Stabilization Scenario	340ppm Scenario	Department Store	Ice Cover
ALL	CORRECT	N/A	38%	33%	25%	43%
	INCORRECT	N/A	62%	67%	75%	57%
	BASE		50	51	51	49

Detailed Responses

		PRETEST										
		Form A					Form B				Form C	ALL
		Department Store					Ice Cover				IPCC Reading	Stabilization Scenario
Treatment	**Correct**	**A.Shape**	**A.1st**	**A.2nd**	**A.Eq.**	**A.Correl.**	**B.Shape**	**B.1st**	**B.2nd**	**B.Eq.**	**C**	**D.Shape**
A	**TRUE**	4	12	5	16	10						7
	FALSE	14	6	13	2	8						11
	N/A	0	0	0	0	0						0
	TOTAL	**18**	**18**	**18**	**18**	**18**						**18**
B	**TRUE**						4	11	5	11		7
	FALSE						12	5	11	5		9
	N/A						0	0	0	0		0
	TOTAL						**16**	**16**	**16**	**16**		**16**
C	**TRUE**										17	5
	FALSE										0	11
	N/A										0	1
	TOTAL										**17**	**17**

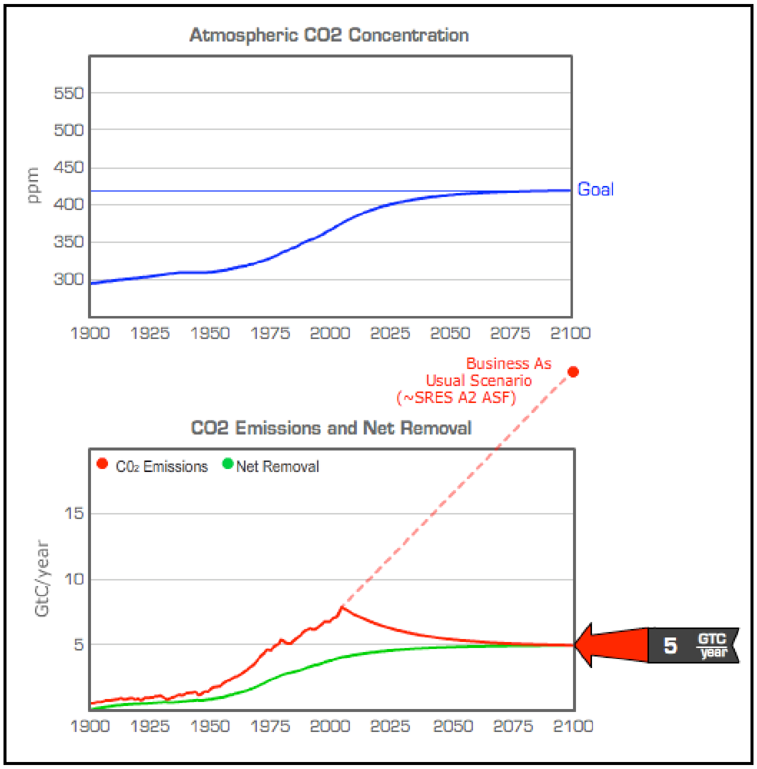
		POSTEST												
		ALL			ALL					ALL				
		340ppm Scenario			Department Store					Ice Cover				
Treatment	**Correct**	**E.Shape**	**E.(E-R)**	**E.1st**	**F.Shape**	**F.1st**	**F.2nd**	**F.Eq.**	**F.Correl.**	**G.Shape**	**G.1st**	**G.2nd**	**G.Eq.**
A	**TRUE**	4	8	4	4	14	8	10	5	7	13	11	13
	FALSE	14	10	14	14	4	10	8	13	11	5	7	5
	N/A	0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**
B	**TRUE**	5	10	5	4	13	6	7	2	6	10	8	10
	FALSE	11	6	11	12	3	10	9	14	9	5	7	5
	N/A	0	0	0	0	0	0	0	0	1	1	1	1
	TOTAL	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**
C	**TRUE**	8	13	9	5	14	7	11	6	8	14	10	11
	FALSE	9	4	8	12	3	10	6	11	8	2	6	5
	N/A	0	0	0	0	0	0	0	0	1	1	1	1
	TOTAL	**17**	**17**	**17**	**17**	**17**	**17**	**17**	**17**	**17**	**17**	**17**	**17**

		POSTEST		
		ALL		
		340ppm Scenario		
Treatment		**E.R max**	**E.R max yr**	**E.R@2100**
A	**Mean**	5.0	2056	4.5
	Median	4.8	2050	4.5
	Mode	4.5	2100	4.5
B	**Mean**	5.0	2056	4.5
	Median	4.8	2050	4.5
	Mode	4.5	2100	4.5
C	**Mean**	5.3	2049	4.2
	Median	5.0	2040	4.5
	Mode	4.5	2020	4.5
ALL	**Mean**	5.1	2049	4.3
	Median	4.5	2040	4.5
	Mode	4.5	2100	4.5

	POSTEST			
	ALL			
	340ppm Scenario			
E.Shape	**A**	**B**	**C**	**ALL**
CONSTANT	3	2	0	**5**
LINEAR (+)	1	2	4	**7**
LINEAR (-)	3	1	1	**5**
STABILIZATION (+)	8	7	3	**18**
STABILIZATION (-)	0	0	1	**1**
BELL (+)	1	1	2	**4**
BELL (-)	0	1	0	**1**
S-SHAPE (+)	2	2	6	**10**
S-SHAPE (-)	0	0	0	**0**
	18	**16**	**17**	**51**

Stabilization Scenario SF Challenge - Answer Key

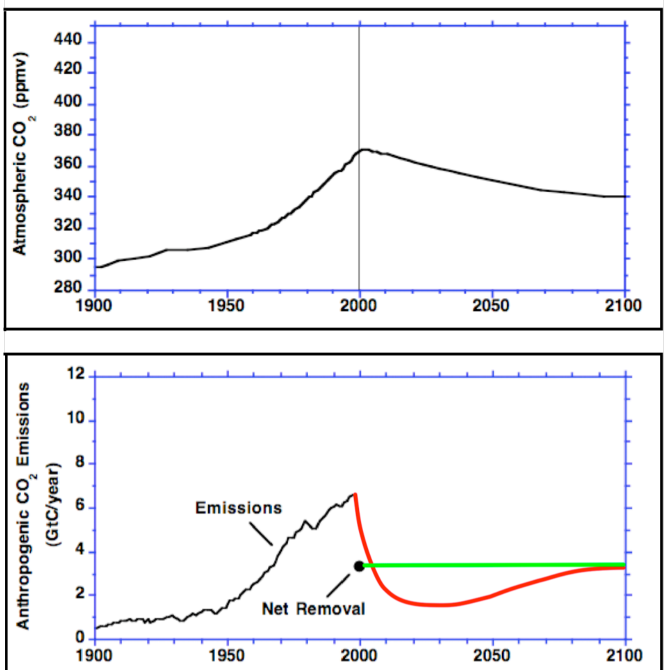
Stabilization Scenario Challenge (Online)



ANSWER KEY
Emissions (2100) 5 GTC / year

340-ppm Scenario SF Challenge - Answer Key

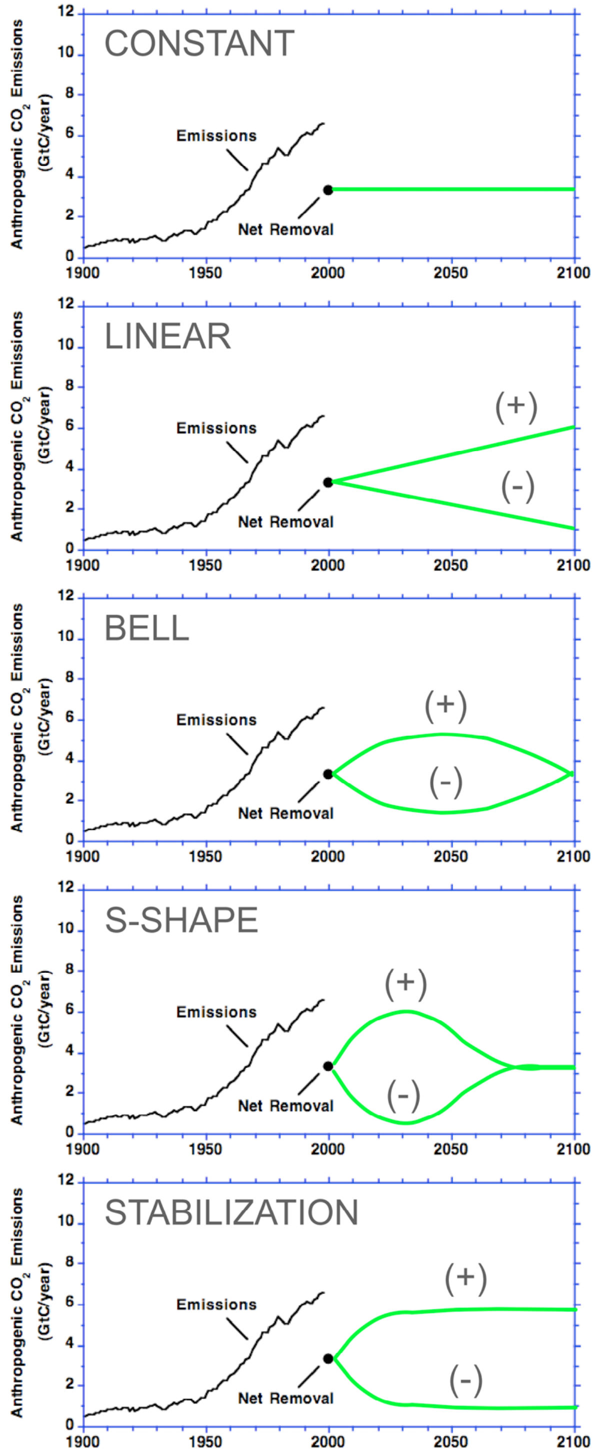
340ppm Scenario Chalenge



ANSWER KEY

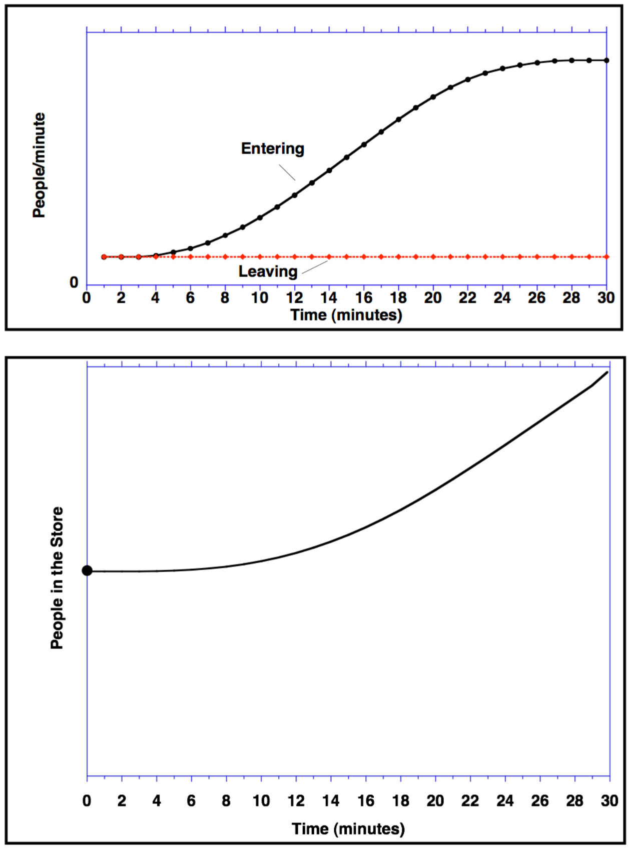
Shape correct?
True if (E.R)(2100) = 0 & 1st = true
Emissions - Removals (2100)
Difference between E and R should be zero in order to stabilize
1st derivative?
E should fall inmediately below R in order to follow the stabilization path and gradually increase to match R by 2100
Removals (max, year)
R's peak is used to characterize the path they chose
Removals (2100)
R's final value is used to characterize the path they chose
Removals Shape
Categorization of shape of the R's path they chose

Possible Net Removals Shapes in the 340-ppm Scenario SF Challenge



Department Store SF Challenge - Answer Key

Department Store Challenge

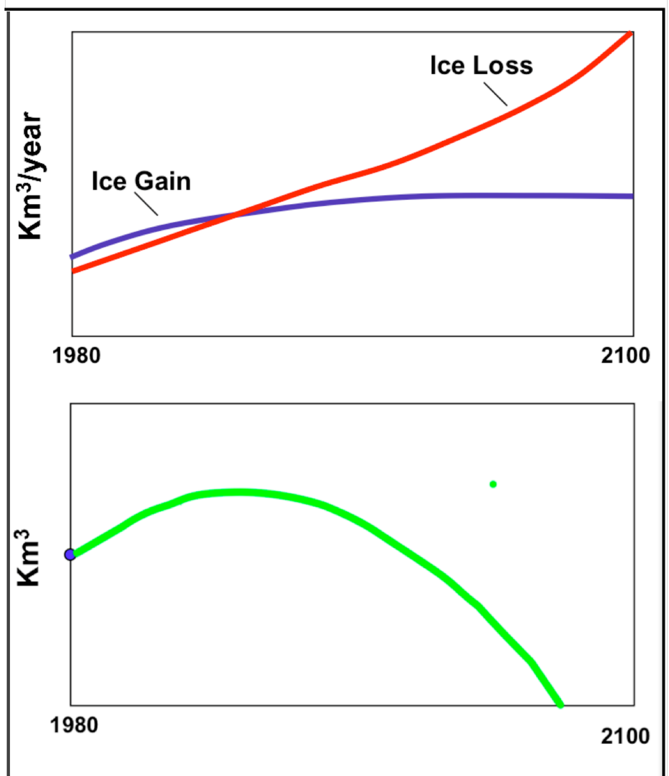


ANSWER KEY

Shape correct?
True if 1st & 2nd & Equilibrium are true
1st derivative?
True if positive in all the range, flat at the beginning, increasing in the center and constant slope at the end
2nd derivative?
Positive. True if curve is concave.
Equilibrium?
Equilibrium under in the first 3 periods
Inflow correlation?
True if the accumulation pattern resembles an "s-shape"

Ice Cover SF Challenge - Answer Key

Ice Cover Challenge

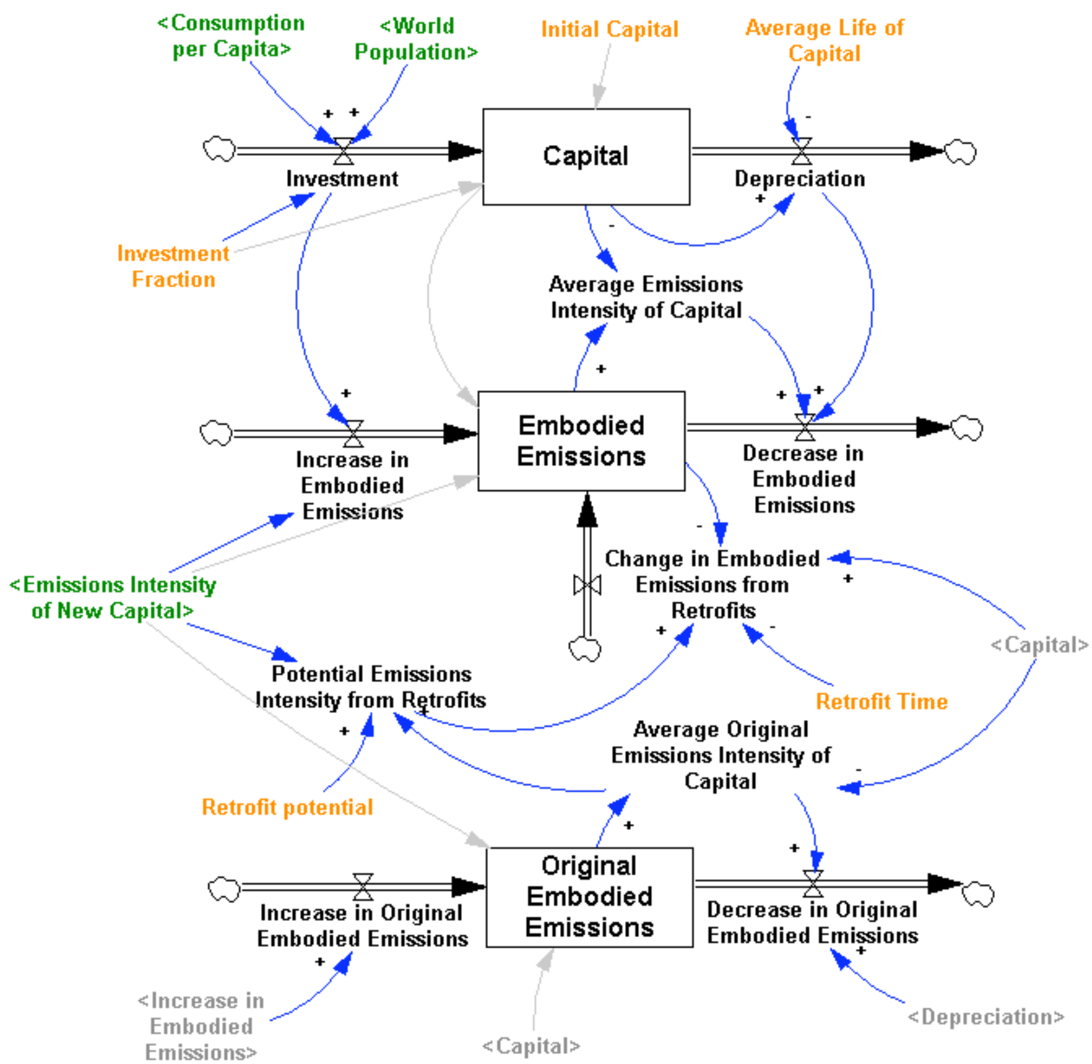


ANSWER KEY

Shape correct?
True if 1st & 2nd & Equilibrium are true
1st derivative?
Total mass should increase initially, peak at the crossing point of inflow and outflow and decrease at an increasing rate from then on
2nd Derivative?
Negative. True if curve is convex
Equilibrium?
Total mass should reach its maximum at the crossing point of inflow and outflow

VI.3 Climate-economy model version 3.0

Growth and Technology



EQUATIONS

Average Emissions Intensity of Capital[sector] = Embodied Emissions[sector]/Capital[sector]
Units: (GTC/Year)/B$

Average Original Emissions Intensity of Capital[sector] = Original Embodied Emissions[sector]/Capital[sector]
Units: (GTC/Year)/B$

Capital[sector] = INTEG (Investment[sector]-Depreciation[sector], 1+Investment Fraction[sector]*Initial Capital[sector])
Units: B$

Change in Embodied Emissions from Retrofits[sector] = (Potential Emissions Intensity from Retrofits[sector]*Capital[sector]-Embodied Emissions [sector])/Retrofit Time[sector]
Units: GTC/(Year*Year)

Consumption per Capita = IF THEN ELSE(Time <= Simulation Start Year, Historic GWP/World Population, Projected Consumption per Capita)
Units: B$/(Year*Billion Person)

Decrease in Embodied Emissions[sector] = Average Emissions Intensity of Capital[sector]*Depreciation[sector]
Units: (GTC/Year)/Year

Decrease in Original Embodied Emissions[sector] = Average Original Emissions Intensity of Capital[sector]*Depreciation[sector]
Units: (GTC/Year)/Year

Depreciation[sector] = Capital[sector]/Average Life of Capital[sector]
Units: B$/Year

Embodied Emissions[sector] = INTEG (Change in Embodied Emissions from Retrofits[sector]+Increase in Embodied Emissions[sector]-Decrease in Embodied Emissions [sector], Capital[sector]*Emissions Intensity of New Capital[sector])
Units: GTC/Year

Emissions Intensity of New Capital[sector] = IF THEN ELSE(Time <= Simulation Start Year, Historic CO2 Emissions/Historic GWP, Projected Emissions Intensity of New Capital [sector])
Units: (GTC/Year)/B$

Increase in Embodied Emissions[sector] = Investment[sector]*Emissions Intensity of New Capital[sector]
Units: (GTC/Year)/Year

Increase in Original Embodied Emissions[sector] = Increase in Embodied Emissions[sector]
Units: (GTC/Year)/Year

Investment[sector] = Investment Fraction[sector]*Consumption per Capita*World Population
Units: B$/Year

Original Embodied Emissions[sector] = INTEG (Increase in Original Embodied Emissions[sector]-Decrease in Original Embodied Emissions [sector], Capital[sector]*Emissions Intensity of New Capital[sector])
Units: GTC/Year

Potential Emissions Intensity from Retrofits[sector] = Retrofit potential[sector]*Emissions Intensity of New Capital[sector]+(1-Retrofit potential [sector])*Average Original Emissions Intensity of Capital [sector]
Units: GTC/(Year*B$)

World Population = IF THEN ELSE (Time<=2000, Historic World Population Lookup(Time), World Population Scenario Medium Lookup (Time))
Units: Billion Person

PARAMETERS

Average Life of Capital[sector] = 15
Units: Year

Initial Capital[sector] = 1000
Units: B$

Investment Fraction[sector] = 0.1
Units: Dmnl

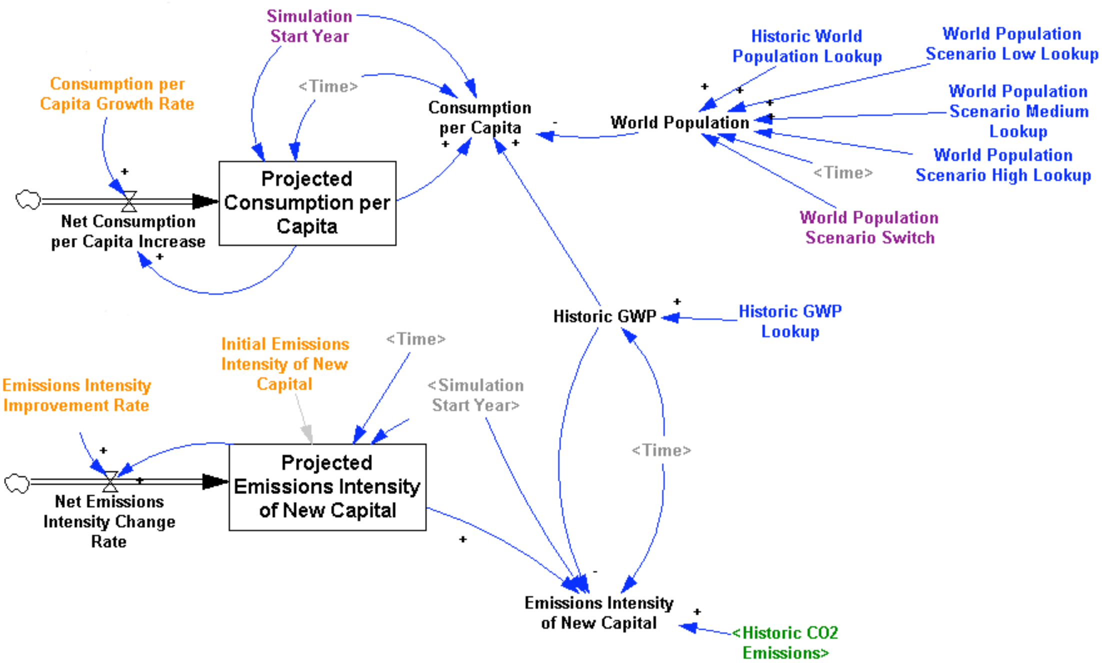
Retrofit Time[sector] = 2
Units: Year

Retrofit potential[sector] = 0.8
Units: Dmnl

NOTES:

Subscripts were included to divide the economy subsystem into multiple economic sectors (e.g. infraestructure, transportation). This version of the model aggregates the entire economy into only one sector.

Growth and Technology Scenarios



EQUATIONS

Consumption per Capita = IF THEN ELSE (Time <= Simulation Start Year, Historic GWP/World Population, Projected Consumption per Capita)
Units: B$/(Year*Billion Person)

Net Consumption per Capita Increase = Projected Consumption per Capita*Consumption per Capita Growth Rate
Units: B$/(Billion Person*Year)/Year

Net Emissions Intensity Change Rate[sector] = -(Emissions Intensity Improvement Rate[sector])*Projected Emissions Intensity of New Capital [sector]
Units: ((GTC/Year)/B$)/Year

Projected Consumption per Capita = INTEG (IF THEN ELSE (Time < Simulation Start Year, 0, Net Consumption per Capita Increase), 6757.3)
Units: B$/Billion Person/Year

Projected Emissions Intensity of New Capital[sector] = INTEG (IF THEN ELSE(Time < Simulation Start Year, 0 , Net Emissions Intensity Change Rate[sector]), Initial Emissions Intensity of New Capital[sector])
Units: (GTC/Year)/B$

Historic CO2 Emissions= Historic CO2 Emissions Lookup(Time)
Units: GTC/Year

Historic GWP = Historic GWP Lookup(Time)
Units: B$

World Population = IF THEN ELSE(Time<=2000, Historic World Population Lookup(Time), IF THEN ELSE(World Population Scenario Switch\ =1, World Population Scenario Low Lookup(Time), IF THEN ELSE(World Population Scenario Switch\ =2, World Population Scenario Medium Lookup(Time), World Population Scenario High Lookup\ (Time))))
Units: Billion Person

PARAMETERS

Consumption per Capita Growth Rate = 0.02
Units: 1/Year

Emissions Intensity Improvement Rate[sector] = 0.0165
Units: 1/Year

Initial Emissions Intensity of New Capital[sector] = 0.000162568
Units: GTC/(Year*B$)

Historic GWP Lookup([(1900,0)-(2000,60000)],(1900,1102.96),(1920,1733.67),(1925,2102.88),(1930,2253.81),(1940,3001.36),(1950,4081.81),(1955,5430.44),(1960,6855.25),(1965,9126.98),(1970,12137.9),(1975,15149.4),(1980,18818.5),(1985,22481.1),(1990,27539.6),(1995,33644.3),(2000, 41016.7))
Units: B$ (Billions of 1990 International Dollars)
Source: Estimating World GDP, One Million B.C. - Present J. Bradford DeLong Department of Economics, U.C. Berkeley

Historic World Population Lookup([(1900,0)-(2000,8)],(1900,1.66),(1910,1.75),(1920,1.86),(1930,2.07),(1940,2.3),(1950 ,2.52),(1955,2.76),(1960,3.02),(1965,3.34),(1970,3.69),(1975,4.07),(1980,4.44),(1985,4.83),(1990,5.26),(1995,5.67),(2000,6.07))
Units: Billion Person
Sources:
[1900-1950] The World at Six Billion, United Nations, NY 1999
[1955-2100] World Population to 2300, United Nations, NY 2004

Simulation Start Year = 2000
Units: Year

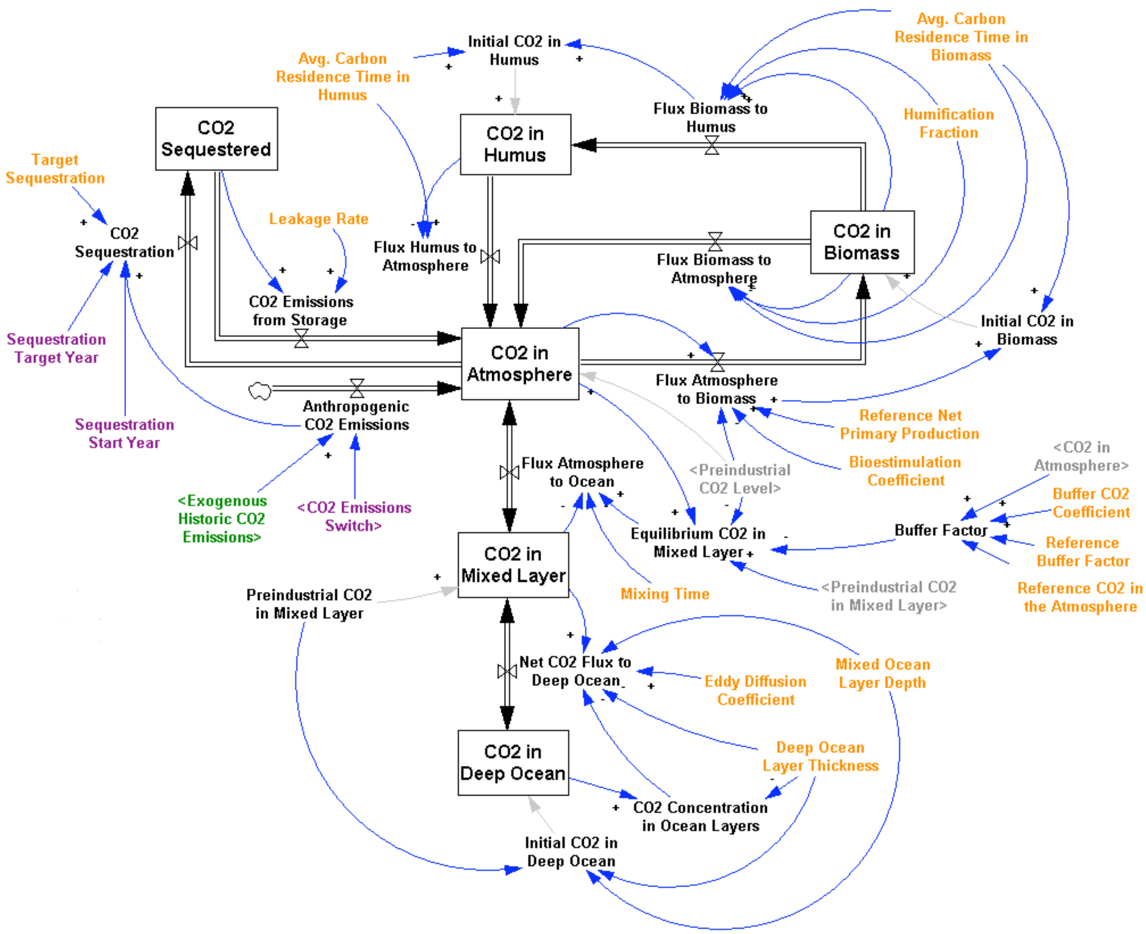
World Population Scenario Switch = 2
Units: Dmnl [1,3,1]
Comment: Options for World Population Scenarios are 1="low", 2="medium" or 3="high"

World Population Scenario Low Lookup([(2000,4)-(2100,8)],(2000,6.07),(2005,6.4),(2010,6.69),(2015,6.94),(2020,7.16), (2025,7.33),(2030,7.45),(2035,7.52),(2040,7.53),(2045,7.49),(2050,7.41),(2055,7.3),(2060,7.16),(2065,6.99),(2070,6.81), (2075,6.6),(2080,6.38),(2085,6.15),(2090,5.93), (2095 ,5.71),(2100,5.49))
Units: Billion Person

World Population Scenario Medium Lookup([(2000,6)-(2100,10)],(2000,6.07),(2005,6.45),(2010,6.83),(2015,7.2),(2020,7.54),(2025 ,7.85),(2030,8.13),(2035,8.38),(2040,8.59),(2045,8.77),(2050,8.92),(2055,9.03),(2060,9.11),(2065,9.17),(2070,9.21),(2075,9.22),(2080,9.22),(2085,9.2),(2090,9.16),(2095,9.12),(2100,9.06))
Units: Billion Person

World Population Scenario High Lookup([(2000,0)-(2100,20)],(2000,6.07),(2005,6.5),(2010,6.97),(2015,7.45),(2020,7.91),(2025,8.37),(2030,8.82),(2035,9.28),(2040,9.74), (2045,10.19),(2050,10.63),(2055,11.05),(2060,11.43),(2065,11.79),(2070,12.15), (2075,12.49),(2080,12.83),(2085,13.15), (2090, 13.46),(2095,13.74),(2100,14.02))
Units: Billion Person

Carbon Cycle



EQUATIONS

Anthropogenic CO2 Emissions = IF THEN ELSE(CO2 Emissions Switch = 1, Exogenous Historic CO2 Emissions, IF THEN ELSE (CO2 Emissions Switch = 2, Endogenous CO2 Emissions, Scenario CO2 Emissions))
Units: GTC/Year

Buffer Factor = Reference Buffer Factor+Buffer CO2 Coefficient*LN(CO2 in Atmosphere/Reference CO2 in the Atmosphere)
Units: Dmnl
Comment: The ratio of the instantaneous fractional change in the partial pressure of CO2 (pCO2) exerted by seawater

to the fractional change in total CO2 dissolved in the ocean waters. The buffer factor relates the partial pressure of CO2 in the ocean to the total ocean CO2 concentration at constant temperature, alkalinity and salinity. The Revelle factor is a useful parameter for examining the distribution of CO2 between the atmosphere and the ocean, and measures in part the amount of CO2 that can be dissolved in the mixed surface layer. (http://cdiac.ornl.gov/glossary.html#B)

CO2 in Deep Ocean[upper] = INTEG (Net CO2 Flux to Deep Ocean[upper]-Net CO2 Flux to Deep Ocean[lower], Initial CO2 in Deep Ocean[upper])
Units: GTC

CO2 in Deep Ocean[layer10] = INTEG (Net CO2 Flux to Deep Ocean[layer10], Initial CO2 in Deep Ocean[layer10])
Units: GTC

CO2 Emissions from Storage = CO2 Sequestered*Leakage Rate
Units: GTC/Year

CO2 in Atmosphere = INTEG (Anthropogenic CO2 Emissions+CO2 Emissions from Storage+Flux Biomass to Atmosphere+Flux Humus to Atmosphere -CO2 Sequestration -Flux Atmosphere to Biomass-Flux Atmosphere to Ocean, Preindustrial CO2 Level)
Units: GTC

CO2 in Biomass = INTEG (Flux Atmosphere to Biomass-Flux Biomass to Atmosphere-Flux Biomass to Humus, Initial CO2 in Biomass)
Units: GTC

CO2 in Humus = INTEG (Flux Biomass to Humus-Flux Humus to Atmosphere, Initial CO2 in Humus)
Units: GTC

CO2 in Mixed Layer = INTEG (Flux Atmosphere to Ocean-Net CO2 Flux to Deep Ocean[layer1], Preindustrial CO2 in Mixed Layer)
Units: GTC

CO2 Concentration in Ocean Layers[layers] = CO2 in Deep Ocean[layers]/Deep Ocean Layer Thickness[layers]
Units: GTC/meter

CO2 Sequestered = INTEG (CO2 Sequestration-CO2 Emissions from Storage, 0)
Units: GTC

CO2 Sequestration = MIN(Anthropogenic CO2 Emissions, RAMP(Target Sequestration/(Sequestration Target Year - Sequestration Start Year), Sequestration Start Year , Sequestration Target Year))
Units: GTC/Year

Endogenous CO2 Emissions = SUM(Embodied Emissions[sector!])
Units: GTC/Year

Equilibrium CO2 in Mixed Layer = Preindustrial CO2 in Mixed Layer * (CO2 in Atmosphere/Preindustrial CO2 Level) ^(1/Buffer Factor)
Units: GTC

Exogenous Historic CO2 Emissions = IF THEN ELSE(Time < Simulation Start Year, Historic CO2 Emissions, Endogenous CO2 Emissions)
Units: GTC/Year

Flux Atmosphere to Biomass = Reference Net Primary Production*(1+Bioestimulation Coefficient*LN(CO2 in Atmosphere / Preindustrial CO2 Level))
Units: GTC/Year
Comment: This flux depends on the Net primary production, which is the rate at which new biomass accrues in an

ecosystem (Wikipedia)
Flux Atmosphere to Ocean = (Equilibrium CO2 in Mixed Layer-CO2 in Mixed Layer)/Mixing Time
Units: GTC/Year

Flux Biomass to Atmosphere = (CO2 in Biomass/"Avg. Carbon Residence Time in Biomass")*(1-Humification Fraction)
Units: GTC/Year

Flux Biomass to Humus = (Humification Fraction*CO2 in Biomass)/"Avg. Carbon Residence Time in Biomass"
Units: GTC/Year

Flux Humus to Atmosphere = CO2 in Humus/Avg Carbon Residence Time in Humus"
Units: GTC/Year

Initial CO2 in Biomass = Flux Atmosphere to Biomass*Avg Carbon Residence Time in Biomass
Units: GTC

Initial CO2 in Deep Ocean[layers] = (Preindustrial CO2 in Mixed Layer*Deep Ocean Layer Thickness[layers])/Mixed Ocean Layer Depth
Units: GTC

Initial CO2 in Humus = Flux Biomass to Humus*Avg Carbon Residence Time in Humus
Units: GTC

Net CO2 Flux to Deep Ocean[layer1] = ((CO2 in Mixed Layer/Mixed Ocean Layer Depth)-CO2 Concentration in Ocean Layers[layer1])*Eddy Diffusion Coefficient*2/(Mixed Ocean Layer Depth+Deep Ocean Layer Thickness [layer1])
Units: GTC/Year

Net CO2 Flux to Deep Ocean[lower] = (CO2 Concentration in Ocean Layers[upper]-CO2 Concentration in Ocean Layers[lower])* Eddy Diffusion Coefficient*2/(Deep Ocean Layer Thickness[upper]+Deep Ocean Layer Thickness [lower])
Units: GTC/Year

Scenario CO2 Emissions = IF THEN ELSE(Time < Simulation Start Year, Historic CO2 Emissions, Endogenous CO2 Emissions*(1-Fraction Target Implemented)+ CO2 Emissions Target*Fraction Target Implemented)
Units: GTC/Year

PARAMETERS

Avg Carbon Residence Time in Biomass = 10.6
Units: Year

Avg. Carbon Residence Time in Humus = 27.8
Units: Year

Buffer CO2 Coefficient = 4.05
Units: Dmnl
Comment: Coefficient of CO2 concentration influence on buffer factor.

Deep Ocean Layer Thickness[top5] = 200
Units: meter

Deep Ocean Layer Thickness[bottom5] = 560
Units: meter

Eddy Diffusion Coefficient = 3600
Units: (meter*meter)/Year

Leakage Rate = 0
Units: 1/Year

Mixed Ocean Layer Depth = 75 meter

Preindustrial CO2 in Mixed Layer = 700.678
Units: GTC

Reference CO2 in the Atmosphere = 760
Units: GTC
Comment: Reference CO2 in atmosphere at normal buffer factor.

Reference Net Primary Production = 80.5177
Units: GTC/Year

Target Sequestration = 0
Units: GTC/Year

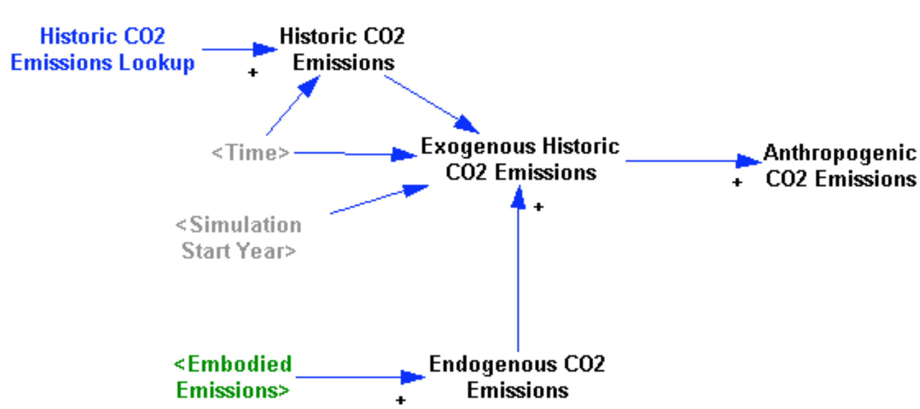
Sequestration Start Year = 2007
Units: Year

Sequestration Target Year = 2050
Units: Year

NOTES

The ocean is modeled using a 10-layer box diffusion model. Layers 1 through 9 are referred as 'upper' and layers 2 through 10 are referred as 'lower'. The top five layers are thin (200m), while the lower five are thick (560m). Additionally, the 'mixed ocean layer' refers to the 75m ocean's surface layer that is in contact with the atmosphere. The model was implemented in Vensim using subscripts.

Emissions Scenarios



EQUATIONS

Anthropogenic CO2 Emissions = Exogenous Historic CO2 Emissions
Units: GTC/Year

Embodied Emissions[sector] = INTEG (Change in Embodied Emissions from Retrofits[sector]+Increase in Embodied Emissions[sector]-Decrease in Embodied Emissions [sector], Capital[sector]*Emissions Intensity of New Capital[sector])
Units: GTC/Year

Endogenous CO2 Emissions = SUM(Embodied Emissions[sector!])
Units: GTC/Year

Exogenous Historic CO2 Emissions = IF THEN ELSE(Time < Simulation Start Year, Historic CO2 Emissions, Endogenous CO2 Emissions)
Units: GTC/Year

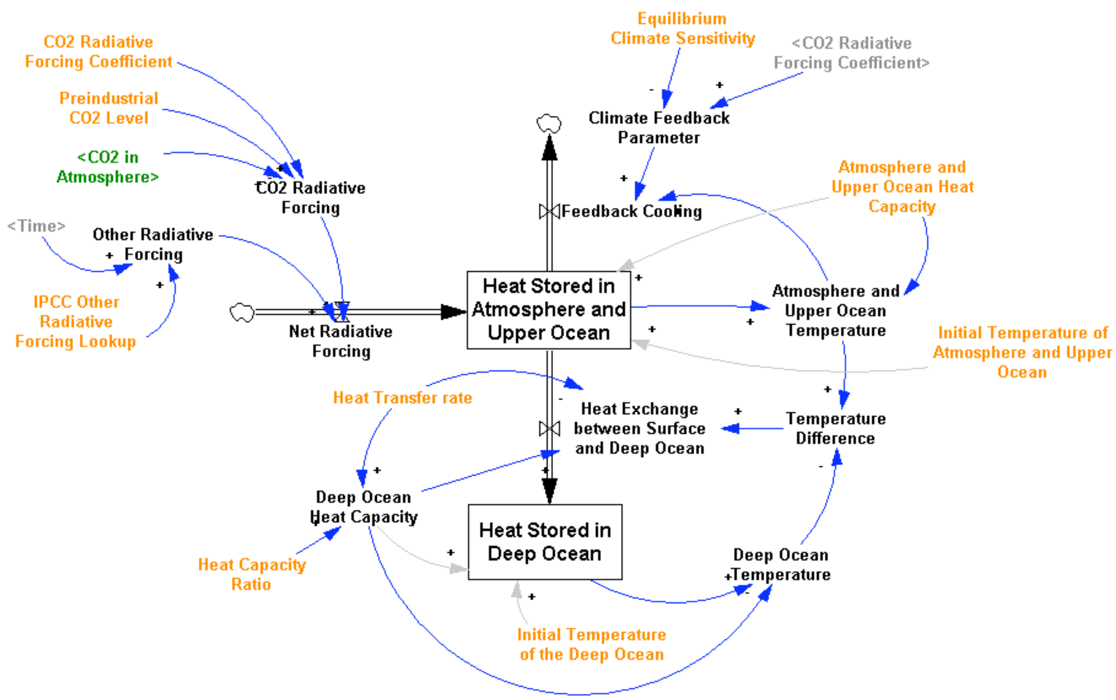
Historic CO2 Emissions = Historic CO2 Emissions Lookup(Time)
Units: GTC/Year

PARAMETERS

Historic CO2 Emissions Lookup ([(1900,0)-(2100,8)],(1900,0.534),(1901,0.552),(1902,0.566),(1903,0.617),(1904,0.624) ,(1905,0.663),(1906,0.707),(1907,0.784),(1908,0.75),(1909,0.785),(1910,0.819),(1911 ,0.836),(1912,0.879),(1913,0.943),(1914,0.85),(1915,0.838),(1916,0.901),(1917,0.955),(1918,0.936),(1919,0.806),(1920,0.932),(1921,0.803),(1922,0.845),(1923,0.97),(1924 ,0.963),(1925,0.975),(1926,0.983),(1927,1.062),(1928,1.065),(1929,1.145),(1930,1.053),(1931,0.94),(1932,0.847),(1933,0.893),(1934,0.973),(1935,1.027),(1936,1.13),(1937 ,1.209),(1938,1.142),(1939,1.192),(1940,1.299),(1941,1.334),(1942,1.342),(1943,1.391),(1944,1.383),(1945,1.16),(1946,1.238),(1947,1.392),(1948,1.469),(1949,1.419),(1950 ,1.63),(1951,1.767),(1952,1.795),(1953,1.841),(1954,1.865),(1955,2.043),(1956,2.177),(1957,2.27),(1958,2.33),(1959,2.462),(1960,2.577),(1961,2.594),(1962,2.7),(1963,2.847),(1964,3.008),(1965,3.145),(1966,3.305),(1967,3.411),(1968,3.588),(1969,3.8),(1970 ,4.077),(1971,4.231),(1972,4.399),(1973,4.635),(1974,4.644),(1975,4.615),(1976,4.884),(1977,5.035),(1978,5.107),(1979,5.403),(1980,5.348),(1981,5.186),(1982,5.144),(1983 ,5.126),(1984,5.308),(1985,5.464),(1986,5.629),(1987,5.762),(1988,5.992),(1989,6.106),(1990,6.196),(1991,6.312),(1992,6.187),(1993,6.203),(1994,6.344),(1995,6.487),(1996 ,6.649),(1997,6.84),(1998,6.788),(1999,6.804),(2000,6.981),(2001,7.116),(2002,7.167),(2003,7.504),(2004,7.91))
Units: GTC/Year
Source: Marland et al (2007)

Simulation Start Year = 2000
Units: Year

Climate



EQUATIONS

Atmosphere and Upper Ocean Temperature = Heat Stored in Atmosphere and Upper Ocean/Atmosphere and Upper Ocean Heat Capacity
Units: Celsius

Climate Feedback Parameter = CO2 Radiative Forcing Coefficient/Equilibrium Climate Sensitivity
Units: (Watt/(meter*meter))/Celsius

CO2 in Atmosphere = INTEG (Anthropogenic CO2 Emissions+CO2 Emissions from Storage+Flux Biomass to Atmosphere+Flux Humus to Atmosphere -CO2 Sequestration -Flux Atmosphere to Biomass-Flux Atmosphere to Ocean, Preindustrial CO2 Level)
Units: GTC

CO2 Radiative Forcing = CO2 Radiative Forcing Coefficient*LOG(CO2 in Atmosphere/Preindustrial CO2 Level,2)
Units: Watt/(meter*meter)

Deep Ocean Heat Capacity = Heat Transfer rate*Heat Capacity Ratio
Units: (Watt*Year)/(meter*meter*Celsius)

Deep Ocean Temperature = Heat Stored in Deep Ocean/Deep Ocean Heat Capacity
Units: Celsius

Heat Stored in Atmosphere and Upper Ocean = INTEG (Net Radiative Forcing-Feedback Cooling-Heat Exchange between Surface and Deep Ocean, Initial Temperature of Atmosphere and Upper Ocean*Atmosphere and Upper Ocean Heat Capacity)
Units: (Watt*Year)/(meter*meter)

Feedback Cooling = Climate Feedback Parameter*Atmosphere and Upper Ocean Temperature
Units: Watt/(meter*meter)

Heat Exchange between Surface and Deep Ocean = (Temperature Difference*Deep Ocean Heat Capacity)/Heat Transfer rate
Units: Watt/(meter*meter)

Heat Stored in Deep Ocean = INTEG (Heat Exchange between Surface and Deep Ocean, Initial Temperature of the Deep Ocean*Deep Ocean Heat Capacity)
Units: Year*Watt/(meter*meter)

Net Radiative Forcing = CO2 Radiative Forcing+Other Radiative Forcing
Units: Watt/(meter*meter)
Comment: Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it (IPCC AR4)

Other Radiative Forcing = IPCC Other Radiative Forcing Lookup(Time)
Units: Watt/(meter*meter)

Temperature Difference = Atmosphere and Upper Ocean Temperature-Deep Ocean Temperature
Units: Celsius

PARAMETERS

Atmosphere and Upper Ocean Heat Capacity = 44.248
Units: (Watt*Year)/(Celsius*meter*meter)

CO2 Radiative Forcing Coefficient = 4.1
Units: Watt/(meter*meter)

Equilibrium Climate Sensitivity = 3
Units: Celsius
Comment: The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. (IPCC AR4)

Heat Capacity Ratio = 0.44
Units: Watt/(meter*meter*Celsius)
Comment: Ratio of Thermal Capacity of Deep Ocean to Heat Transfer Time Constant

Heat Transfer rate = 500
Units: Year

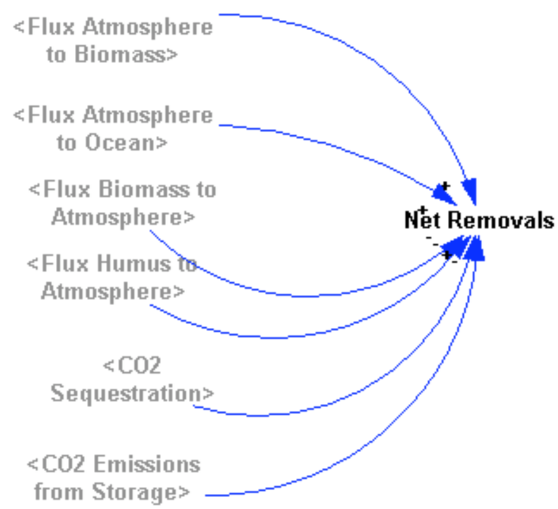
Initial Temperature of Atmosphere and Upper Ocean = 0
Units: Celsius

Initial Temperature of the Deep Ocean = 0
Units: Celsius

IPCC Other Radiative Forcing Lookup ([(1600,0)-(2100,2)],(1600,0),(1900,0.16),(1960,0.37),(1970,0.45),(1980,0.55),(1990,0.66),(2000,0.73),(2025,0.96),(2050,1.18),(2075,1.29),(2100,1.36))
Units: Watt/(meter*meter)
Comment: Radiative forcing from other greenhouse gases (Methane, N2O). From IPCC assumptions cited in Nordhaus (Managing the Global Commons, 1994). Apparently neglects other gases and cooling effects of aerosols.

Preindustrial CO2 Level = 629.5
Units: GTC
Comment: Adjusted from historical data (1900->295.55ppm->629.5GTC)

Net Removals



EQUATIONS

CO2 Emissions from Storage = CO2 Sequestered*Leakage Rate
Units: GTC/Year

CO2 Sequestration = MIN(Anthropogenic CO2 Emissions, RAMP(Target Sequestration/(Sequestration Target Year - Sequestration Start Year), Sequestration Start Year , Sequestration Target Year))
Units: GTC/Year

Net Removals = Flux Atmosphere to Biomass+Flux Atmosphere to Ocean+CO2 Sequestration-Flux Biomass to Atmosphere -Flux Humus to Atmosphere-CO2 Emissions from Storage
Units: GTC/Year

Flux Atmosphere to Biomass = Reference Net Primary Production*(1+Bioestimulation Coefficient*LN(CO2 in Atmosphere / Preindustrial CO2 Level))
Units: GTC/Year
Comment: This flux depends on the Net primary production, which is the rate at which new biomass accrues in an ecosystem (Wikipedia)

Flux Atmosphere to Ocean = (Equilibrium CO2 in Mixed Layer-CO2 in Mixed Layer)/Mixing Time
Units: GTC/Year

Flux Biomass to Atmosphere = (CO2 in Biomass/"Avg. Carbon Residence Time in Biomass")*(1-Humification Fraction)
Units: GTC/Year

Flux Humus to Atmosphere = CO2 in Humus/Avg Carbon Residence Time in Humus"
Units: GTC/Year

Model Parameters

FINAL TIME= 2100
Units: Year
Comment: The final time for the simulation.

INITIAL TIME = 1900
Units: Year
Comment: The initial time for the simulation.

SAVEPER = TIME STEP
Units: Year
Comment: The frequency with which output is stored.

TIME STEP = 1
Units: Year
Comment: The time step for the simulation.

VI.4 Simulation Code

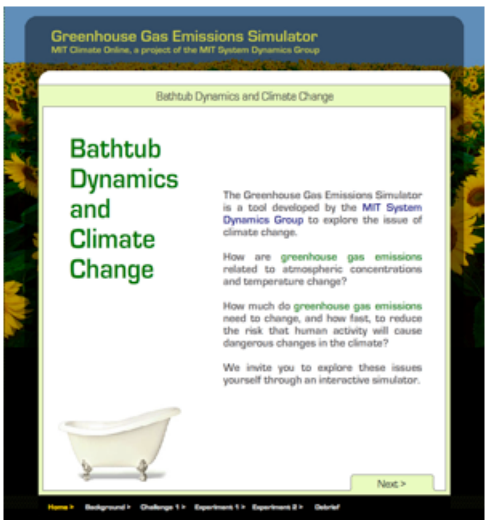
Directory Structure of the simulation code

```
img
    border.png
    burst.png
    graph1.png
    graph2.png
    graph3.png
    sip background.gif
    sip background.png
    sponsors.jpg
    sunflowers.jpg
    top.gif
    top.png
    tops.png
master
    master.swf
    AC_RunActiveContent.js
    content.css
    index.html
    challenge1
        challenge1.swf
        AC_RunActiveContent.js
        xml
            emissionsData.xml
            concentrationData.xml
    challenge2
        challenge2.swf
        AC_RunActiveContent.js
        xml
            emissionsData.xml
            concentrationData.xml
    debrief
        debrief.swf
        credits.swf
        AC_RunActiveContent.js
        content.css
        content.html
experiment1
    experiment1.swf
    introexp1.swf
    AC_RunActiveContent.js
    xml
        accumulationData.xml
        flowData.xml
experiment2
    experiment2.swf
    introexp2.swf
    AC_RunActiveContent.js
    xml
        accumulationData.xml
        flowData.xml
introduction
    home.swf
    introduction.swf
    AC_RunActiveContent.js
    content.css
    content.html
resources
    resources.swf
    AC_RunActiveContent.js
    content.css
    content.html
```

Description of the simulation modules

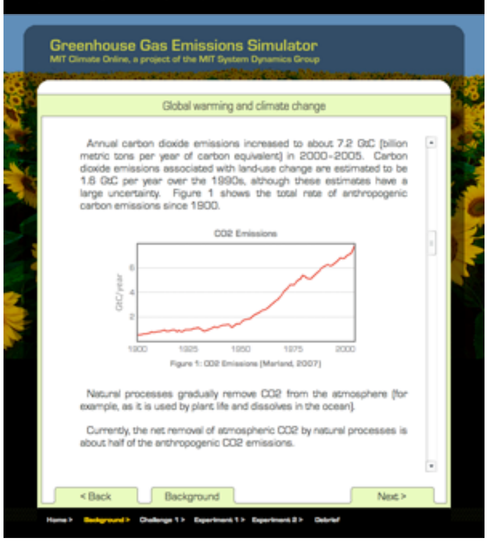
Master.swf

The *master.swf* document is the first flash object to load. It is embedded in *index.html* and formatted using Cascading Style Sheets (CSS). *master.swf* is used to load the different simulation modules at runtime. All modules are contained in independent flash objects, which are located in separate folders labeled using the module name. All resources for a particular module are placed in their respective folder.



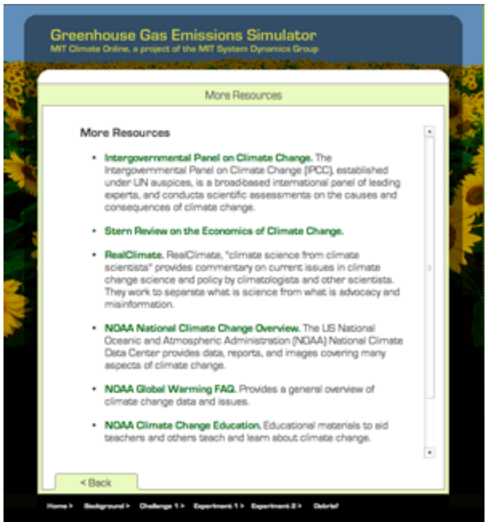
Home.swf

The *home.swf* flash object is the first page the user is presented when loading the simulation. It describes the simulation contents briefly and invites the user to proceed with the experience.



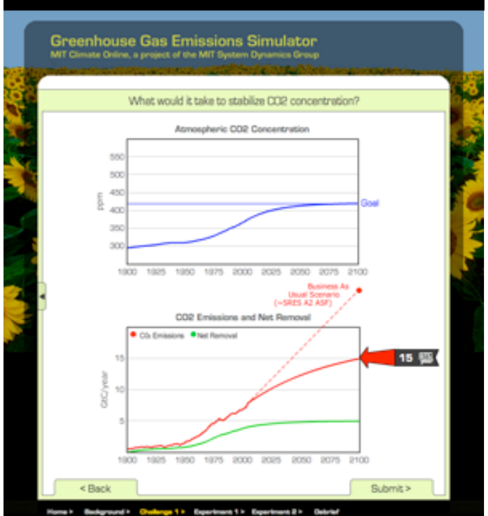
Introduction.swf

The *introduction.swf* flash object contains the IPCC excerpt that introduces climate change concepts. It presents a brief text based on the IPCC AR4 SPM Report and includes graphs with historical trends for *CO_2 emissions*, *atmospheric CO_2 concentration* and *global mean temperature*. The page is formatted using CSS.



Resources.swf

The *resources.swf* flash object presents a series of external links that complement the information contained in the simulation. The page is formatted using CSS.

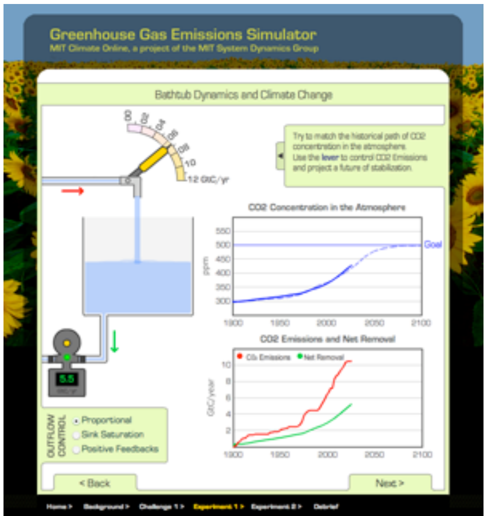


Challenge1.swf

The *challenge1.swf* flash object presents the first SF Challenge to the user. Both graphs are loaded using external XML data sources and InfoSoft Global Fusion Charts library v3. Graph animation is done using Flash Actionscript 2.0.

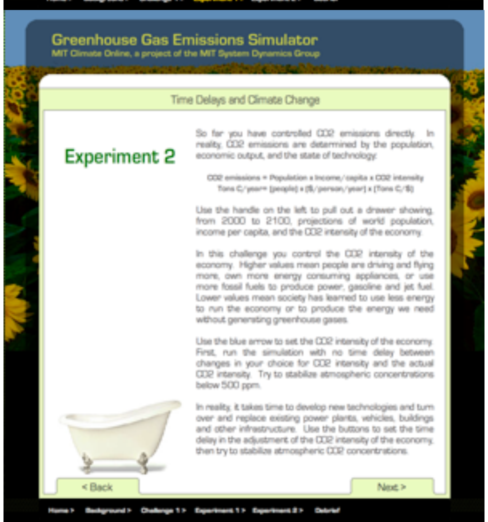
Introexp1.swf

The *Introexp1.swf* flash object contains a description of the task presented in the First Experiment. Text is formatted directly in Flash.



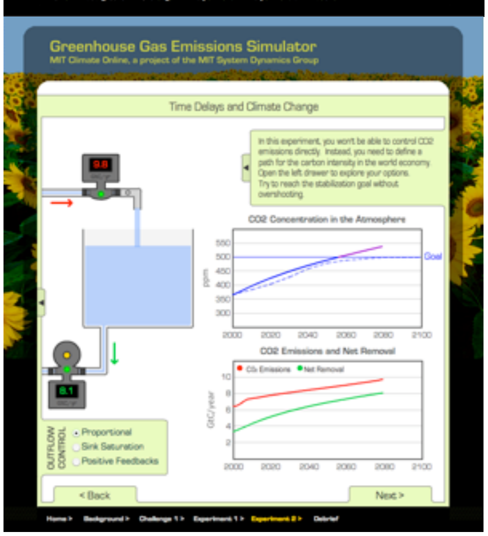
Experiment 1.swf

The *experiment1.swf* flash object presents the First Experiment to the user. Both graphs are loaded using external XML data sources and InfoSoft Global Fusion Charts library v3. The First Experiment is built around the bathtub analogy, which is animated along the simulation. All animation is done using Flash Actionscript 2.0.



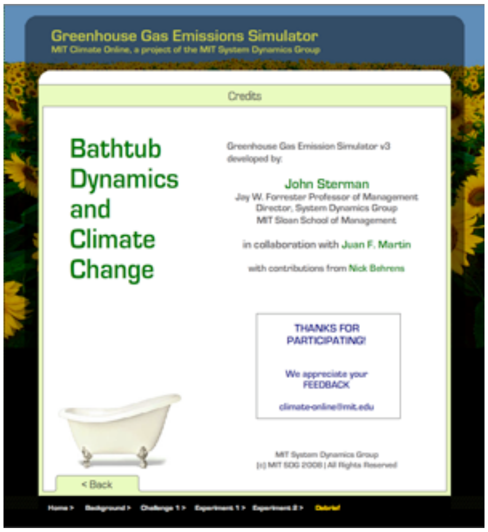
Introexp2.swf

The *Introexp2.swf* flash object contains a description of the task presented in the Second Experiment. Text is formatted directly in Flash.



Experiment2.swf

The *experiment2.swf* flash object presents the Second Experiment to the user. Both graphs are loaded using external XML data sources and InfoSoft Global Fusion Charts library v3. The Second Experiment extends the use of the bathtub analogy, which is animated along the simulation. Additionally, the Second Experiment uses three mini-graphs on a side pane that are animated using Flash Actionscript 2.0.



Debrief.swf

The final document is *debrief.swf*. Since the simulation was run in the context of a climate change workshop, no debrief was included in the online simulation. Instead, the experience was discussed with workshop participants directly. The debrief page was replaced with the simulation credits.

Technologies

Adobe Flash CS3 Professional v.9

http://www.adobe.com/products/flash/

Adobe Flash is a vector-based authoring program for creating graphic displays and animations. It combines the strengths of a graphical programming interface with versatility of the Actionscript scripting language. Applications developed with this software package can be easily deployed on multiple platforms where the Adobe Flash Player plug-in is available (Internet browsers, mobile phones, etc). For the purpose of developing this interactive simulation, Adobe Flash has proven to be an excellent resource because it allows the creation of self-contained modules, provides user interface components, and many graphical resources and animation options.

InfoSoft Global Fusion Charts v3

http://www.fusioncharts.com/

FusionCharts is a charting component developed in Adobe Flash that can be used to render animated charts. Charts can be deployed across browsers and platforms and can be configured using different programming languages (PHP, ASP, etc). The main advantage of this software package is that charts can be configured using external XML files. This makes updating data sources and chart cosmetics very straightforward. In the simulation implementation, I have combined charts created with this package with plot animations controlled with Adobe Flash Actionscript 2.0.

Ghostwire PHPObject

http://www.ghostwire.com/go/28

PHPObject is an opensource alternative to Flash Remoting for PHP developers. It establishes a connection between the Adobe Flash object and a web server running PHP. With PHPObject, you can call a method of a PHP class/library on your web server as if the class/library was defined in Adobe Flash itself.

Source Code Comments

The source code is divided in different Adobe Flash objects as described earlier. Each Adobe Flash object corresponds to a specific simulation module. Within each module, code is organized in layers according to functionality. In specific cases, such as animations, the code is placed within the animated object. The following list gives an overview of the code contained in the layers of main components. For access to the source code, please contact John Sterman at the MIT System Dynamics Group.

Challenge 1, Experiment 1, Experiment 2

- 'Charts' layer: This layer uses the Fusion Charts library to create the base graphs' instances. External XML data sources are loaded and the graphs are populated with the information. Additionally, I use the logCurve class to create curve animation objects to be drawn over the graphs. The logCurve class contains the necessary equations to integrate curve trajectories and fit them to an exponential curve. This class is available in the source code and can access graph parameters via an extension of the Fusion Charts library code (See the simulation's implementation of com/fusioncharts/core/charts/MSLine2DChart.as).
- 'PHPObject' layer: This layer handles the communication with the server to store users' responses. It is an implementation of the PHPObject Flash component.
- 'SideDrawer' layer: This layer implements the drawer functionality that allows additional information to be available to the user in a side pane. It uses the 'mmovement' flash component (available in the source code) to control the animation.
- Interface layer: This is where most graphical interface components are placed and where event-listeners functions are implemented.
- Bathtub: This layer holds the bathtub animation. The code for the animation is embedded in the bathtub Flash object itself. The animation is based on a timer that controls the pace at which curves are plotted and water fills up the tub. All user-interface controls for the animation, like the pipe lever and the flow indicators, are updated within this code.
- The rest of the layers implement the different screens the users are presented before submitting his/her results.