www.sciencemag.org/cgi/content/full/322/5901/532/DC1

Supporting Online Material for

Risk Communication on Climate: Mental Models and Mass Balance

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Published 24 October 2008, *Science* **322**, 532 (2008)
DOI: 10.1126/science.1162574

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Supporting Online Material

This supplement presents the climate stabilization task used in the experiments and discusses alternative explanations for the results. Full documentation, subject demographics and results are presented in (*S1*).

1. Interpreting public opinion surveys. Available public opinion surveys do not directly ask people about their understanding of the stock and flow structures affecting climate change or the time delays between actions to reduce GHG emissions and their impact on the climate. These lags include political delays, economic delays, and delays in the biogeochemical processes affecting climate. Political delays include the lags between passing legislation or ratifying international agreements to reduce emissions and the implementation of the policies (such as cap and trade programs, carbon taxes, subsidies for investments in energy efficiency or low-carbon, renewable sources). Even after policies to promote energy efficiency and non-carbon energy sources are implemented, there are long lags in the development of new technologies such as low-carbon, renewable energy sources and more efficient buildings, vehicles, lighting, and motors. Additional lags arise because existing GHG-generating capital stocks (automobiles, industrial plant and equipment, housing, infrastructure) are only gradually replaced or retrofitted, while low or carbon-neutral energy sources, settlement patterns, transportation networks, and global supply chains are only gradually developed and deployed. The delays in the biogeochemical domain arise from the stock and flow structures in the climate system. First, the concentration of GHGs in the atmosphere will continue to rise even as emissions fall, until emissions fall below the net removal of GHGs from the atmosphere. Second, warming will continue even after atmospheric GHG concentrations stabilize, until global mean surface temperatures and albedo adjust enough for net radiative forcing to fall to a mean of zero. Third, net melting of glaciers and ice sheets will continue until average surface temperature and insolation fall enough to restore mass balance by reducing melting and calving to the rate of ice mass accumulation through new snowfall. Fourth, sea level rise will continue through thermal expansion and net melting of ice sheets, with time constants on the order of centuries to millennia (see references *S3*–*S5*).

While existing polls do not directly ask about people's understanding of the time delays and stock-flow structures that affect the response of the climate to emissions reduction policies, they do provide some insight into the public's understanding of these issues. A WorldPublicOpinion.org poll of March 2007 asked citizens in 17 nations which of the following three statements comes closest to their personal view:

1. Until we are sure that it [global warming] is really a problem, we should not take any steps that would have economic costs.
2. [Global warming] 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.
3. [Global warming] is a serious and pressing problem, we should begin taking steps now even if this involves significant costs.

In the United States, 17 % selected option 1, 37% selected option 2, 43% selected option 3, and the remainder expressed no opinion. Conservatively omitting those expressing no opinion, the results constitute a 54% majority favoring either a "wait and see" or "go slow" approach. Responses for other major GHG emitter nations were:

	Option 1	Option 2	Option 3	No Answer/Don't know
China	8	41	42	9
Russia	22	34	32	12
India	24	30	19	27

In only three nations surveyed did option 3 (begin taking steps now) receive a majority (Argentina, 63%; Australia, 69%; Israel, 54%). The fraction favoring action now in China, Russia and India is lower than that favoring action now in the United States.

The WPO poll has apparently not been repeated since March 2007, but more recent polls show continued confusion and complacency in public attitudes on climate change. Specifically, majorities generally respond that they have heard of climate change, believe it is real, caused by human activity, and constitutes a serious threat, while simultaneously far smaller fractions believe actions to reduce emissions are needed now or support policies that would raise the price of carbon-based energy. For example, a Gallup poll published 21 April 2008 (*S2*) showed that "[w]hile 61% of Americans say the effects of global warming have already begun, just a little more than a third say they worry about it a great deal, a percentage that is roughly the same as the one Gallup measured 19 years ago." Gallup does not ask directly about time delays in the response of the climate to policy choices regarding emissions. However, 58% disagree with the statement that "global warming will pose a serious threat to you or your way of life in your lifetime" while only 40% agree. Since 1995 Gallup has also asked the following question:

> "All in all, which of the following best describes how you feel about the environmental problems facing the earth—life on earth will continue without major environmental disruptions only if we take additional, immediate, and drastic action concerning the environment, we should take some additional actions concerning the environment, or, we should take just the same actions we have been taking on the environment?"

The fraction supporting immediate action was 34%, down from 38% in 2007. The fraction supporting immediate action was 35% in 1995.

A Eurobarometer survey conducted between March and May 2008 (*S3*) showed three-quarters of respondents rank "global warming/climate change" as "a very serious problem." However, when asked "how much would you be prepared to pay more for energy produced from sources that emit less greenhouse gases in order to fight the climate change (sic)," 30% are not willing to pay anything more, only 2% are willing to pay more than 30% more, and only 10% are willing to pay 11-30% more.

A May 2008 survey of Floridians (*S4*) showed 71% were "mostly" or "completely" convinced that "global warming is happening", and 55% attribute it to human activities. However, when asked "when do you think global warming will start to have dangerous impacts on people in Florida?" 51% chose 25 years or more, including 27% choosing "100 years" or "never". A majority of 78% "moderately" or "strongly" support "Agreeing to an international treaty that requires the United States to cut its emissions of carbon dioxide 90% by the year 2050" but a majority of 58% "moderately" or "strongly" oppose a national cap and trade market for GHG emissions.

2. Experimental method. Subjects in the experiment reported were students in a graduate management elective at MIT, including 2nd year MBA students (63%), graduate candidates in other programs (35%) and undergraduates (2%). Reflecting the student body at MIT, the participants were highly educated, particularly in technical fields. Three-fifths were trained in science, technology, engineering or mathematics (STEM); 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 STEM fields, including medicine, 26% in economics or social science, and the remainder in the humanities). Mean age was 30 ($\sigma = 5$, range 20-56). The task was administered at the beginning of the semester, prior to exposure to the course content. Figure S1 (below) shows the explanatory text subjects received. Note that the data were collected prior to the publication of IPCC AR4. The explanatory text in Figure S1 was therefore based on IPCC TAR (see Table S1). Subjects were randomly assigned to either the 400 ppm condition (Figure S2) or the 340 ppm condition (Figure S3). To examine the robustness of the results to the response format, subjects were randomly assigned to one of three response formats: In the Emissions and Removal (ER) condition (shown in Fig. S1, S2) 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 was 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 (MC) condition provided 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 ranged from continued emissions growth to immediate decline below current rates. As detailed in (*S1*), there were no significant differences in emissions trajectories among the three formats (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).

An updated, interactive version of the task is available online at http://scripts.mit.edu/~jsterman/Management_Flight_Simulators_(MFS).html.

Figure S1 Task Description

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.

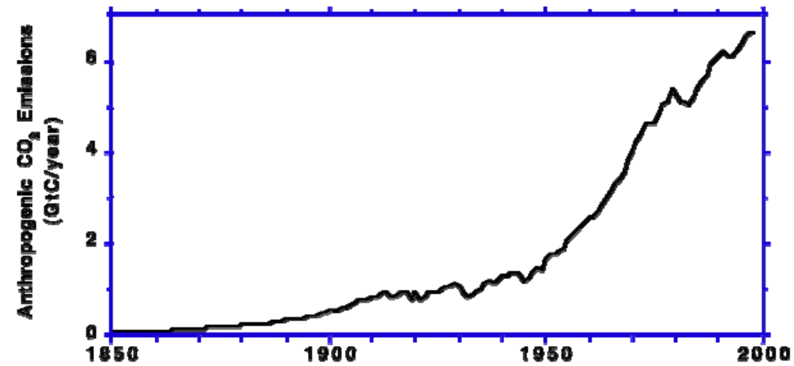


Figure 1. Global CO_2 emissions resulting from human activity (billion tons of carbon per year)

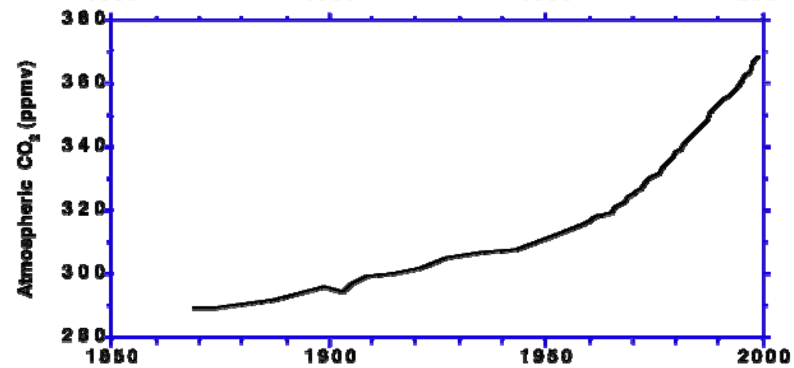


Figure 2. Atmospheric CO_2 concentrations, parts per million.

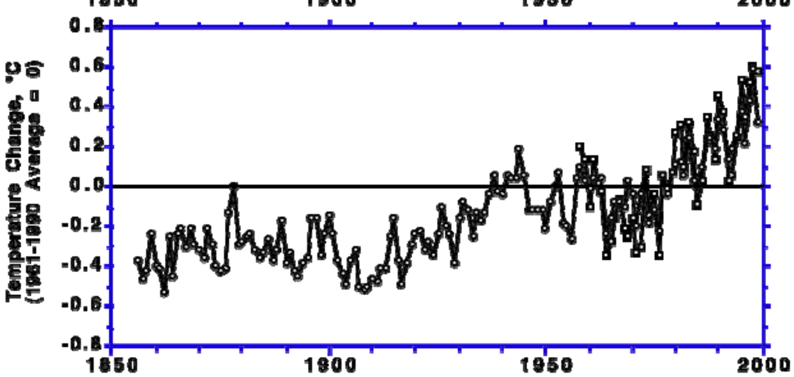
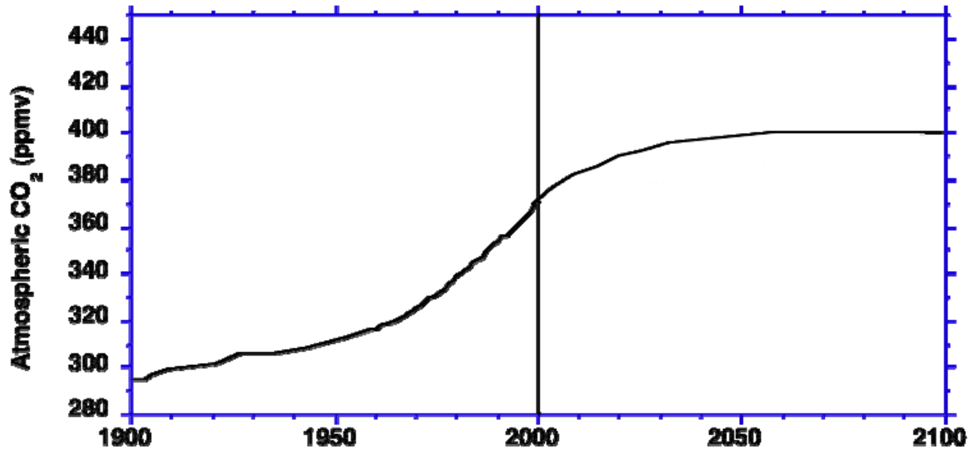


Figure 3. Average global surface temperatures, °C. The zero line is set to the average for the period 1961-1990.

Figure S2 400 ppm scenario

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 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 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.

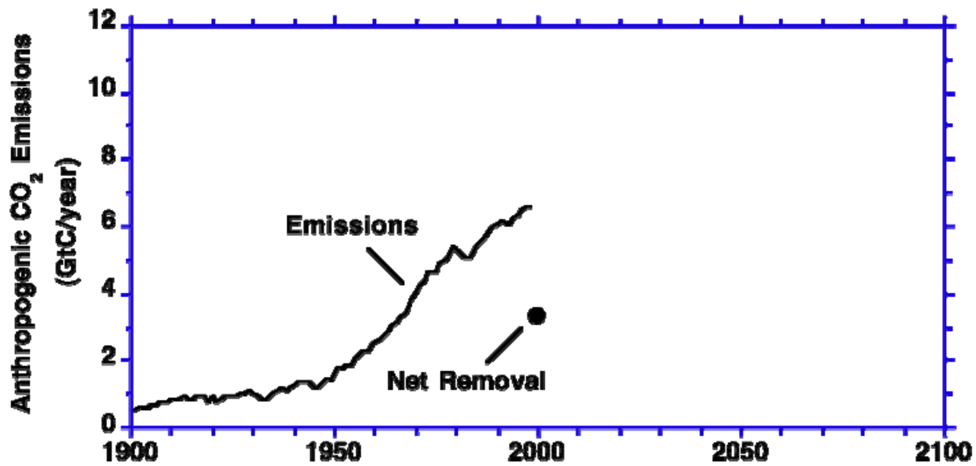
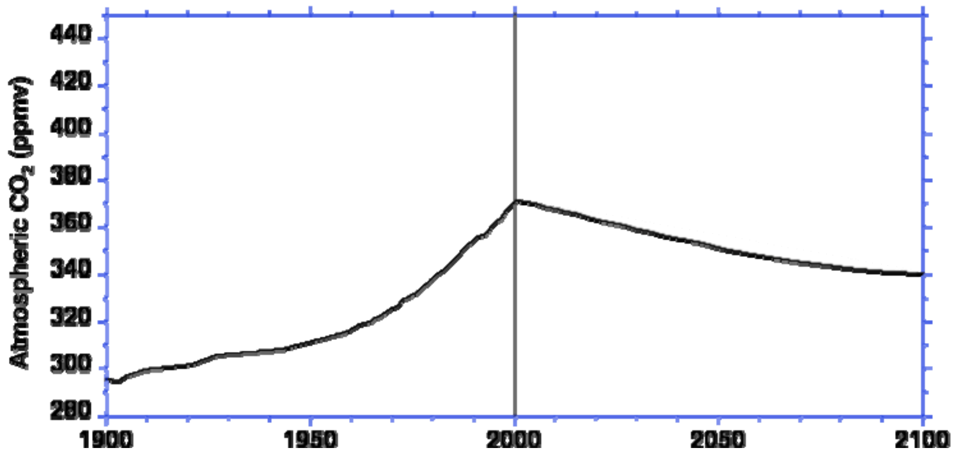


Figure S3 340 ppm scenario

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 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 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.

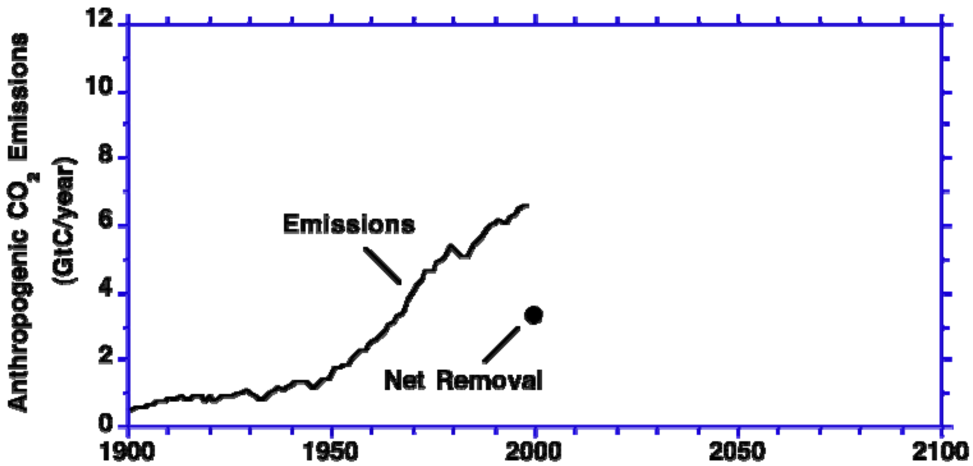


Table S1. The description in the task (Figure S1; reproduced below) is quoted or paraphrased from the IPCC TAR Summary for Policymakers; page numbers in notes below refer to the TAR SPM.

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 (Figure 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 (Figure 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 Figure 3, global average surface temperatures have increased since the start of the industrial revolution.[h]

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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_20] 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.

3. Impact of STEM training on the results. As detailed in (*S1*), approximately 60% of the subjects had a prior degree in a field of Science, Technology, Engineering, or Mathematics (STEM). Most of the rest had prior degrees in business, economics or other social sciences, with only approximately 3% trained in the humanities. Comparing subject estimates of CO_2 emissions in 2100, CO_2 removal from the atmosphere in 2100, and net emissions in 2100, there are no statistically significant differences in the results between those with STEM training and others (Table S2).

Table S2. Impact of STEM training on subject estimates of emissions, removal, and net emissions in 2100. P-values from unpaired t-test. For emissions, data include subject estimates from the EG and ER conditions. Subjects provide estimates of CO_2 removal and net emissions, only in the ER condition.

	400 ppm				340 ppm		
	STEM	Non-STEM	t-test (p)		STEM	Non-STEM	t-test (p)
CO_2 Emissions in 2100 (GtC/year)	7.5	6.6	.39		5.3	5.5	.78
N (pools EG and ER conditions)	38	33			38	26	
CO_2 Removal in 2100 (GtC/year)	5.1	5.7	.64		4.8	4.7	.89
CO_2 Net emissions in 2100 (GtC/year)	2.3	2.4	.90		1.1	1.2	.96
N (ER condition only)	17	15			17	15	

4. Stock and Flow concepts and Time Delays in the IPCC AR4 SPM . Compared to the Third Assessment Report, the Summary for Policymakers in the IPCC Fourth Assessment Report (AR4) Synthesis Report (*S5*) provides even less information on the stock and flow relationships relating GHG emissions and atmospheric concentrations. Whereas the TAR SPM states (p. 7), "Currently the ocean and the land together are taking up about half of the anthropogenic CO_2 emissions" there is no comparable statement comparing the flow of GHG emissions into the atmosphere to the removal of GHGs out of the atmosphere in the AR4 SPM. There is no explicit comparison of GHG emissions and removal from the atmosphere, and no statement of the mass balance principles that stabilizing atmospheric GHG concentrations requires GHG emissions equal GHG removal from the atmosphere, nor that temperatures will continue to rise until net radiative forcing falls to a mean of zero.

The term "inertia" appears once, in note e of Table SPM.6 (p. 20). The term "lag" appears only once (p. 22). Delays in the response of the climate to emissions reductions are explicitly mentioned only twice (p. 19: "Delayed emissions reductions significantly constrin the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts." and p. 22: "choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emissions reductions now against the corresponding medium-term and long-term climate risks of delay."). More general references to lags and the role of stocks and flows in the response of the climate to changes in emissions are sparse and do not include explanations for why the lags exist. For example, p. 12 states "Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if GHG concentrations were to be stabilised." Other than references to “livestock”, the term “stock”—as in stock and flow—appears only once, in reference to the “long lifetimes of energy plants and other infrastructure capital stock” (p. 15). The term “mass balance” appears only once (p. 12), in reference to the Antarctic ice sheet; the term “energy balance” appears once (p. 5). The AR4 SPM does not include an explanation of the conditions required to achieve mass balance in GHG concentrations, in ice sheets, or in radiative forcing.

Finally, the text of the AR4 SPM is not written in plain language. The grade level of the text of section 1 (“Observed changes in climate and their effects”) was analyzed by submitting it to the online text analyzer <http://www.editcentral.com/gwt/com.editcentral.EC/EC.html>. The text analyzed omitted footnotes and captions for figures and tables. Results ranged from a grade level of 12.9 for the Flesch-Kincaid index to 16.6 for the Gunning Fog index, indicating college-level reading skills are needed to understand the text. These estimates are highly likely to underestimate the difficulty of the text as they make no allowance for the complex graphics, scientific concepts, technical jargon and terminology used.

5. Alternative explanations for the results: The poor performance of these highly educated subjects raises the question of alternative explanations for the results. Perhaps the subjects (MIT graduate students) can recognize and understand stocks and flows but were not able to do so in this case due to (1) inadequate time, (2) insufficient explanation of climate change processes, (3) the complexity of the climate context compared to other common stock-flow situations, (4) the information presentation or response format, or other factors.

1. Inadequate time: Subjects had 10 minutes to complete the task. Most finished earlier. Cronin, Gonzalez and Sterman (*S6*) show that performance of similar subjects on stock-flow problems much simpler than the climate stabilization task described here is quite poor even when subjects are given more time, and are provided with outcome feedback, that is, told whether their response is correct or incorrect, then allowed to revise their answers.

2. Insufficient explanation of climate change processes: The description of the climate and the accumulation of GHGs in the atmosphere presented to the subjects (Figure S1) includes information on the stock and flow structure of GHG emissions, uptake, and concentrations. However, the description is very brief and does not include an explicit analogy comparing the emissions and uptake of GHGs to, for example, the flows of water into and out of a tank. Perhaps such information would improve performance. First, the task description is excerpted from the IPCC SPM itself. Information in the SPM regarding the stock and flow structure relating emissions, uptake and atmospheric concentrations is sparse, and the SPM does not include an explicit comparison of the stock and flow structure of emissions, uptake and concentrations to the flow of water into and out of a tank. Such explicit analogies should be included. However, it is unlikely that doing so will, by itself, reduce the prevalence of pattern matching and correlational reasoning. Booth Sweeney and Sterman (*S7*) presented graduate student subjects at MIT (demographically indistinguishable from those who participated in the climate stabilization experiment) with tasks consisting of an explicit description of the flow of water into and out of a bathtub, including a picture of a tub. Subjects were presented with a graph of the flows in and out through faucet and drain over time, then asked to draw the level of water in the tub. Performance was very poor despite use of very simple patterns, e.g., constant outflow and square wave inflow. Cronin et al. (*S6*) and Cronin and Gonzalez (*S8*) find these results to be robust to effort, motivation, and other manipulations.

3. Complexity of climate change: Climate change is complex and involves concepts in which most people have no training. Perhaps people understand stock and flow relationships well but do poorly because they are not sufficiently knowledgeable regarding the carbon cycle and climate. If so, then providing people with more information on these subjects should improve performance. However, prior work (*S6, S7, S8*) shows extremely poor performance among university students including graduate and undergraduate students at MIT, Carnegie-Mellon, and George Mason University on stock-flow tasks with common, everyday contexts including filling a bathtub, managing a bank account, driving a car, managing an inventory of goods, and so on. These situations do not require training in or familiarity with complex biogeophysical concepts. Cronin et al. (*S6*) provided MIT graduate students with a very simple task in which subjects were given simple graphs showing hypothetical data for the number of people entering and leaving a department store over a 30-minute interval. Subjects were asked to sketch the qualitative pattern for the number of people in the store. Overall performance was extremely poor, and the large majority of erroneous responses are consistent with a "correlation heuristic" in which subjects believe that the output of a system, in this case the stock, should look like (be positively correlated with) the input to the system (the inflow or net flow).

4. Information presentation: The description in Figure S1 includes graphs showing anthropogenic emissions, atmospheric CO_2, and global mean temperature from 1850 through 2000. All rise over this time horizon and are highly correlated, perhaps inducing people to use pattern matching rather than stock-flow reasoning. Exposure to such graphs is common: scientific reports and popularized accounts on climate change, including the IPCC SPM, often include graphs of emissions, GHG concentrations, and temperature changes, often over even longer time horizons (e.g., the Vostok proxy records). Nevertheless, it is possible that exposure to such graphical displays biases people towards use of pattern matching. To test this, Sterman and Booth Sweeney (*S1*) presented another group of graduate students at MIT (n = 68) with a version of the task in which the graphs of historical emissions, CO_2 concentration, and mean temperature were omitted. There was, however, no improvement: pattern matching was common, with 96% violating mass balance and 78% asserting that atmospheric CO_2 can be stabilized while emissions continuously exceed uptake (net removal).

5. Response format: The task shown in Figure S1 requires subjects to interpret graphs, and to sketch their responses in graphical form. Perhaps people understand stocks and flows but have difficulty reading and constructing graphs. Sterman and Booth Sweeney (*S1*) tested three response formats, including multiple choice, finding no statistically significant difference by response mode. Cronin et al. (*S6*), using a much simpler stock-flow example, find performance was no better, and sometimes worse, when the data were presented to subjects in the form of numerical tables or text. The results also show high performance on questions testing whether subjects can read the graphs they are given (e.g., identifying when the maximum of a time series is reached), while performance on questions requiring stock-flow reasoning was poor. The inability to interpret or construct graphs does not appear to cause poor performance in stock-flow settings, at least among the highly educated university student and graduate student subjects used in these experiments.

Overall, the results of prior work suggest that the ability to relate the flows affecting a stock to the level of the stock is poor, even among highly educated people with substantial training in STEM. Poor understanding of stock-flow relationships does not appear to be an artifact of task complexity, the familiarity of the context, the time allotted for the task, the mode of data presentation, response format, motivation, or other features.

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