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Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter

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Abstract Public attitudes about climate change reveal a contradiction. Surveys show most Americans believe climate change poses serious risks but also that reductions in greenhouse gas (GHG) emissions sufficient to stabilize atmospheric GHG concentrations can be deferred until there is greater evidence that climate change is harmful. US policymakers likewise argue it is prudent to wait and see whether climate change will cause substantial economic harm before undertaking policies to reduce emissions. Such wait-and-see policies erroneously presume climate change can be reversed quickly should harm become evident, underestimating substantial delays in the climate's response to anthropogenic forcing. We report experiments with highly educated adults – graduate students at MIT – showing widespread misunderstanding of the fundamental stock and flow relationships, including mass balance principles, that lead to long response delays. GHG emissions are now about twice the rate of GHG removal from the atmosphere. GHG concentrations will therefore continue to rise even if emissions fall, stabilizing only when emissions equal removal. In contrast, most subjects believe atmospheric GHG concentrations can be stabilized while emissions into the atmosphere continuously exceed the removal of GHGs from it. These beliefs – analogous to arguing a bathtub filled faster than it drains will never overflow – support wait-and-see policies but violate conservation of matter. Low public support for mitigation policies may arise from misconceptions of climate dynamics rather than high discount rates or uncertainty about the impact of climate change. Implications for education and communication between scientists and nonscientists (the public and policymakers) are discussed.

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1 Introduction

Critical public policy issues increasingly involve complex physical and natural systems. Policies for such systems should be based on the best available scientific knowledge. In democracies, however, the beliefs of the public, not only those of experts, affect government policy and citizen adoption of policies. If widely held mental models of complex systems are faulty, people may inadvertently favor policies that yield outcomes they neither intend nor desire. Climate change is such an issue. Opinion surveys show an apparent contradiction in public attitudes on climate change. Most Americans support the Kyoto Accord and Climate Stewardship Act, believe human activity contributes to climate change, and desire to limit the risk of harm from it (Brechin 2003; Kull 2001; Leiserowitz 2003; Taylor 2001; Krosnick et al. 2000). Yet large majorities oppose mitigation policies such as energy taxes (Leiserowitz 2003; O'Connor et al. 1999). Many advocate a "wait and see strategy." Asked to choose which of several statements came closest to their own view, nearly 60% chose either "until we are sure that global warming is really a problem, we should not take any steps that would have economic costs" or "its effects will be gradual, so we can deal with the problem gradually" (Kull 2001). US federal policymakers similarly argue it is prudent to determine whether anthropogenic climate change will cause substantial harm before reducing GHG emissions.[1] Advocates of the wait-and-see approach reason that uncertainty about the causes and consequences of climate change mean potentially costly actions to address the risks should be deferred. If climate change turns out to be more harmful than expected, policies to mitigate it can then be implemented.

Wait-and-see policies often work well in simple systems, specifically those with short lags between detection of a problem and the implementation and impact of corrective actions. In boiling water for tea, one can wait until the kettle boils before taking action because there is essentially no delay between the boiling of the water and the whistle of the kettle, nor between hearing the whistle and removing the kettle from the flame. Few complex public policy challenges can be addressed so quickly. To be a prudent response to the risks of climate change, wait-and-see policies require short delays in all the links in a long causal chain, stretching from the detection of adverse climate impacts to the decision to implement mitigation policies to emissions reductions to changes in atmospheric GHG concentrations to radiative forcing to surface warming and finally to climate impacts, including changes in ice cover, sea level, weather patterns, agricultural productivity, the distribution of species, extinction rates, and the incidence of diseases, among others. None of these conditions hold: there are long delays in every link of the chain (Wigley 2005; Meehl et al. 2005; Houghton et al. 2001; O'Neill and Oppenheimer 2002; Alley et al. 2003; Thomas et al. 2004; Stachowicz et al. 2002; Rodo et al. 2002; Fiddaman 2002). Some of the response delay arises from the time required to develop scientific understanding and consensus for policy change. Some of

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[1] For example, President Bush introduced the Clear Skies Initiative with the following statement (www.whitehouse.gov/news/releases/2002/02/20020214-5.html, 2002):

> My administration is committed to cutting our nation's greenhouse gas intensity – how much we emit per unit of economic activity – by 18 percent over the next 10 years. This will set America on a path to slow the growth of our greenhouse gas emissions and, as science justifies, to stop and then reverse the growth of emissions. This is the common sense way to measure progress. . . . If, however, by 2012, our progress is not sufficient and sound science justifies further action, the United States will respond with additional measures. . . .

See also Hearing on Global Climate Change and the U.S. Climate Action Report, US Senate Committee on Commerce, Science, and Transportation, July 11, 2002.

the delay arises from the time required to build the public and political support needed to pass legislation and ratify international agreements. Some arises from inertia in the economy and energy system: even after policies to promote energy efficiency and non-carbon energy sources are implemented, existing stocks of GHG-generating capital (automobiles, industrial plant and equipment, housing, infrastructure) are only gradually replaced or retrofitted, while noncarbon alternatives are only gradually developed and deployed (Fiddaman 2002).

The longest response delays, however, arise within the climate itself, from the stock and flow relationships among GHG emissions, GHG concentrations, and global mean temperature. Two stock-flow structures are fundamental: global mean surface temperature integrates (accumulates) net radiative forcing (minus net heat transfer to the deep ocean). In turn, radiative forcing is affected by the level of GHGs in the atmosphere, which integrates emissions less the rate at which GHGs are removed from the atmosphere. Anthropogenic GHG emissions are now roughly double the net rate of GHG removal by natural processes (net uptake by biomass, the ocean, and other sinks) (Houghton et al. 2001). Even if policies to mitigate climate change caused GHG emissions to fall, atmospheric GHG concentrations would continue to rise until emissions fell to the removal rate. GHG concentrations can fall only if emissions drop below removal. Warming would continue until atmospheric concentrations fell enough, and global mean temperature rose enough, to restore net radiative balance. Global mean surface temperature would then peak, and climate changes such as sea level rise from ice melt and thermal expansion would continue (Wigley 2005; Meehl et al. 2005). The belief that wait-and-see policies are prudent implicitly presumes the climate is roughly a first-order linear system with a short time constant, rather than a high-dimensional dynamical system with long delays, multiple positive feedbacks and nonlinearities that might cause abrupt, persistent and costly regime changes (Alley et al. 2003; Scheffer et al. 2001).

Why do people underestimate the time delays in the response of climate to GHG emissions? Obviously the average person is not trained in climatology, and studies document low levels of public understanding of climate processes (Kasemir et al. 2000; Kempton 1997; Bostrom et al. 1994; Read et al. 1994). We hypothesize, however, that widespread underestimation of climate inertia arises from a more fundamental limitation of people's mental models: weak intuitive understanding of stocks and flows – the concept of accumulation in general, including principles of mass and energy balance.[2] Prior work shows people have difficulty relating the flows into and out of a stock to the trajectory of the stock, even in simple situations such as filling a bathtub or managing a firm's inventory (Booth Sweeney and Sterman 2000). Instead, people often assess system dynamics using a *pattern matching* heuristic, seeking correlations among the data and using these to project future values. Humans can detect positive correlations in data well, indeed often perceiving patterns where none exist (Plous 1993 reviews relevant studies). In the context of climate change, a prototype experiment (Sterman and Booth Sweeney 2002) found that many people used a pattern-matching heuristic to project future climate variables, concluding that system outputs (e.g., global mean temperature) are positively correlated with inputs (e.g., emissions).[3]

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[2] Definitions of the term 'mental model' are many and varied, including domain knowledge, typologies for categorizing experience, and heuristics for judgment and decisionmaking, among others (see, e.g., Axelrod 1976; Gentner, and Stevens 1983; Johnson-Laird 1983; Morgan et al. 2002). As used here, the term 'mental model' includes a person's (often implicit) beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model (which factors are considered endogenous, exogenous, or immaterial) and the time horizon considered relevant.

[3] Sterman and Booth Sweeney (2002) report a prototype of the present experiment. However, while the results were consistent with pattern matching, the tasks used did not control for different information displays, and

Pattern matching often works well in simple systems but fails in systems with significant stock and flow structures: a stock can rise even as its net inflow falls, as long as the net inflow is positive. For example, a nation's debt rises as long as its fiscal deficit is positive, even as the deficit falls; debt falls only when the government runs a surplus. Since anthropogenic GHG emissions are now roughly double net removal, atmospheric GHGs would continue to accumulate, increasing net radiative forcing, even if emissions drop – until emissions fall to net removal (of course, removal is not constant; we consider the dynamics of removal below). In contrast, pattern matching incorrectly predicts mean temperature and atmospheric GHGs closely track emissions; hence stabilizing emissions would rapidly stabilize climate, and emissions cuts would quickly reverse warming and limit damage from climate change. People who assess the dynamics of the climate using a pattern matching heuristic – projecting past correlations among emissions, CO_2 concentrations, and temperature – will significantly underestimate the lags in the response of the climate to changes in emissions and the magnitude of emissions reductions needed to stabilize atmospheric GHG concentrations.

We conducted experiments to determine the extent to which highly educated adults understand the fundamental relationship between flows of GHGs and the stock of GHGs in the atmosphere. We find significant misperceptions of basic climate dynamics in a population of graduate students at an elite university. Pattern matching is widespread. Worse, a large majority violate fundamental physical constraints including conservation of mass. Most believe atmospheric greenhouse gas concentrations can be stabilized even as emissions into the atmosphere continuously exceed removal of GHGs from it, analogous to arguing a bathtub filled faster than it drains will never overflow. These beliefs favor wait-and-see policies, but violate basic laws of physics. After presenting the experiment and results, we consider the implications for risk communication, education, and the process of social change required for widespread adoption of policies to mitigate GHG emissions.

2 Method

2.1 Task description and information display

We first presented subjects with a brief nontechnical summary of climate change such as would be suitable for the policymaker or intelligent layperson. The descriptive text (Fig. 1A) is quoted or paraphrased from the IPCC's Third Assessment Report [TAR] Summary for Policymakers [SPM] (Houghton et al. 2001), a document intended for nonscientists (Table 1 shows the sources for each statement in the description provided to the subjects). The text explicitly describes the stock of atmospheric CO_2 (the principal anthropogenic GHG), CO_2 emissions, and the removal of CO_2 from the atmosphere by natural processes, including the magnitude of the net removal flow, providing cues prompting subjects to notice the relationship between the stock of CO_2 in the atmosphere and the emissions and removal flows that alter it.

Subjects were then presented with a scenario for the evolution of atmospheric CO_2 and asked to describe the emissions trajectory required to realize it (Fig. 1B). We defined two scenarios in which atmospheric CO_2 gradually rises (falls) from year 2000 levels of about 370 ppm to 400 (340) ppm by 2100, changes of roughly ±8%. The two CO_2 scenarios were designed to discriminate sharply between the predictions of pattern matching and those based

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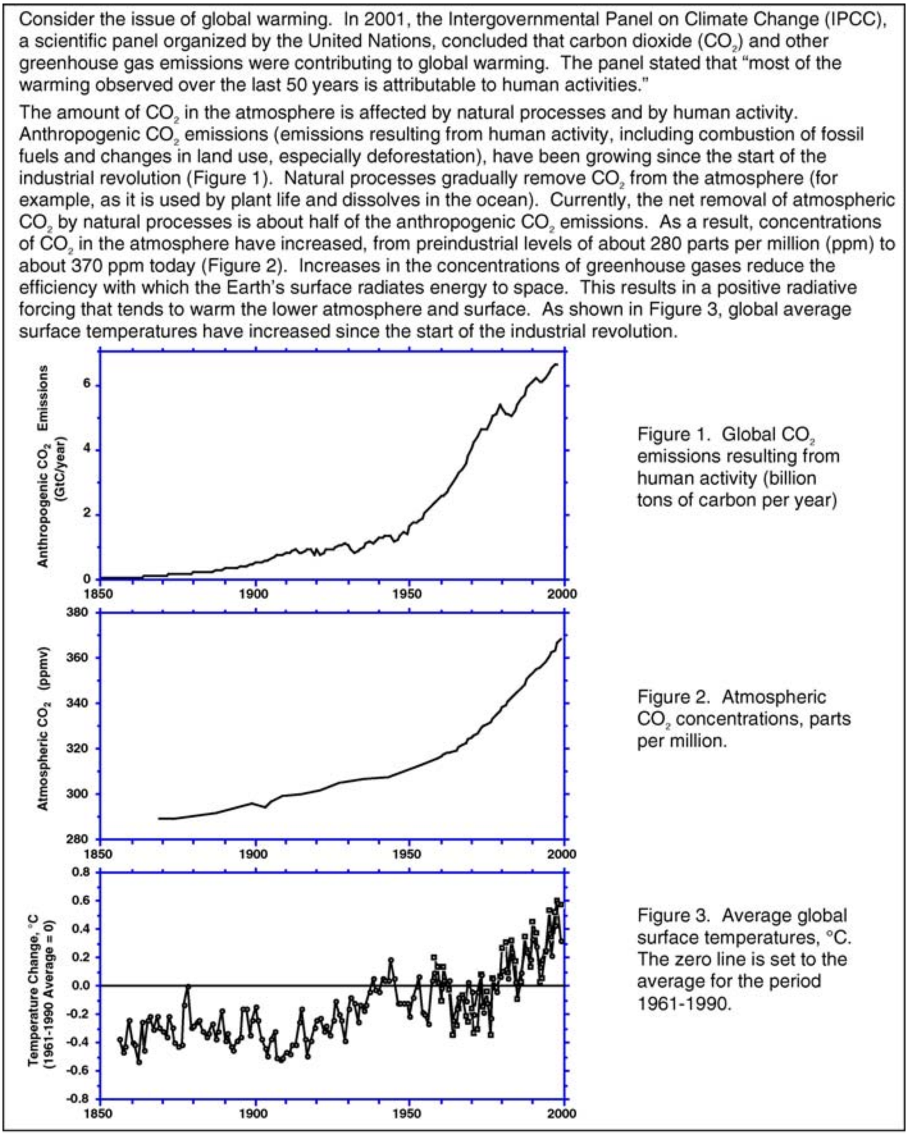
did not enable subjects' conformance with conservation principals to be assessed. These factors are controlled here.



Consider the issue of global warming. In 2001, the Intergovernmental Panel on Climate Change (IPCC), a scientific panel organized by the United Nations, concluded that carbon dioxide (CO_2) and other greenhouse gas emissions were contributing to global warming. The panel stated that "most of the warming observed over the last 50 years is attributable to human activities."

The amount of CO_2 in the atmosphere is affected by natural processes and by human activity. Anthropogenic CO_2 emissions (emissions resulting from human activity, including combustion of fossil fuels and changes in land use, especially deforestation), have been growing since the start of the industrial revolution (Figure 1). 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, concentrations of CO_2 in the atmosphere have increased, from preindustrial levels of about 280 parts per million (ppm) to about 370 ppm today (Figure 2). Increases in the concentrations of greenhouse gases reduce the efficiency with which the Earth's surface radiates energy to space. This results in a positive radiative forcing that tends to warm the lower atmosphere and surface. As shown in Figure 3, global average surface temperatures have increased since the start of the industrial revolution.

Figure 1. Global CO_2 emissions resulting from human activity (billion tons of carbon per year)

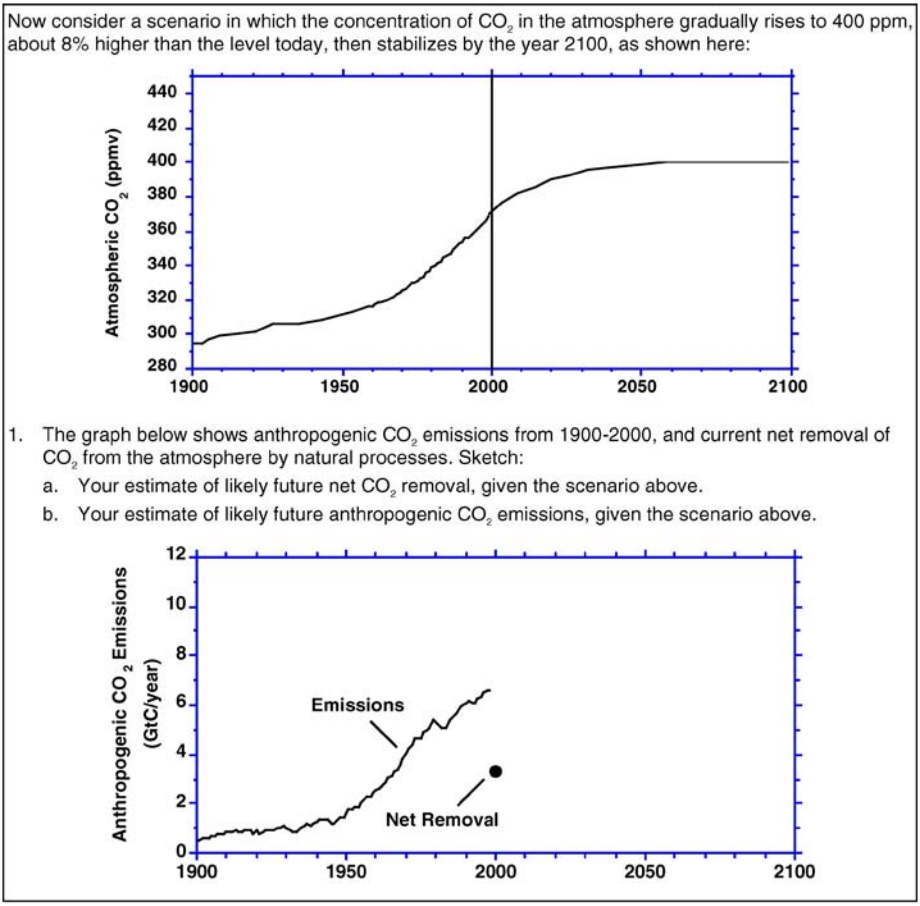
Figure 2. Atmospheric CO_2 concentrations, parts per million.

Figure 3. Average global surface temperatures, °C. The zero line is set to the average for the period 1961-1990.

(A) Task Description

Fig. 1 Climate policy task. Subjects were presented with the description in (A), drawn from the IPCC TAR Summary for Policymakers (Houghton et al. 2001), followed by one of two CO_2 scenarios. Half the subjects received the scenario shown in (B; next page) in which atmospheric CO_2 rises to 400 ppm and then stabilizes; the other half received a scenario in which atmospheric CO_2 gradually falls and stabilizes at 340 ppm, as shown in (C). Subjects then sketch their estimate of the emissions path needed to achieve the CO_2 scenario, on the graph of emissions provided. The Emissions and Removal (ER) graphical response format is shown. In the Emissions Graph (EG) format, the data point for net removal on the graph of emissions in (B) and (C) is omitted, and the prompt reads "The graph below shows anthropogenic CO_2 emissions from 1900–2000. Sketch your estimate of likely future anthropogenic CO_2 emissions, given the scenario above." In the multiple choice (MC) condition, subjects received the choices shown in Table 2. In all cases subjects were also asked to select the behavior of global mean temperature, in MC format, and to provide a brief written explanation for their emissions and temperature trajectories (Table 2).

(*Continued on next page*)



Now consider a scenario in which the concentration of CO_2 in the atmosphere gradually rises to 400 ppm, about 8% higher than the level today, then stabilizes by the year 2100, as shown here:

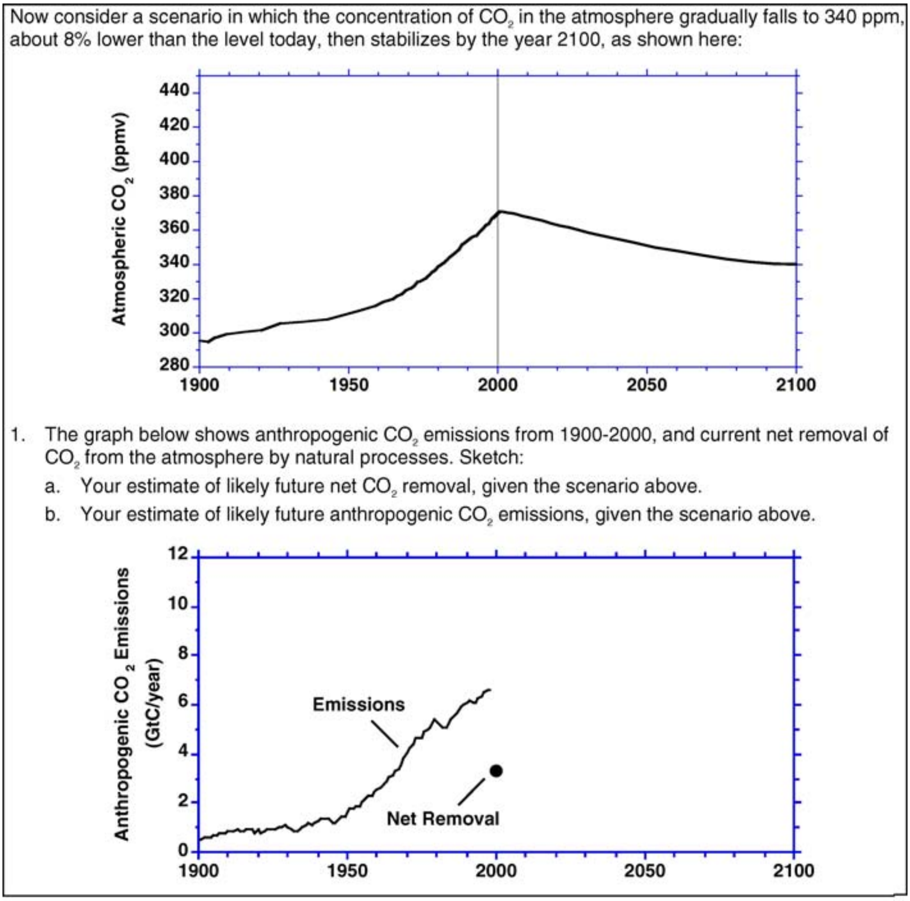
1. The graph below shows anthropogenic CO_2 emissions from 1900-2000, and current net removal of CO_2 from the atmosphere by natural processes. Sketch:
   a. Your estimate of likely future net CO_2 removal, given the scenario above.
   b. Your estimate of likely future anthropogenic CO_2 emissions, given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

(B) 400 ppm scenario

Fig. 1 (*Continued*)

on understanding of the stock and flow structure and are therefore lower than those in, e.g., the IPCC Special Report on Emissions Scenarios [SRES] (Houghton et al. 2001), in which CO_2 concentrations rise through 2100. When atmospheric CO_2 rises throughout the time horizon, pattern matching and conservation principles yield similar predictions. Such scenarios would not reveal whether subjects understand stock-flow relationships, specifically that atmospheric CO_2 rises as long as emissions exceed removal and stabilizes only if emissions equal removal.

Studies show that information displays may affect people's responses in judgment and decision making tasks (e.g., Kleinmuntz and Schkade 1993). To minimize potential response bias we tested three question formats. In the Emissions and Removal (ER) condition (shown in Fig. 1B) subjects were explicitly directed to draw their estimate of future CO_2 removal, then draw the emissions path needed to achieve the scenario for atmospheric CO_2 they were given. Prompting subjects to consider removal should increase use of stock-flow and mass balance principles, favoring high performance. The Emissions Graph (EG) condition is similar but omits the prompt for the removal trajectory and the data point showing current net removal, testing whether subjects spontaneously consider removal. The Multiple Choice



Now consider a scenario in which the concentration of CO_2 in the atmosphere gradually falls to 340 ppm, about 8% lower than the level today, 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 CO_2 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.

(C) 340 ppm scenario

Fig. 1 (*Continued*)

(MC) condition (Table 2) provides a textual rather than graphical response format in which subjects select which of seven emissions trajectories they believe to be most consistent with the specified CO_2 scenario. Choices range from continued emissions growth to immediate decline below current rates. The MC condition is less cognitively demanding but provides limited choice; the EG and ER formats do not constrain subject choice but require construction of a graph.

Each format was designed, wherever possible, to reduce bias that might arise from asymmetries in the presentation of the response options. The seven choices in the MC format are symmetric around the neutral choice of stabilization at current rates (no change in emissions). The graph provided for the EG and ER formats shows emissions on a scale from 0–12 GtC/year, placing current emissions at the neutral point approximately halfway between axis limits. A scale from 0–7 GtC/year would likely bias responses towards lower emissions; a scale from 5–29 GtC/year, as used in the TAR to show emissions under the SRES scenarios (Houghton et al. 2001, Fig. 17, p. 64), would likely bias responses towards higher emissions. In all conditions subjects were also asked for the likely response of global

Table 1 The description in the task (Fig. 1A; reproduced below) is quoted or paraphrased from the IPCC TAR Summary for Policymakers; page numbers in notes below refer to the TAR.

Consider the issue of global warming. In 2001, the Intergovernmental Panel on Climate Change (IPCC), a scientific panel organized by the United Nations, concluded that carbon dioxide (CO_2) and other greenhouse gas emissions were contributing to global warming.[a] The panel stated that "most of the warming observed over the last 50 years is attributable to human activities."[b]

The amount of CO_2 in the atmosphere is affected by natural processes and by human activity. Anthropogenic CO_2 emissions (emissions resulting from human activity, including combustion of fossil fuels and changes in land use, especially deforestation)[c], have been growing since the start of the industrial revolution (Fig. 1).[d] 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.[e] As a result, concentrations of CO_2 in the atmosphere have increased, from preindustrial levels of about 280 parts per million (ppm) to about 370 ppm today (Fig. 2).[f] Increases in the concentrations of greenhouse gases reduce the efficiency with which the Earth's surface radiates energy to space. This results in a positive radiative forcing that tends to warm the lower atmosphere and surface.[g] As shown in Fig. 3, global average surface temperatures have increased since the start of the industrial revolution.[h]

[a] pp. 5–7, e.g.: "Concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities"

[b] p. 10.

[c] p. 5: "Changes in climate occur as a result of both internal variability within the climate system and external factors (both natural and anthropogenic)." p. 7: "About three-quarters of the anthropogenic emissions of CO_2 to the atmosphere during the past 20 years is due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation." p. 12: "Emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century"

[d] p. 6: "All three records [concentrations of CO_2, CH_4, and N_2O] show effects of the large and increasing growth in anthropogenic emissions during the Industrial Era"

[e] p. 7: "Currently the ocean and the land together are taking up about half of the anthropogenic CO_2 emissions"

[f] p. 39: "The atmospheric concentration of CO_2 has increased from 280 ppm in 1750 to 367 ppm in 1999"

[g] p. 5: "A positive radiative forcing, such as that produced by increasing concentrations of greenhouse gases, tends to warm the surface." p. 5, note 8: "*Radiative forcing* is a measure of the influence 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"

[h] p. 2, "The global average surface temperature (the average of near surface air temperature over land, and sea surface temperature) has increased since 1861." Also, p. 3, Fig. 1a,b.

mean temperature given the CO_2 scenario and to provide a brief written explanation for their responses (Table 2). We implemented the full factorial design (2 CO_2 scenarios × 3 response modes), with subjects assigned randomly to each.

2.2 Subjects

Subjects were students in a management elective at MIT, including MBA students (63%), graduate candidates in other programs (35%) and undergraduates (2%). Reflecting the student body at MIT, the subject pool was highly educated, particularly in technical fields. Three-fifths were trained in engineering, science, or mathematics; most others were trained in the social sciences, primarily economics. Only 3% reported undergraduate degrees in the humanities. Over 30% held a prior graduate degree (70% in engineering, science, mathematics, or medicine, 26% in economics or social science, and the remainder in the humanities). Mean age was 30 ($\sigma = 5$, range 20–56). Subjects carried out the task in class

Table 2 The multiple choice (MC) condition. In the MC condition, subjects select one of the options below to describe the trajectory of emissions required to achieve the CO_2 scenario they received instead of the graph shown in Fig. 1B,C. All subjects also received the question below regarding mean global temperature (in MC format) and were asked to provide a written explanation for their CO_2 and temperature trajectories

1. For this to occur, CO_2 emissions resulting from human activity would have to:
    - Continue to rise through the year 2100.
    - Gradually rise about 8% and then stabilize by the year 2100.
    - Gradually rise less than 8% and then stabilize by the year 2100.
    - Stabilize now at current rates.
    - Gradually fall about 8% and then stabilize by the year 2100.
    - Gradually fall more than 8% and then stabilize by the year 2100.
    - Immediately drop more than 8% and then stabilize by the year 2100.
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*):

Table 3 Distribution of subjects among experimental conditions

	CO_2 scenario					
	400 ppm		340 ppm		Total	
Response mode	(*N*)	(%)	(*N*)	(%)	(*N*)	(%)
MC	38	17.9	35	16.5	73	34.4
EG	34	16.0	35	16.5	69	32.5
ER	37	17.5	33	15.6	70	33.0
Total	109	51.4	103	48.6	212	100.0

and were given approximately ten minutes; many finished earlier. The subjects were informed that the exercise illustrated important concepts they were about to study and would be used anonymously in this research. Subjects were informed that participation was voluntary and that the results would not be graded. The response rate exceeded 90%, yielding $N = 212$ usable responses, approximately balanced among the six cells of the design (Table 3).

2.3 Mass balance vs. pattern matching

Subjects do not need training in climatology or calculus to respond correctly. The dynamics can be understood using a bathtub analogy in which the water level represents the stock of atmospheric CO_2. Like any stock, atmospheric CO_2 rises only when the inflow to the tub (emissions, E) exceeds the outflow (net removal, R), is unchanging only when inflow equals outflow ($E = R$) and falls only when outflow exceeds inflow ($R > E$). Subjects should be able to use these basic stock-flow relationships and the task description to constrain possible emissions trajectories. The description (Fig. 1A) informs subjects that anthropogenic CO_2 emissions are now roughly double net removal, so the level of water in the tub is rising. Given an estimate of future removal, the emission path required to achieve the specified scenario for atmospheric CO_2 is readily determined. In the 400 ppm case, CO_2 increases at a diminishing rate after 2000. Unless subjects believe net removal will at least double, emissions must peak near the present time (the inflection point in atmospheric CO_2) and fall below current rates to reach removal by 2100. In the 340 ppm case, atmospheric CO_2 peaks near the present time, then gradually falls. Emissions must immediately fall below removal, then gradually approach removal from below. In contrast, pattern matching incorrectly suggests emissions will be correlated with atmospheric CO_2, gradually rising above current rates when CO_2 rises to 400 ppm and gradually falling when CO_2 falls to 340 ppm.

3 Results

3.1 Emissions

To respond correctly subjects must first estimate future net CO_2 removal. Studies suggest net removal is likely to fall (Houghton et al. 2001; Cox et al. 2000; Sarmiento et al. 1998) as terrestrial and oceanic carbon sinks fill (Casperson et al. 2000; House et al. 2002), as the partial pressure of CO_2 in the mixed layer of the ocean rises (Oeschgar et al. 1975; Sarmiento et al. 1995), or if climate change enhances carbon release from boreal forests, tundra, the tropics, and other biomes (White et al. 2000; Betts 2000; Goulden et al. 1998; Milyukova et al. 2002; Malhi et al. 2002; Page et al. 2002; Gill et al. 2002). In the long run (after 2100), stabilizing atmospheric CO_2 requires emissions “to decline to a very small fraction of current emissions” determined by persistent carbon sinks such as peat formation and rock weathering (Houghton et al. 2001, p. 12). Not surprisingly, subjects’ knowledge of these biogeochemical processes is limited. Few believe net removal will fall. Some assume removal remains constant, a belief that reduces the cognitive effort required to determine emissions. Some believe removal is roughly proportional to atmospheric CO_2 (through CO_2 fertilization). In the Emissions and Removal (ER) condition 72% show net removal rising by 2100 and 31% show it more than doubling. Such beliefs grossly overestimate current models of natural uptake and potential rates of carbon capture and sequestration (Herzog et al. 2003; Chisholm et al. 2001; Buesseler and Boyd 2003; Jean-Baptiste and Ducroux 2003; Buesseler et al. 2004; Scott et al. 2004). Subjects’ estimates of removal suggest a need for public education about the basics of the carbon cycle, consistent with studies showing low awareness of basic climate structure and carbon sequestration (Kempton 1997; Kasemir et al. 2000; Palmgren et al. 2004).

Our focus, however, is not whether people understand the processes governing CO_2 removal but whether they can describe an emissions path consistent with CO_2 stabilization *given* their estimated removal path. If people do not understand the fundamental mass balance principle that stabilizing GHG concentrations requires emissions equal net removal, providing them with better information on future removal will do little to alter the belief that stabilizing emissions would quickly stabilize the climate.

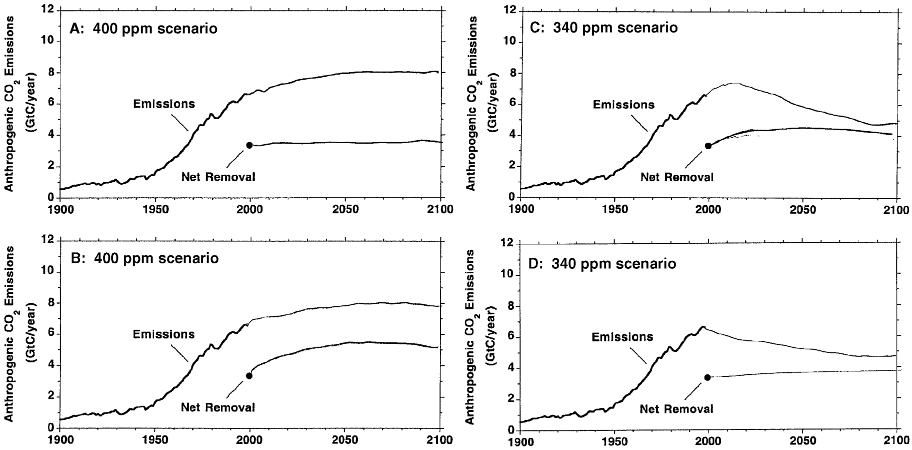


Fig. 2 Typical responses, illustrating pattern matching. (A, B): 400 ppm case. Note that both subjects select emissions $E \gg$ net removal R in 2100, though atmospheric CO_2 is unchanging by 2100, which requires $E = R$. (C, D): 340 ppm case. Note that the subjects select emissions paths such that $E > R$ throughout, though declining atmospheric CO_2 requires $E < R$. In all four cases subjects chose emissions paths that match the atmospheric CO_2 path in the scenario.

Results show evidence of pattern matching in all response formats. To illustrate, Fig. 2 shows typical responses in the ER condition in which subjects draw both emissions and removal. Panels A and B show two subjects who faced the 400 ppm condition. Both subjects draw emissions patterns that match the path of atmospheric CO_2 – a gradual rise to stabilization above current rates. Further, both subjects show emissions exceed net removal at all times. Instead of stabilizing by 2100, atmospheric CO_2 would continue to rise. Indeed, the gap between the subjects' estimates of emissions and removal is near a maximum in 2100, when it must be zero to stabilize atmospheric CO_2. Panels C and D show typical responses in the 340 ppm case. Both subjects draw emissions paths that match the pattern of gradual decline in atmospheric CO_2. Both subjects show emissions exceeding removal throughout. Instead of falling, as specified in the scenario, atmospheric CO_2 would rise at a diminishing rate. All four subjects violate mass balance requirements.

Subjects' emissions estimates generally followed the path of atmospheric CO_2 (Fig. 3, Table 4). In the Emissions and Removal condition, emissions in the 400 ppm scenario rise to a mean of 8.0 GtC/year by 2100 and fall to a mean of 5.9 GtC/year in the 340 ppm case, a significant difference ($t = 2.40$, $p = 0.019$). In the Emissions Graph condition, mean emissions in 2100 were 6.5 GtC/yr in the 400 ppm scenario, significantly higher than the mean of 4.6 GtC/yr in the 340 ppm case ($t = 2.32$, $p = 0.024$). In the Multiple Choice condition, only 46% conclude that emissions must fall by more than 8% to stabilize CO_2 at 400 ppm, while 71% select a drop of more than 8% in the 340 ppm case. Across all three response formats, 58% incorrectly believe emissions can rise above current rates (or remain constant) when atmospheric CO_2 rises to equilibrium at 400 ppm, while 78% believe emissions fall when CO_2 falls to 340 ppm. The differences between the 400 and 340 ppm scenarios are significant in all three formats ($p = 0.0003$, $p = 0.004$, $p = 0.02$ for MC, EG, and ER, respectively). There are no significant differences among the three formats, suggesting the results are robust to the response mode (the hypothesis that the response frequencies in the three formats are equal cannot be rejected, $\chi^2(2) = 3.53$, $p = 0.17$, and $\chi^2(2) = 5.15$, $p = 0.08$, for the 400 and 340 ppm scenarios, respectively).

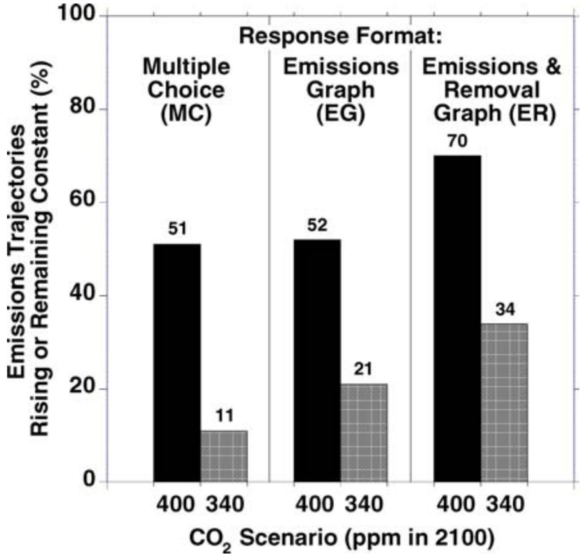
Table 4 Results for CO_2 emissions. (A) MC condition. (B) Responses indicating emissions would rise/remain constant vs. falling by 2100. The number rising/remaining constant is the sum of the first four responses in the MC conditions, and the number with final emissions values ≥ 6.5 GtC/year in the EG/ER conditions. Response frequencies for 340 vs. 400 ppm scenarios are significantly different in all response modes (p-values from the Fisher exact test). Excludes five subjects not responding/giving ambiguous answers. The hypothesis that response frequencies across MC, EG, and ER are equal cannot be rejected: 400 ppm case, $\chi^2(2) = 3.53$, $p = 0.17$; 340 ppm case, $\chi^2(2) = 5.15$, $p = 0.08$.

	CO_2 scenario			
	400		340	
	N	%	*N*	%
A. CO_2 Emissions would have to…				
1 Continue to rise through the year 2100	3	8	0	0
2 Gradually rise about 8% and then stabilize by the year 2100	6	16	0	0
3 Gradually rise less than 8% and then stabilize by the year 2100	7	19	2	6
4 Stabilize now at current rates	3	8	2	6
5 Gradually fall about 8% and then stabilize by the year 2100	1	3	6	17
6 Gradually fall more than 8% and then stabilize by the year 2100	6	16	12	34
7 Immediately drop more than 8% and then stabilize by the year 2100	11	30	13	37
Total	37		35	

B. Response mode

	Multiple choice				Emissions graph				Emissions and removal graph			
CO_2 Scenario (ppm):	400		340		400		340		400		340	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
CO_2 Emissions in 2100:												
Rise or remain constant	19	51	4	11	17	52	7	21	26	70	11	34
Fall	18	49	31	89	16	48	26	79	11	30	21	66
H_0: 400 ppm = 340 ppm; By response mode	$p = 0.0003$				$p = 0.004$				$p = 0.02$			
Total, all responses					$p = 1.3 \times 10^{-7}$							

Fig. 3 Results. Responses indicating emissions would rise (or remain constant) vs. falling by 2100, by response format and CO_2 scenario. The majority exhibit pattern matching: subjects project emissions should rise to stabilize atmospheric CO_2 when CO_2 concentrations rise, and fall when CO_2 concentrations fall. The differences between the two CO_2 scenarios are significant in all response modes (Fisher exact test; $p = 0.0003$, $p = 0.004$, $p = 0.02$ for MC, EG, and ER, respectively). Differences in response frequencies across response formats are not significant.



3.2 Violations of mass balance

While consistent with pattern matching, the results of the MC and EG conditions do not necessarily indicate that subjects violated mass balance principles. Atmospheric CO_2 could stabilize even if emissions grow, provided removal more than doubles, so emissions equal net removal by 2100. The ER condition, however, enables direct assessment of stock-flow consistency because subjects specify both emissions and removal. We judged emissions and removal trajectories to be consistent with mass balance principles if $E > R$ when atmospheric CO_2 is rising (as in the first part of the 400 ppm scenario); $E < R$ when atmospheric CO_2 is falling (as in the first part of the 340 ppm scenario); and $E \approx R$ when atmospheric CO_2 is unchanging (as at the end of both scenarios). Note that these criteria judge only the qualitative conformance to mass balance and judge only the first-order conditions (we did not penalize subjects for failure to capture the rate of change in net emissions $E - R$ implied by their CO_2 scenario). Further, we considered a subject's estimates of E and R in the year 2100 to be different only if the gap between them exceeded 0.5 GtC/year. Such a large tolerance is an *a fortiori* procedure: we assume subjects whose estimates of E and R in 2100 differed by up to 0.5 GtC/year nevertheless correctly understand that CO_2 stabilization requires $E = R$.

Despite these generous criteria, fully 84% drew trajectories violating mass balance requirements (Table 5). Three-fourths violate the equilibrium condition that CO_2 stabilization requires emissions equal removal. A large majority, 63%, assert atmospheric CO_2 can be stabilized while emissions into the atmosphere exceed removal from it. These violations of the equilibrium condition are large, averaging 2.8 GtC/year (compared to year 2000 emissions of about 6.5 GtC/year).

3.3 Global mean temperature

Subjects' temperature responses similarly show evidence of pattern matching (Table 6). The temperature trajectory under the two scenarios is unknown, but subjects should be able to use stock-flow principles, energy conservation, and the information provided to constrain the

Table 5 Conformance to conservation of matter

	(1)	(2)		(3)		(4)		(5)	
		Final net emissions $E_{\text{net}} = E - R$						Stock/flow consistency?	
	Mean absolute final net emissions,	$E_{\text{net}} > \delta$		$E_{\text{net}} = 0 \pm \delta$		$E_{\text{net}} < -\delta$			
CO_2 in 2100 (ppm)	$\lvert E - R \rvert$ (GtC/yr)	*N*	%	*N*	%	*N*	%	*N*	%
400	2.9	22	63	11	31	2	6	9	26
340	2.7	20	63	6	19	6	19	2	6
Total	2.8	42	63	17	25	8	12	11	16

Net emissions $E_{\text{net}}=E - R$ should be zero in 2100 when CO_2 concentrations are stable. Column 1: the mean absolute difference between subjects' final emissions and removal estimates. Columns 2–4: the fraction of final net emissions above, below and approximately equal to zero. Emissions and removal values were judged to be different only if they differed by more than a tolerance of $\pm\delta = 0.5$ GtC/yr, so that subjects intending their E and R curves to be equal but who drew curves differing by small amounts are considered equal, an *a fortiori* assumption. Column 5: the fraction of responses consistent with conservation of matter. Trajectories were judged consistent if $E > R$ when d[CO2]/dt > 0 (the first part of the 400 ppm scenario); $E < R$ when d[CO2]/dt < 0 (the first part of the 340 ppm scenario); and $E \approx R$ when d[CO2]/dt≈0 (at the end of both scenarios).

possibilities. The description provided to subjects (Fig. 1A) indicates that atmospheric CO_2 concentration has risen from preindustrial levels of about 280 to 370 ppm, causing a "positive radiative forcing that tends to warm the lower atmosphere and surface." In the scenario where CO_2 rises to 400 ppm, subjects can reasonably conclude that forcing would remain positive and temperature would continue to rise. In the case where CO_2 falls to 340 ppm, net forcing would fall but likely remain positive since the CO_2 concentration remains well above the preindustrial level when anthropogenic forcing was roughly zero. Subjects should conclude that warming would continue, though perhaps at a diminishing rate. Subjects can exclude temperature declines below current levels since temperature reduction would require negative net forcing. Hence pattern matching and energy balance both suggest continued warming when CO_2 rises to 400 ppm, but when CO_2 falls to 340 ppm, pattern matching incorrectly predicts temperature decline.[4]

As expected, 92% receiving the 400 ppm scenario predict mean global temperature in 2100 will rise or stay constant: pattern matching and conservation principles yield the same result when CO_2 continues to grow. However, only half judge that temperature in 2100 would exceed current levels when CO_2 falls to 340 ppm; the difference is significant, as are the differences between CO_2 scenarios within individual response formats (differences across the response formats were not significant). Shockingly, 13% of those in the 340 ppm scenario

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[4] Sophisticated subjects may reason that temperature will eventually stabilize at higher CO_2 levels when temperature has risen enough for the earth's black body radiation to once again balance insolation (that is, they may recognize the negative feedback between temperature and net radiative forcing). Such reasoning, however, would not support responses indicating temperature decline below current levels. IPCC TAR simulations of stabilization scenarios from 450 to 1000 ppm show equilibrium occurs well after 2100: stabilization at 450 ppm yields $\Delta T \approx 1.8\,^{\circ}\mathrm{C}$ above current levels by 2100, growing to $\Delta T \approx 2.2\,^{\circ}\mathrm{C}$ by 2350. Stabilization at 500 ppm yields $\Delta T \approx 2.1\,^{\circ}\mathrm{C}$ by 2100 and 2.8 °C by 2350. Extrapolating assuming response linearity (approximately exhibited by the TAR simulations between 450 and 1000 ppm), yields $\Delta T \approx 1.5\,^{\circ}\mathrm{C}$ by 2100 for stabilization at 400 ppm; extrapolating further to 340 ppm yields $\Delta T \approx 1.1\,^{\circ}\mathrm{C}$ by 2100, though the validity of such extrapolation is unknown. Simulations in Wigley (2005) and Meehl et al. (2005) show similar climate inertia for scenarios with stabilization at year 2000 levels.

Table 6 Results for temperature trajectory

(1) Response format	(2) Temp choice	(3) 400 ppm	(4) 340 ppm	(5) Temp choice	(6) 400 ppm	(7) 340 ppm	(8) H_0:400 = 300 ppm?
MC	1	9	5	Rise or stay constant	36	15	$p = 1.3 \times 10^{-6}$
	2	17	1				
	3	8	8				
	4	2	1				
	5	2	12	Fall	2	20	
	6	0	4				
	7	0	4				
EG	1	11	12	Rise or stay constant	29	20	$p = 0.016$
	2	11	4				
	3	6	3				
	4	1	1				
	5	4	9	Fall	5	15	
	6	0	3				
	7	1	3				
ER	1	14	10	Rise or stay constant	35	18	$p = 0.00037$
	2	17	3				
	3	4	5				
	4	0	1				
	5	0	3	Fall	2	15	
	6	1	5				
	7	1	6				
Total	1	34	27	Rise or stay constant	100	53	$p = 2.7 \times 10^{-11}$
	2	45	8				
	3	18	16				
	4	3	3				
	5	6	24	Fall	9	50	
	6	1	12				
	7	2	13				

Columns 1–4 show subject responses by CO_2 scenario and response format. Temperature choices as in Table 2: 1. Continue to rise through the year 2100; 2. Continue to rise, then stabilize by the year 2100; 3. Rise for a few more years, then peak, gradually fall and stabilize above current levels; 4. Stabilize now at current levels; 5. Rise for a few more years, then peak, gradually fall and stabilize below current levels; 6. Rise for a few more years, then peak and continue to fall through the year 2100; 7. Immediately drop, then stabilize by the year 2100 below current levels. Columns 5–7 aggregate responses into those selecting temperature trajectories that rise or stay constant (sum of responses 1–4) vs. those selecting a drop in temperature by 2100 (sum of responses 5–7). Column 8 shows p-values for the 2-tailed Fisher exact test with null hypothesis that response frequencies in the two CO_2 scenarios are equal. Differences across response formats were not significant. Results robust to inclusion of item 4 (temperature would stabilize now) with items 5–7 vs. 1–3.

assert that a peak in atmospheric CO_2 would cause temperature to drop below current levels immediately.

3.4 Coding of written comments

We coded subject's written explanations for evidence of stock-flow reasoning and use of mass and energy conservation principles compared to pattern matching. Table 7 shows definitions and coding criteria for each concept, examples, and the number and proportion of written responses coded as including each concept. Individual written explanations can be coded positively for multiple concepts. For example, subjects may use mass balance principles to describe their emissions trajectory and pattern matching to explain their temperature choice. The proportions mentioning each concept are relative to 198 subjects providing a written explanation. The absence of a concept in an explanation does not necessarily indicate the subject is unaware of the concept, hence the relative frequencies among mentioned concepts are more relevant than their raw proportion in the sample.

We considered a response to mention a concept even if the explanation was incorrect, incomplete, or ambiguous. For example,

> "We're still putting out more CO_2 than we are absorbing, even after the stabilize level [sic]. Therefore, it will continue to rise"

codes for awareness of mass balance because it mentions the relation between the inflow to atmospheric CO_2 and the outflow, though the subject (a native English speaker with a BS in engineering) apparently asserts that emissions continue to exceed removal even after atmospheric CO_2 stabilizes. Similarly, the following codes positively for recognition of energy conservation, despite its vagueness, because the subject suggests that heat accumulates:

> "Well it is not the amount of CO_2 that causes the rise but more trapped heat, so heat continues to be collected."

Despite these generous criteria, only 25% indicate awareness of mass balance and only 6% mention energy balance considerations, including those whose descriptions were incomplete or incorrect. In contrast, 35% explicitly indicate use of pattern matching, e.g., "Concentrations of CO_2, CO_2 emissions, and temperature seem to move together" and "atmospheric CO_2 seems to be fairly proportional to the anthropogenic CO_2 emissions. Since the atmospheric levels seem to level off, it seems to imply that the emissions do the same." Pattern matching is indicated 1.4 times more than mass balance concepts and 5.8 times more than energy balance concepts (the differences are highly significant (Fisher exact test, $p < 0.025$ for mass balance and $p \approx 0.00$ for energy conservation).

We also coded for awareness that climate responds to emissions with lags. However, mention of delays alone does not indicate understanding of stock-flow concepts in general; their instantiation in climate change, nor how long the resulting delays will be. Mentioning delays does not indicate awareness of key stock-flow relationships, e.g., that atmospheric CO_2 continues to rise even as emissions fall, as long as emissions exceed removal. Thus mention of lags is a much weaker indication of understanding of relevant physical principles than comments indicating awareness of mass or energy balance. Nevertheless, pattern matching is mentioned 1.15 times more than delays. Many subjects combine pattern matching with lags, for example:

> "For a starter, there is a relationship between CO_2 concentration and the surface temperature. Therefore, if the CO_2 concentration falls, the temperature will fall accordingly.

Table 7 Coding of written explanations

Concept/coding criteria	Examples	*N*	%
Mass balance			
Description indicating awareness of relationship between emissions and removal flows and the stock of atmospheric CO_2; terms such as mass balance, accumulation, rate of change, etc., whether explanation is correct or complete.	"As long as the emissions are higher then the consumption of CO_2 by other mechanisms, then CO_2 concentration will continue to rise…" "Currently net removal = 1/2 anthropogenic CO_2 emissions. Therefore, unless the emissions drop by 1/2, the atmospheric CO_2 concentrations continue to increase above 370 ppm (current). For this to fall, the emissions have to drop by >50% so that net removal > net emissions. In this way, CO_2 concentration would fall and ultimately (with lag) the temp aver. would fall." "You need to emit less than half to make it [CO_2 concentration] drop."	50	25.3
Energy balance			
Description indicating awareness of energy conservation or surface energy budget, that global mean surface temperature integrates net radiative forcing, or that warming depends on level of atmospheric CO_2, whether explanation is correct or complete.	"Insolation still high – temp. builds even though insolation is not growing." "I guess that the accumulation of CO_2 is already so much that the increasing heat overwhelms the out going heat in quantity. [Temperature will continue to rise through 2100] "Because with the concentration of gases above equilibrium, the system will keep warming." "Since atmospheric CO_2 remains high, temperatures will continue to rise unless there is a decrease in atmospheric CO_2."	12	6.1
Pattern matching			
Description mentioning correlations or similarity of behavior or patterns among emissions, atmospheric CO_2, and/or temperature; indication that emissions or temperature change should be proportional to changes in atmospheric CO_2 (perhaps with lags).	"From the earlier scenario, the atmospheric CO_2 seems to be fairly proportional to the anthropogenic CO_2 emissions. Since the atmospheric levels seem to level off, it seems to imply that the emissions do the same."	69	34.8

(*Continued on next page*)

> However, I guess there is a time lag between the fall of CO_2 concentration and the fall of the temperature. Maybe a couple of years…."

Typically, the subject severely underestimates the length of the lag between changes in CO_2 concentrations and changes in global mean temperature.

Table 7 (*Continued...*)

Concept/coding criteria	Examples	*N*	%
	"From Fig.1 it appears that CO_2 emissions are directly correlated to atmospheric CO_2. Therefore, I expect CO_2 emissions to behave similarly to atmospheric CO_2. Same goes for temp. If there is a delay in this system, my answer would be different." "Temperature correlates to changes in CO_2 concentration."		
Inertia/Delays			
Mention of delays in response of system to changes in emissions, atmospheric CO_2, or temperature; terms such as 'delay', 'lag', 'inertia' etc.	"(1) The rise in atmospheric CO_2 concentration seems to lag somewhat the increase in anthropogenic CO_2 emissions. Therefore in order to stabilize CO_2 concentration by 2100, I think the level of emissions has to stabilize before then. (2) [temperature] just a guess (some lag effect)." "...There is a delay between level of CO_2 and temperature." "Lag in effect of rise in emissions, and the impact on global temperature."	60	30.3
CO_2 fertilization			
Mention of possibility that removal may rise due to enhanced plant growth, other effects of higher atmospheric CO_2 or higher temperatures.	"The temperature increases due to concentration of CO_2, therefore increases natural removal of CO_2...." "(1) More CO_2 than before → more nutrients to flourish → more fluids → less CO_2 in the future (plants have time to react and man don't [sic] cut trees)...." "Removal likely to go up as temp. goes up, plant life amount goes up as temp goes up...."	3	1.5
Sink saturation			
Mention of possibility that removal may fall due to C sink saturation, e.g. deforestation, ocean saturation, C discharge stimulated by higher temperatures, etc.	"Emissions need to fall at rate faster than observed decrease because other factors such as destruction of plant life may decrease the rate at which CO_2 removed from atmosphere." "(2) The greenhouse effect will amplify as CO_2 levels increase...." "Removal of CO_2 by plant life/oceans will decrease due to deforestation and ocean processes."	15	7.6

(*Continued on next page*)

Table 7 (*Continued*)

Concept/Coding Criteria	Examples	*N*	%
Technology			
Indicates belief that technology will enable emissions reductions (e.g. alternative energy sources) or enhance removal (e.g. anthropogenic C capture and sequestration).	"Industries will try to reduce CO_2 emissions...." "If we maintain and aid net removal and reduce emissions the concentration will fall as the graph suggests...." "As removal techniques improve, efforts to restrict CO_2 emissions will fail...." "Technology can only get better. However, possibly by 2100 we will reach an industrial plateau thus the emission will stabilize."	9	4.5

We also coded for mention of biogeochemical processes relevant to climate change. These include natural processes such as CO_2 fertilization and sink saturation that may enhance or reduce future removal, and technologies such as energy efficiency, alternative energy sources, or carbon capture and sequestration programs that may reduce emissions or enhance removal. Mention of these processes is low (1.5% for CO_2 fertilization, 7.6% for sink saturation, and 4.5% for technology), consistent with the hypothesis that subjects relied on pattern matching rather than attempting to reason from physical principles.

4 Discussion

Before discussing the implications we consider alternative explanations for the results. One possibility is that the subjects did not apply much effort because they were not graded on the results. Contrary to many people's intuition, research shows that incentives in judgment and decision-making tasks do not always improve performance, and can sometimes worsen it (Camerer and Hogarth 1999). Explanations for weak or negative effects of incentives include stress and anxiety induced by larger stakes, and failure to explore the space of possibilities when search is costly or time consuming. Whether payment or incentives would alter the results here remains an issue for future research. Note, however, that members of the public are neither graded nor paid based on their understanding of the climate. There is little incentive for people to learn about climate change other than intrinsic interest or a sense of civic responsibility.

Another possibility is that the task presented to subjects may bias them towards use of pattern matching. The description includes graphs showing the evolution of anthropogenic emissions, atmospheric CO_2, and global mean temperature from 1850 through 2000 (Fig. 1A). All three variables rise over this time horizon, and the correlations among them may induce people to use pattern-matching rather than stock-flow reasoning. The information provided in the description is typical of many presentations on climate change. Both scientific reports and popularized accounts, including the IPCC Summary for Policymakers, commonly include graphs of emissions, GHG concentrations, and temperature changes, often over even longer time horizons (e.g., the proxy records from the Vostok and Dome C ice cores).

Table 8 Impact of exposure to graphs of historic data on pattern matching and conformance with mass balance principles. An additional 68 subjects were presented with the ER condition, but with the graphs of historic emissions, CO_2 concentration, and global mean temperature shown in Fig. 1A deleted. Compare to Table 5. Note that 14 subjects did not provide estimates of both emissions and removal, yielding 54 useable responses.

	(1)	(2)		(3)		(4)		(5)	
		Final net emissions $E_{\text{net}}=E-R$						Stock/flow consistency?	
	Mean absolute final net emissions, $\lvert E-R \rvert$ (GtC/yr)	$E_{\text{net}}>\delta$		$E_{\text{net}}=0\pm\delta$		$E_{\text{net}}<-\delta$			
CO_2 in 2100 (ppm)		N	%	N	%	N	%	N	%
400	5.1	20	80	2	8	3	12	2	8
340	2.9	22	76	2	7	5	17	0	0
Total	3.9	42	78	4	7	8	15	2	4

Nevertheless, it is possible that the graphical presentation of the historic data predisposes people to use pattern matching instead of stock-flow reasoning. We tested this possibility by creating a version of the task in which we deleted the graphs shown in Fig. 1A, along with reference to them in the description. All other aspects of the task remained unchanged. We administered the modified task to sample of 68 mid-career managers enrolled in a full-time executive MBA program at the MIT Sloan School of Management. The participants had more business experience than most in the original dataset, but otherwise were demographically similar. The protocol for the task was the same (voluntary participation, in-class administration with 10 min allowed, random assignment to the 400 or 340 ppm scenario). We used the Emissions and Removal condition since it allows direct assessment of subjects' conformance to conservation of mass. Results show strong evidence of pattern matching and widespread violations of conservation principles (Table 8). Absolute net emissions, $|E-R|$, which must be zero in 2100 in both scenarios, averaged 5.1 GtC/year in the 400 ppm case and 2.9 GtC/year in the 340 ppm case, a significant difference ($p = 0.01$). Fully 96% violated conservation of mass, and 93% fail to conform to the equilibrium condition that $E = R$ when atmospheric CO_2 is constant. As in the original sample, the large majority, 78%, assert that atmospheric CO_2 can be stabilized while emissions continuously exceed removal. We hypothesize that the pattern matching heuristic is so commonly used, and knowledge of stock-flow relationships is so weak, that graphical presentation of the data is not needed to trigger it.

Performance might also improve if subjects were given more time or more extensive data and background on climate dynamics. The information provided to subjects was drawn from the IPCC's Summary for Policymakers, a document intended for nonscientists. The description explicitly cites the rate at which natural processes remove CO_2 from the atmosphere, providing cues designed to increase the salience of the stock-flow relationship between emissions and atmospheric CO_2 levels. Few used this information effectively – only one quarter of subjects' written descriptions mention mass balance. The large majority either ignored the stock-flow cues in the task description or used that information incorrectly. Most relied on pattern matching, with 58% incorrectly asserting emissions can rise above current rates when atmospheric CO_2 rises to 400 ppm, and 78% asserting emissions will fall when atmospheric CO_2 falls. Pattern matching leads people to violate fundamental conservation laws: only 16% provide emissions and removal trajectories consistent with mass balance requirements.

We hypothesize that typical media reports and other information conditioning public views of climate change (e.g., through television, the internet, and print media) are less demanding of attention and effort than the experimental context here. Most information available to the public does not describe the relevant data or stock-flow structures. The data presentation, time available, and setting in our experiment favor good performance compared to the naturalistic context in which people are exposed to information on climate change. Further, the subjects were highly educated compared to the general public, particularly in science and mathematics.

An evolutionary perspective may shed light on why pattern matching dominates stock-flow reasoning. Decision-making consumes scarce time and cognitive resources. Selection pressures favor the evolution of "fast and frugal" heuristics that "are successful to the degree they are ecologically rational, that is, adapted to the structure of the information in the environment in which they are used..." (Gigerenzer et al. 1999; vii; Payne et al. 1993 document many examples and review the extensive literature). The overwhelming majority of everyday experience involves simple systems where cause and effect are closely related in time and space, time delays are short, and information cues are highly correlated. The water in the teakettle boils and the whistle sounds; eating certain mushrooms is quickly followed by illness. The ability to detect correlations among cues in the environment is highly rewarded, and people's judgments about causal relationships are strongly conditioned by proximity and covariation (Einhorn and Hogarth 1986).

In contrast, it is not necessary to understand stocks and flows to fill a bathtub – the water accumulates "automatically." It is far more efficient to watch the water in the tub and shut off the tap when it reaches the desired level – a simple, effectively first-order negative feedback process. For a wide range of everyday tasks, people have no need to infer how flows relate to stocks – it is better to simply wait and see how the state of the system changes, and then take corrective action. Wait-and-see is therefore a valuable heuristic in common tasks with low dynamic complexity, where delays are short, outcome feedback is unambiguous and timely, opportunities for corrective action are frequent, and the costs of error are small (Hogarth 1981). None of these conditions hold in dynamically complex systems like the climate, where there are multiple positive and negative feedbacks, delays between actions and impacts are long, outcome feedback is ambiguous and delayed, many actions have irreversible consequences, and the costs of error are potentially large.

Some in the scientific community may argue that poor public understanding of climate dynamics is unimportant because climate change policy should be informed by scientific expertise. Policymakers should use the best available scientific understanding to determine the optimal response to the risks of climate change, given societal goals. However, reducing GHG emissions enough to stabilize atmospheric GHG concentrations requires changes in technology, energy prices, business practices, consumer behavior, and other activities affecting people's daily lives. When people do not understand the basis for proposed policies, when the best available science conflicts with "common sense" suggested by existing mental models, they are unlikely to adopt appropriate policies or generate political support for legislation to implement them (Bostrom et al. 1994; Read et al. 1994; Morgan et al. 2002). For example, the benefits of seat belts, motorcycle helmets, and childhood vaccinations are well supported by scientific evidence, yet legislation mandating their use took decades. Citizen groups campaign actively against many of these policies, and compliance remains spotty (e.g., US Freedom Foundation 2005; Jansen et al. 2003; Feudtner and Marcuse 2001). The connection between actions and outcomes in these cases is far simpler than the connection between GHG emissions and climate change.

When policy implementation depends on widespread citizen understanding and behavior change, risk communication is as important as risk assessment (Morgan et al. 2002; Slovic

2000). There are implications for education, for risk communication about climate change, and for the policy process.

4.1 Education

Perhaps people understand stock-flow relationships but are unable to apply their knowledge to climate change due to inadequate background knowledge of climate and GHGs. If true, education about the sources of GHGs, the biogeochemical cycles that regulate them, and their role in radiative forcing would overcome the problems observed here. Studies provide ample evidence that members of the general public are ill-informed about science in general, and climate change in particular (Kempton 1997; Sturgis and Allum 2004). Researchers documenting such deficits call for greater education (e.g., Bord et al. 2000). While surely needed, such education is not sufficient. Prior research shows pattern matching and violations of conservation principles are prevalent in much simpler contexts requiring no specialized background knowledge, for example, filling a bathtub. Booth Sweeney and Sterman (2000) presented subjects from the same elite university population with a picture of a bathtub and graphs showing the inflow to and outflow from the tub. Extremely simple patterns for the inflow and outflow were used, for example, a constant outflow and piecewise linear change in the inflow (a sawtooth pattern). More than half violate the most basic stock-flow relationships, for example, failing to show that the water level rises when inflow exceeds outflow, and falls when outflow exceeds inflow. Better information on climate or the carbon cycle is unlikely to overcome weak knowledge of stocks and flows and consequent violations of conservation laws in intuitive assessments of policies to address climate change.

Pattern matching and violation of conservation principles lead people to underestimate the emissions reductions required to stabilize atmospheric GHG concentrations and reduce net radiative forcing. These flawed mental models support the belief that it is best to wait and see if further warming will be harmful before supporting action. The subjects in our experiment may sincerely believe that wait-and-see policies are a prudent response to the risks, though such policies ensure that climate change would continue long after emissions reductions are undertaken. Misconceptions of stocks and flows may be an important part of the explanation for the contradiction between the public's avowed desire to limit climate change while simultaneously arguing for wait-and-see policies that ensure the anthropogenic contribution to climate change continues to grow. The pervasive violation of these physical principles stands in contrast to the common explanation that people oppose stronger actions to cut emissions because they are short-sighted and self-interested, discounting the future at high rates. Rather, people may simply, but erroneously, believe that stabilizing emissions quickly stabilizes the climate.

4.2 Communication and the policy process

It would be naïve to suggest that educating the public about stocks and flows would somehow cause people to suddenly support emissions reductions consistent with their avowed desire to limit the risks of harmful climate change. Successful implementation of policies based on the best available science is a process of knowledge diffusion and social change, a process involving word of mouth, imitation of trusted authority figures and respected elites, media influence, and emotions, not only rational judgments of costs and benefits (Kempton 1993; Kempton et al. 1995; Kasemir et al. 2000; Slovic 2000; Stoll-Kleemann et al. 2001; Meijnders et al. 2001; Moser and Dilling 2004). Contextual factors such as people's social background, religious beliefs, and political orientation are, along with their education, important predictors of attitudes towards science and science policy issues (O'Connor et al. 2002; Sturgis and Allum 2004).

Adoption and diffusion are facilitated when innovations and new policies are simple, easy to test, have clear advantages over alternatives, and where costs and benefits are quickly and easily observed (Rogers 2003). Climate change ranks poorly on all these dimensions: it is complex, policies are difficult to test, and the benefits of emissions reductions are delayed and ambiguous. When people cannot readily assess costs and benefits for themselves, and when they are unable to interpret the best available scientific evidence, imitation of elite reference groups, word of mouth, media and marketing play stronger roles in opinion and behavior change. Are these sources of information reliable? Our results suggest that significant misperceptions of basic climate dynamics are prevalent even among highly educated adults. These individuals are demographically similar to influential leaders in business, government, and the media, though perhaps more highly trained in mathematics and science than most. Indeed, many of the subjects in our study will later take leadership roles in business and other institutions with significant potential impact on policy formation and adoption. Overcoming misperceptions of climate change and violations of conservation laws in the judgments of these potentially influential groups may have high leverage in catalyzing changes in public attitudes and behavior.

Effective risk communication strategies are tailored to suit the mental models of the audience, as Morgan et al. (2002, p. 19) pointedly argue:

> "Rather than conduct a systematic analysis of what the public believes and what information they need to make the decisions they face, communicators typically ask technical experts what they think people should be told.... Those passing judgment may know very little about either the knowledge or the needs of the intended audience. Under such conditions, it is not surprising that audiences often miss the point and become confused, annoyed, or disinterested. If the communicators feel that they have done everything that is expected of them, they may conclude that their audience was responsible for the communications failure."

Most scientific and popularized accounts of climate change, including the IPCC's Summary for Policymakers, do not present the fundamental stock-flow relationships among emissions, removal, GHG concentrations, radiative forcing, and temperature in ways the highly educated subjects here, much less the public at large, can understand. The language of the SPM and similar accounts is highly technical, requiring knowledge of terms such as CO_2, gigatons of carbon equivalents, ppm, radiative forcing, albedo, and so on. Overwhelmed by technical detail, people's mental models lead them to rely on pattern matching and correlations rather than stock-flow reasoning. Effective communication about climate change should help people understand these relationships in familiar terms. Pictures of stock-flow structures as bathtubs with tap and drain have proven effective in fostering greater understanding and policy change in a number of settings, from automobile leasing to the war on drugs (e.g., Sterman 2000, ch. 2.2, 6, 7). The prevalence of basic misconceptions about stocks and flows among the highly educated subjects we tested suggests the climatology community should consider similar representations in communications designed for both the public and policymakers. As an example, an interactive simulator to help people understand stocks and flows is available online, along with the questions used in this experiment (http://web.mit.edu/jsterman/www/GHG.html).

5 Conclusion

In democracies, public opinion constrains the ability of governments to implement policies consistent with the best available scientific knowledge. Successful implementation of policies to address problems such as climate change requires "broader public understanding of the need to limit carbon dioxide emissions ... and an approach to public communication, regulation, monitoring, and emergency response that is open and respectful of public concerns" (Palmgren et al. 2004, p. 6449).

We carried out experiments to assess whether highly educated adults understand basic processes affecting the climate, specifically, the relationship between atmospheric GHG concentrations and flows of greenhouse gases into and out of the atmosphere. Though the subjects, graduate students at MIT, were highly educated, particularly in mathematics and the sciences, results showed widespread misunderstanding of mass balance principles and the concept of accumulation. Instead, most subjects relied on pattern matching to judge climate dynamics. The belief that emissions, atmospheric CO_2, and temperature are correlated leads to the erroneous conclusion that a drop in emissions would soon cause a drop in CO_2 concentrations and mean global temperature. Mean surface temperature keeps rising as long as radiative forcing (minus net heat transfer to the deep ocean) is positive, even if atmospheric CO_2 – and hence net forcing – falls. Atmospheric CO_2 keeps rising even as emissions fall – as long as emissions exceed removal. Because emissions are now roughly double net removal, stabilizing emissions near current rates will lead to continued increases in atmospheric CO_2.

In contrast, most subjects believe atmospheric CO_2 can be stabilized by stabilizing emissions at or above current rates, and while emissions continuously exceed removal. Such beliefs – analogous to arguing a bathtub filled faster than it drains will never overflow – support wait-and-see policies, but violate basic laws of physics. People of good faith can debate the costs and benefits of policies to mitigate climate change, but policy should not be based on mental models that violate the most fundamental physical principles. The results suggest the scientific community should devote greater resources to developing public understanding of these principles to provide a sound basis for assessment of climate policy proposals.

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References

Alley R, Marotzke J, Nordhaus W, Overpeck J, Peteet D, Pielke R, Pierrehumbert R, Rhines P, Stocker T, Talley L, Wallace J (2003) Abrupt climate change. Science 299:2005–2010

Axelrod R (1976) The Structure of Decision: The Cognitive Maps of Political Elites. Princeton University Press, Princeton

Betts R (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408:187–190

Booth Sweeney L, Sterman JD (2000) Bathtub dynamics: initial results of a systems thinking inventory. Syst Dyn Rev 16(4):249–294

Bord R, O'Connor R, Fisher A (2000) In what sense does the public need to understand global climate change? Public Understanding Sci 9:205–218

Bostrom A, Morgan MG, Fischhoff B, Read D (1994) What do people know about global climate change? Part 1: Mental models. Risk Anal 14(6):959–970

Brechin S (2003) Comparative public opinion and knowledge on global climatic change and the kyoto protocol: The U.S. versus the World? Int J Sociol Soc Policy 23:106–134

Buesseler K, Andrews J, Pike S, Charette M (2004) The effects of iron fertilization on carbon sequestration in the southern ocean. Science 304:414–417

Buesseler K, Boyd P (2003) Will ocean fertilization work? Science 300:67–68

Camerer C, Hogarth R (1999) The effects of financial incentives in experiments: a review and capital-labor-production framework. J. Risk Uncertainty 19(1–3):7–42

Caspersen J, Pacala S, Jenkins J, Hurtt G, Moorcroft P, Birdsey R (2000) Contributions of land-use history to carbon accumulation in U.S. forests. Science 290:1148–1151

Chisholm S, Falkowski P, Cullen J (2001) Dis-crediting ocean fertilization. Science 294:309–310

Cox P, Betts R, Jones C, Spall S, Totterdell I (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408:184–187

Einhorn H, Hogarth R (1986) Judging probable cause. Psychol Bull 99(1):3–19

Feudtner C, Marcuse E (2001) Ethics and immunization policy: promoting dialogue to sustain consensus. Pediatrics 107(5):1158–1164

Fiddaman T (2002) Exploring policy options with a behavioral climate-economy model. Syst Dyn Rev 18(2):243–267

Gentner D, Stevens A (1983) Mental Models. Lawrence Erlbaum Associates, Hillsdale, NJ

Gigerenzer G, Todd P, et al. (1999) Simple Heuristics that Make us Smart. Oxford University Press, New York

Gill R, Polley H, Johnson H, Anderson L, Maherali H, Jackson R (2002) Nonlinear grassland responses to past and future atmospheric CO_2. Nature 417:279–282

Goulden M, Wofsy S, Harden J, Trumbore S, Crill P, Gower S, Fries T, Daube B, Fan S-M, Sutton D, et al. (1998) Sensitivity of boreal forest carbon balance to soil thaw. Science 279:214–217

Herzog H, Caldeira K, Reilly J (2003) An issue of permanence: assessing the effectiveness of temporary carbon storage. Climatic Change 59:293–310

Hogarth R (1981) Beyond discrete biases – functional and dysfunctional aspects of judgmental heuristics. Psychol Bull 90(2):197–217

Houghton J, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson C (eds) (2001) Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK

House J, Prentice IC, LeQuéré C (2002) Maximum impacts of future reforestation or deforestation on atmospheric CO_2. Global Change Biol 8:1047–1052

Jansen V, Stollenwerk N, Jensen H, Ramsay M, Edmunds W, Rhodes C (2003) Measles outbreaks in a population with declining vaccine uptake. Science 301:804

Jean-Baptiste P, Ducroux R (2003) Potentiel des méthodes de séparation et stockage du CO_2 dans la lutte contre l'effect de serre. Comptes Rendus Geoscience 335:611–625

Johnson-Laird P (1983) Mental Models: Toward a Cognitive Science of Language, Inference, and Consciousness. Cambridge University Press, Cambridge, England

Kasemir B, Dahinden U, Swartling A, Schüle R, Tabara D, Jaeger C (2000) Citizens' perspectives on climate change and energy use. Global Environ Change 10:169–184

Kempton W (1997) How the public views climate change. Environment 39(9):12–21

Kempton W (1993) Will public environmental concern lead to action on global warming? Annu Rev Energy Environ 18:117–145

Kempton W, Boster J, Hartley J (1995) Environmental Values in American Culture. MIT Press, Cambridge, MA

Kleinmuntz D, Schkade D (1993) Information displays and decision-processes. Psychol Sci 4:221–227

Krosnick J, Holbrook A, Visser P (2000) The impact of the fall 1997 debate about global warming on American public opinion. Public Understanding Sci 9:239–260

Kull S (2001) Americans on the Global Warming Treaty. Program on International Policy Attitudes, www.pipa.org/OnlineReports/GlobalWarming/buenos_aires_02.00.html

Leiserowitz A (2003) American Opinions of Global Warming. University of Oregon Survey Research Laboratory, osrl.uoregon.edu/projects/globalwarm

Malhi Y, Meir P, Brown S (2002) Forests, carbon and global climate. Philos T Roy Soc A 360:1567–1591

Meehl GA, Washington WM, Collins WD, et al. (2005) How much more global warming and sea level rise? Science 307:1769–1772

Meijnders A, Midden C, Wilke H (2001) Role of negative emotion in communication about CO_2 risks. Risk Anal 21(5):955–966

Milyukova I, Kolle O, Varlagin A, Vygodskaya N, Schulze E, Lloyd J (2002) Carbon balance of a southern taiga spruce stand in European Russia. Tellus B 54:429–442

Morgan MG, Fischhoff B, Bostrom A, Atman C (2002) Risk Communication: A mental models approach. Cambridge University Press, New York

Moser S, Dilling L (2004) Making climate hot. Environment 46(10):32–46

Oeschger H, Siegenthaler U, Schotterer U, Gugelmann A (1975) Box diffusion-model to study carbon-dioxide exchange in nature. Tellus 27:168–192

O'Connor R, Bord R, Fisher A (1999) Risk perceptions, general environmental beliefs, and willingness to address climate change. Risk Anal 19(3):461–471

O'Connor R, Bord R, Yarnal B, Wiefek N (2002) Who wants to reduce greenhouse gas emissions? Soc Sci Q 83(1):1–17

O'Neill B, Oppenheimer M (2002) Dangerous climate impacts and the Kyoto protocol. Science 296:1971–1972

Page S, Siegert F, Rieley J, Boehm H, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61–65

Palmgren C, Morgan MG, de Bruin W, Keith D (2004) Initial public perceptions of deep geological and oceanic disposal of carbon dioxide. Environ Sci Technol 38(24):6441–6450

Payne J, Bettman J, Johnson E (1993) The Adaptive Decision Maker. Cambridge University Press, Cambridge

Plous S (1993) The Psychology of Judgment and Decision Making. McGraw Hill, New York

Read D, Bostrom A, Morgan MG, Fischhoff B, Smuts D (1994) What do people know about global climate change? Part 2: Survey studies of educated laypeople. Risk Anal 14(6):971–982

Rodo X, Pascual M, Fuchs G, Faruque A (2002) ENSO and cholera: a nonstationary link related to climate change? Proc Natl Acad Sci USA 99:12901–12906

Rogers E (2003) Diffusion of Innovations, 5th ed. Free Press, New York

Sarmiento J, Hughes T, Stouffer R, Manabe S (1998) Simulated response of the ocean carbon cycle to anthropogenic climate warming. Nature 393:245–249

Sarmiento JL, Le Quéré C, Pacala SW (1995) Limiting future atmospheric carbon dioxide. Global Biogeochemical Cycles 9(1):121–137

Scheffer M, Carpenter S, Foley J, Folkes C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596

Scott MJ, Edmonds JA, Mahasenan N, Roop JM, Brunello AL, Haites EF (2004) International emissions trading and the cost of greenhouse gas emissions mitigation and sequestration. Climatic Change 64:257–287

Slovic P (ed) (2000) The Perception of Risk. Earthscan, London

Stachowicz J, Terwin J, Whitlatch R, Osman R (2002) Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. Proc Natl Acad Sci USA 99:15497–15500

Sterman J (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, New York

Sterman J, Booth Sweeney L (2002) Cloudy skies: assessing public understanding of global warming. Syst Dyn Rev 18:207–240

Stoll-Kleemann S, O'Riordan T, Jaeger C (2001) The psychology of denial concerning climate mitigation measures: evidence from Swiss focus groups. Global Environ Change 11:107–117

Sturgis P, Allum N (2004) Science in society: re-evaluating the deficit model of public attitudes. Public Understanding Sci 13:55–74

Taylor H (2001) Large Majority of Public Now Believes in Global Warming and Supports International Agreements to Limit Greenhouse Gases. Harris Poll 45, Harris Interactive, www.harrisinteractive.com/harris_poll/index.asp?PID = 256

Thomas C, Cameron A, Green R, Bakkenes M, Beaumont L, Collingham Y, Erasmus B, Ferreira de Siqueira M, Grainger A, Hannah L, et al. (2004) Extinction risk from climate change. Nature 427:145–148

United States Freedom Foundation. Helmet laws of the 50 states and how to beat them! Available at usff.com/hldl/hlstatutes/50statehls.html

White A, Cannell M, Friend A (2000) CO_2 stabilization, climate change, and the terrestrial carbon sink. Global Change Biol 6:817–833

Wigley T (2005) The climate change commitment. Science 307:1766–1769