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 or net radiative forcing 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, results show 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 be based more on misconceptions of climate dynamics than high discount rates or uncertainty about the risks of harmful climate change.

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1. Introduction

In democracies the beliefs of the public affect government policy. 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). Yet most also believe that "its effects will be gradual, so we can deal with the problem gradually" or that "until we are sure that global warming is really a problem, we should not take any steps that would have economic costs" (Kull, 2001), and large majorities oppose mitigation policies such as energy taxes (Leiserowitz, 2003). US 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 greater and 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

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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.

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 of the causal chain 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, changes in the distribution of species, extinction rates, and the incidence of diseases, among others. None of these conditions hold (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 build scientific understanding and consensus for policy change. 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 (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. Wait-and-see policies presume 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. 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. Prior work shows people have difficulty relating the flows into and out of a stock to the trajectory of the stock (Booth Sweeney and Sterman, 2000). Instead, people often assess system dynamics using a *pattern matching* heuristic (Sterman and Booth Sweeney, 2002), concluding that system outputs (e.g., global mean temperature) are positively correlated with inputs (e.g., emissions). Pattern matching can work 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 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.

2. Method

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 presented subjects with a brief nontechnical summary of climate change such as would be suitable for the policymaker or intelligent layperson, then asked them to relate GHG emissions to atmospheric concentrations. The descriptive text (Fig. 1A) is quoted or paraphrased from the IPCC's Third Assessment Report (TAR) Summary for Policymakers (Houghton et al., 2001), a document intended for nonscientists (Table 1 shows the sources in the SfP for each statement in the description provided to the subjects). The text explicitly describes the stock of atmospheric CO_2, emissions (the principal anthropogenic GHG), 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.

2.1 Task Description and Information Display: 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 on understanding of the stock and flow structure and are therefore lower than those in, e.g., the IPCC SRES scenarios (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 (MC) condition (Table 2) provides a textual rather than graphical response format in which subjects selected which of seven emissions trajectories they believed to be most consistent with the specified CO_2 scenario. Choices ranged 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. Further, 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 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 x 3 response modes), with subjects assigned randomly to each.

2.2 Subjects: Subjects were students in a management elective at MIT, including MBA (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 (σ=5, range 20-56). Subjects carried out the task in class 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 the results would not be graded. Participation was voluntary and 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 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.

Our main 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.

Results show evidence of pattern matching in all response formats. To illustrate, Fig. 2A, B show typical responses to the 400 ppm scenario in the ER condition where subjects draw both emissions and removal. Both subjects draw emissions patterns that match the path of atmospheric CO_2. Both emissions paths exceed their estimates of 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. Fig. 2C, D show typical responses to the 340 ppm case. Both subjects draw emissions paths that match the pattern of decline in atmospheric CO_2. Both show emissions exceeding removal throughout—instead of falling by 2100, atmospheric CO_2 would rise at a diminishing rate. All four examples violate mass balance requirements.

Subjects' emissions estimates generally followed the path of atmospheric CO_2 (Figure 3, Table 4). In the ER 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 EG 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 MC 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).

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 they differed by more than 0.5 GtC/year. Such a large tolerance is an *a fortiori* procedure ensuring that subjects who understood CO_2 stabilization requires $E = R$, but whose drawings of E and R in 2100 may have differed slightly, are still counted as correct. 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. The 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 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." While rising to 400 ppm, subjects can reasonably conclude that forcing would remain positive and temperature would continue to rise. While falling 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.[2]

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. Shockingly, 13% of those in the 340

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[2] 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 $\Delta T \approx 1.8$ °C above current levels by 2100, growing to $\Delta T \approx 2.2$°C by 2350. Stabilization at 500 ppm yields $\Delta T \approx 2.1$°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 $\Delta T \approx 1.5$ °C by 2100 for stabilization at 400 ppm; extrapolating further to 340 ppm yields $\Delta T \approx 1.1$ °C by 2100, though the validity of such extrapolation is unknown.

ppm scenario 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 is 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 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.

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 specific instantiation in climate change, how long the resulting delays will be, nor important dynamics such as the fact 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 mention 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. 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.

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. Research shows that incentives in judgment and decision-making tasks sometimes improve performance, sometimes have no impact, and sometimes worsen performance (Camerer and Hogarth, 1999). Further, 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. 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. Subjects' written explanations show that some used this information effectively. Yet far more ignored the cues in the task description designed to increase the salience of the stock and flow structure and relied on pattern matching instead. Many more use the stock and flow information incorrectly, violating fundamental conservation laws. Similar subjects in prior experiments (Booth Sweeney and Sterman, 2000) violated the same conservation principles in much simpler tasks such as filling a bathtub.

We hypothesize that typical media reports and other information conditioning public views of climate change (e.g., television 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 incentives 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, particularly in science and mathematics, compared to the general public.

The difficulties people experience in our experiments should perhaps be expected. It is not necessary to understand stocks and flows to fill a bathtub. 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 the flows relate to the 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. 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, without broad public understanding there can be little public support for appropriate policies. Widespread reliance on pattern matching and violation of conservation principles leads people to underestimate the magnitude of the emissions reductions required to stabilize atmospheric GHG concentrations and reduce net radiative forcing. Consequently, people 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. People may favor policies that would fail to stabilize net forcing or GHG concentrations at the levels they consider appropriate, whatever those levels may be. The misconception of stocks and flows and conservation principles 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 or even grows. The misconception of these physical principles stands in contrast to the common explanation for the contradiction that people oppose policies to stabilize GHG concentrations because they are short-sighted and self-interested, discounting the future at high rates.

5. Conclusion

Public beliefs about climate change constrain the ability of governments to implement policies consistent with the best available scientific knowledge. We carried out experiments to assess public understanding of basic processes affecting the climate, specifically, whether adults understand the relationships 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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Figure 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) 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 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).

Figure 1A 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.

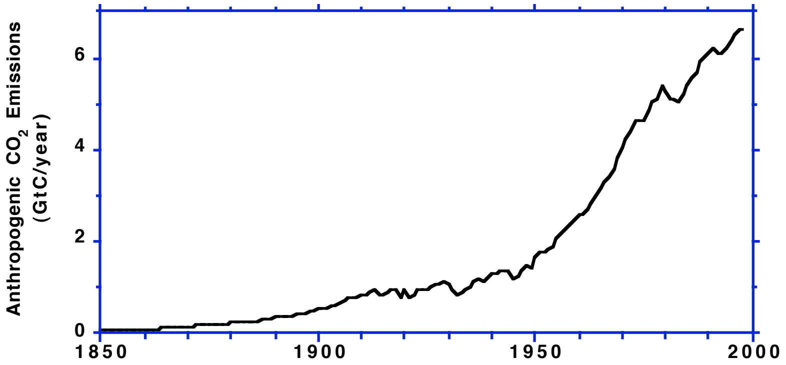


Figure 1. Global CO_2 emissions resulting from human activity (billion tons of carbon per year)

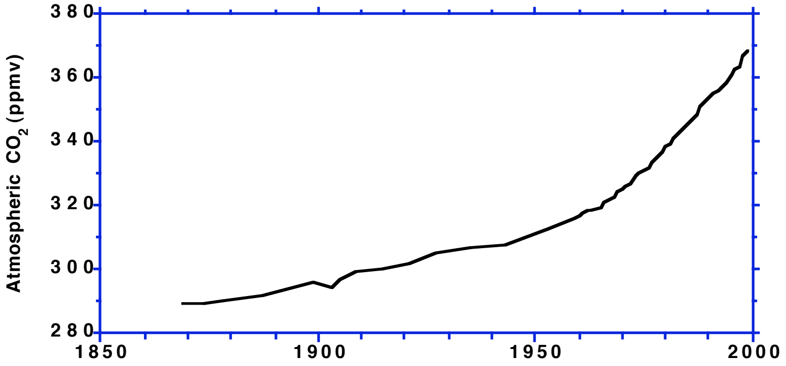


Figure 2. Atmospheric CO_2 concentrations, parts per million.

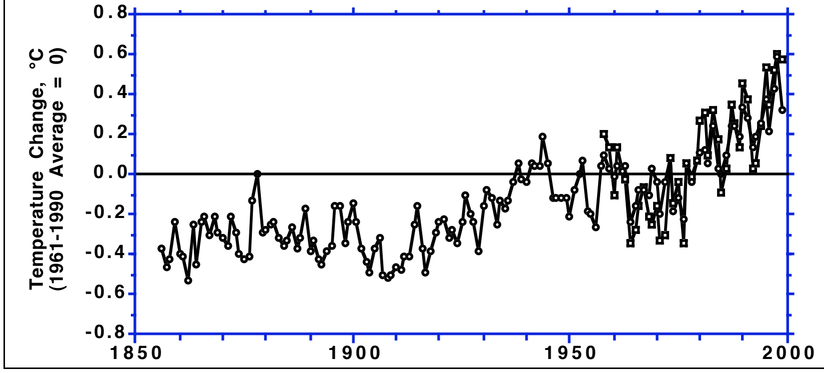
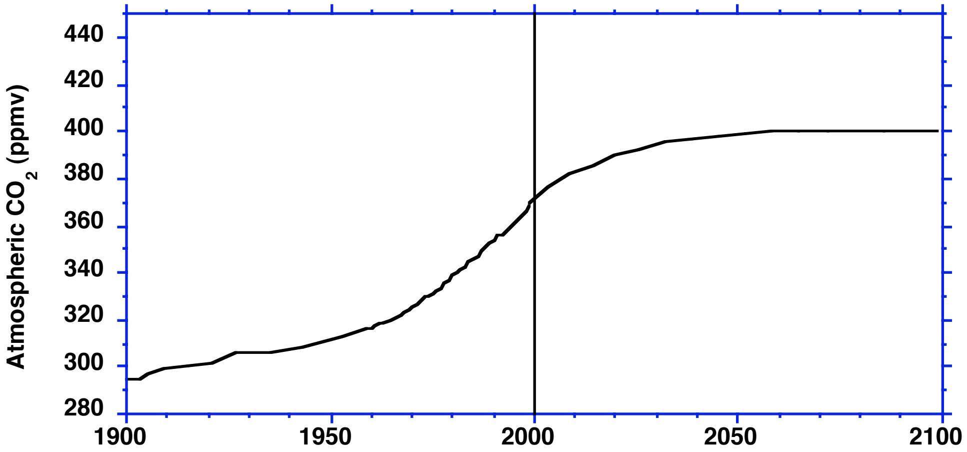


Figure 3. Average global surface temperatures, °C. The zero line is set to the average for the period 1961-1990.

Figure 1B 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 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.

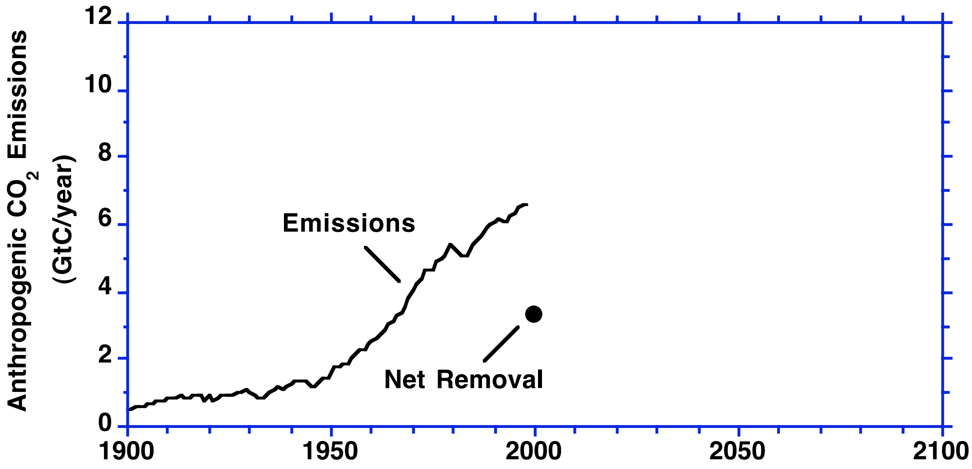
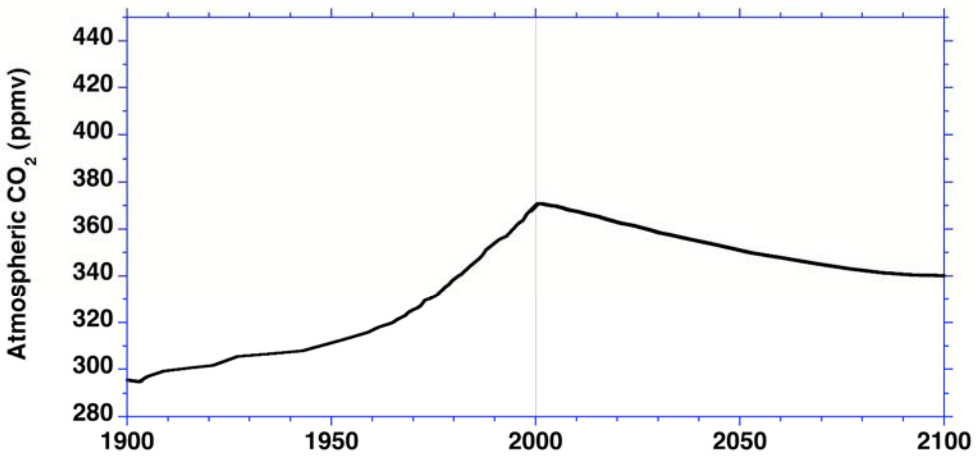


Figure 1C 340 ppm scenario

Now consider a scenario in which the concentration of CO_2 in the atmosphere gradually falls to 400 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.

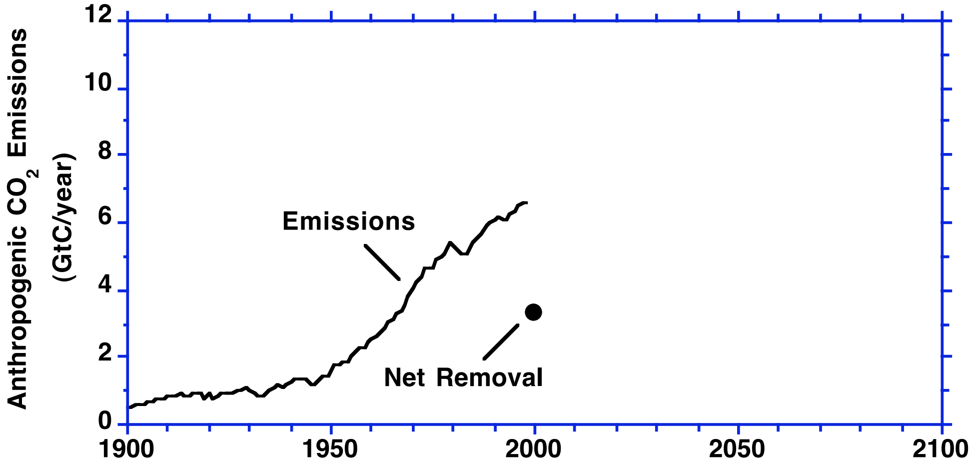


Table 1. The description in the task (Figure 1A; reproduced below) is quoted or paraphrased from the IPCC TAR Summary for Policymakers; page numbers in notes below refer to the TAR.

> 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 (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]

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.

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					
Response Mode:	**400 ppm (N)**	***(%)***	**340 ppm (N)**	***(%)***	**Total (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*

Figure 2. Typical responses, illustrating pattern matching. *(A, B)*: 400 ppm case. Note that both subjects select emissions E >> 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 path that match the atmospheric CO_2 path in the scenario.

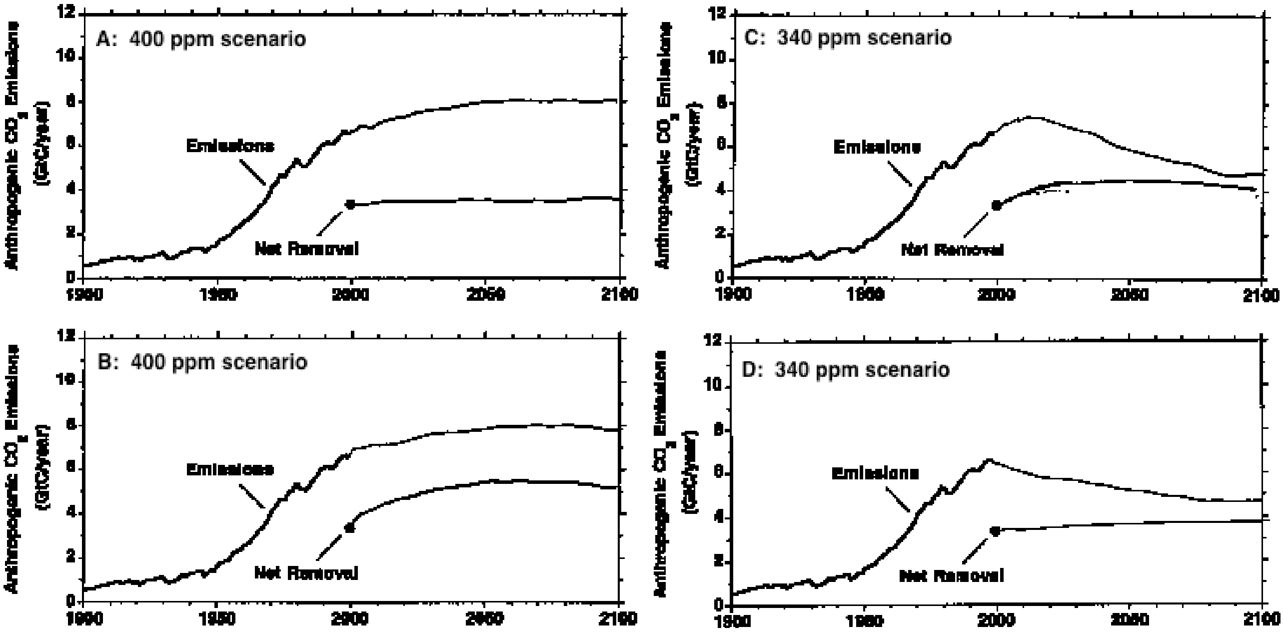


Figure 3. Results. Responses indicating emissions would rise (or remain constant) vs. falling by 2100, by response format and CO_2 scenario. The majority exhibit pattern matching: subjects project emissions should rise to stabilize atmospheric CO_2 when CO_2 concentrations rise, and fall when CO_2 concentrations 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.

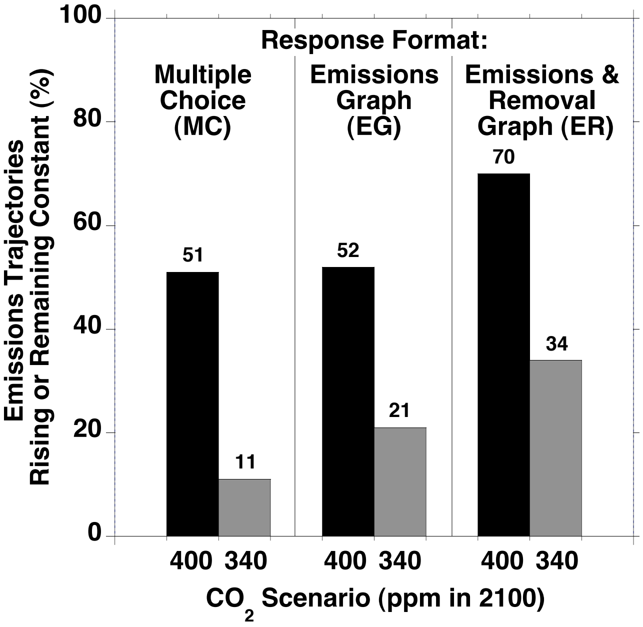


Table 4. Results for CO_2 emissions. (**A**) MC condition. (**B**) Responses indicating emissions would rise/remain constant vs. falling by 2100. The number rising/remaining constant is the sum of the first four responses in the MC conditions, and the number with final emissions values ≥ 6.5 GtC/year 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, $\chi^2(2) = 5.15$, $p = 0.08$.

A	**CO_2 Emissions would have to…**	**CO_2 Scenario: 400**		**340**	
		N	%	N	%
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**	
CO_2 Emissions in 2100:	N	%	N	%	N	%	N	%	N	%	N	%
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	$p = 1.3 \times 10^{-7}$											

Table 5. Conformance to conservation of matter. Net emissions $E_{net} = E – R$ 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 $d[CO2]/dt \approx 0$ (at the end of both scenarios).

	(1)	(2)		(3)		(4)		(5)	
CO_2 in 2100 (ppm)	Mean absolute final emissions, $\lvert E – R \rvert$ (GtC/yr)	Final net emissions $E_{net} = E – R$						Stock/flow consistency?	
		$E_{net} > \delta$		$E_{net} = 0 \pm \delta$		$E_{net} < -\delta$			
		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*

Table 6. Results for temperature trajectory. 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.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Response Format:	**Temp. Choice**	**400 ppm**	**340 ppm**	**Temp. Choice**	**400 ppm**	**340 ppm**	**H_0: 400 =340 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				

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." "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."	69	34.8

Table 7 (continued)

Concept/Coding Criteria	Examples	N	%
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
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