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Communicating climate change risks in a skeptical world

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Abstract The Intergovernmental Panel on Climate Change (IPCC) has been extraordinarily successful in the task of knowledge synthesis and risk assessment. However, the strong scientific consensus on the detection, attribution, and risks of climate change stands in stark contrast to widespread confusion, complacency and denial among policymakers and the public. Risk communication is now a major bottleneck preventing science from playing an appropriate role in climate policy. Here I argue that the ability of the IPCC to fulfill its mission can be enhanced through better understanding of the mental models of the audiences it seeks to reach, then altering the presentation and communication of results accordingly. Few policymakers are trained in science, and public understanding of basic facts about climate change is poor. But the problem is deeper. Our mental models lead to persistent errors and biases in complex dynamic systems like the climate and economy. Where the consequences of our actions spill out across space and time, our mental models have narrow boundaries and focus on the short term. Where the dynamics of complex systems are conditioned by multiple feedbacks, time delays, accumulations and nonlinearities, we have difficulty recognizing and understanding feedback processes, underestimate time delays, and do not understand basic principles of accumulation or how nonlinearities can create regime shifts. These problems arise not only among laypeople but also among highly educated elites with significant training in science. They arise not only in complex systems like the climate but also in familiar contexts such as filling a bathtub. Therefore they cannot be remedied merely by providing more information about the climate, but require different modes of communication, including experiential learning environments such as interactive simulations.

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> “Dr. *Burgess*. Well, let me ask you this…. Why do you think it is—if the vast preponderance of science and scientists agree with you and your position [that anthropogenic climate change is real and poses serious risks], why haven’t you closed the deal with the public?
> Mr. *Somerville*. That is a very good question. I think that we, as a science community, suffer as communicators. I think that we have not done a good job of outreach….
> Dr. *Burgess*. ….So why—again, I would pose my question to you—why have you not closed the deal with the public? Why, when I go home to my district and have my town-halls, why is the public not clamoring for me to control carbon in the atmosphere…?”
> —Representative Michael Burgess, M.D., questioning Dr. Richard Somerville, Scripps Institution of Oceanography, 8 March 2011, in US House of Representatives Subcommittee on Energy and Power hearing on “Climate Science and the EPA’s Greenhouse Gas Regulations”; http://bit.ly/etpa11.

1 The challenge of risk communication on climate change

The Intergovernmental Panel on Climate Change (IPCC) constitutes a remarkable mobilization of the world’s best climate scientists and has unquestionably had a major impact on our knowledge of climate change. However, the strong scientific consensus on the detection, attribution, and risks of climate change stands in stark contrast to widespread confusion, complacency and denial among policymakers, the media and the public. Although the IPCC’s Fourth Assessment Report (AR4) clearly states: “Warming of the climate system is unequivocal” and “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations” (IPCC 2007, SPM pp. 2, 5; emphasis in the original), public opinion surveys show the opposite. Americans are now “less worried about the threat of global warming, less convinced that its effects are already happening, and more likely to believe that scientists themselves are uncertain about its occurrence” (Gallup 2010). There is a huge and growing gap between the science and the understanding of that science in society at large. Why does this gulf exist, why does it matter, and what are its implications for the IPCC and scientific community?

Policies to manage complex natural and technical 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. Without effective risk communication, the most thorough risk assessment is, at best, wasted (Olson 2009; Dean 2009). At worst, poor risk communication creates a knowledge vacuum that is then filled by error, disinformation and falsehood—some supplied inadvertently by people without knowledge of the science and some injected deliberately by ideologues and vested interests (Oreskes and Conway 2010).

Here I argue that the effectiveness of the IPCC can be improved through readily implemented changes in the way it creates and presents technical reports and communications intended for policymakers, the media, business leaders and the general public. The recommended changes are grounded in decades of research on the errors and biases arising from the mental models and heuristics we use to evaluate risks and make decisions in complex systems. These errors and biases are common not only among the general public but also among scientists and other highly educated individuals. They arise not only in the context of unfamiliar systems like the climate but also in familiar, everyday contexts such as compound interest or filling a bathtub. Therefore they cannot be remedied merely by providing more information about the climate, but require different kinds of communication, including the use of experiential learning environments such as interactive simulations that allow people to discover, for themselves, the dynamics of complex systems like the climate. While surely not sufficient, the principles articulated here can help improve the effectiveness of scientific communication and overcome the disinformation, political polarization, and denial that now prevent science from informing public policy.

First, I review the large gap between scientific knowledge of climate change and public understanding and describe the challenge of risk communication around complex issues such as climate change. I trace this gap to pervasive errors and biases in judgment and decision making generally, and specifically to people's mental models about the structure and behavior of complex dynamic systems. Where the dynamics of complex systems are conditioned by multiple feedbacks, time delays, accumulations and nonlinearities, mental models, including those of highly educated elites, often fail to account for these elements of dynamic complexity. I conclude with recommendations to improve the way the IPCC, and scientists generally, can communicate complex concepts to policymakers, the media and the public so that both public policy and private behavior can be grounded in the best scientific understanding.

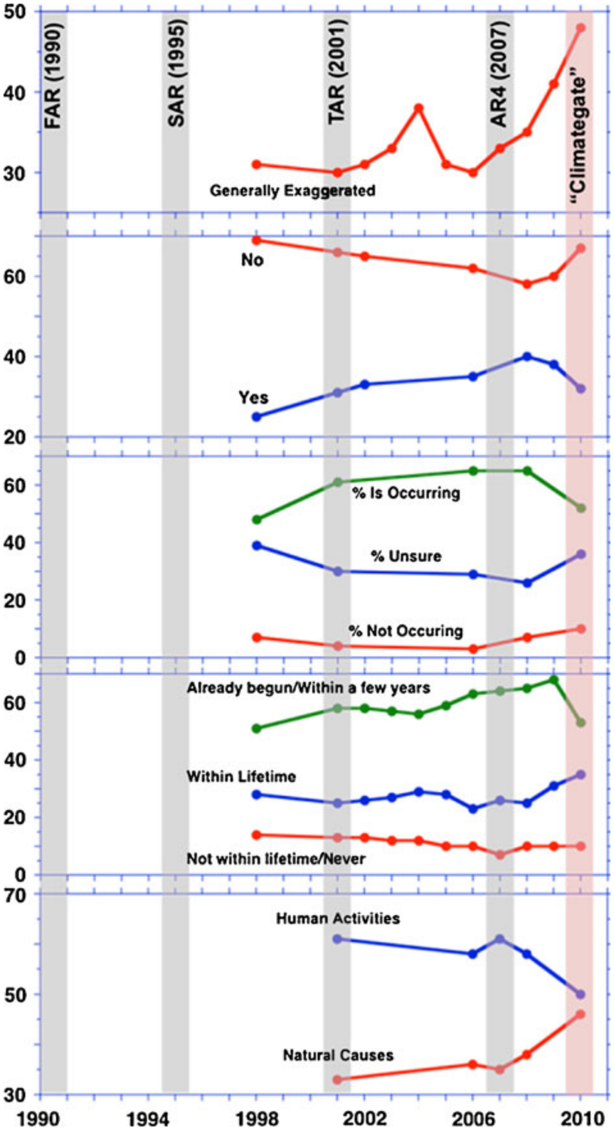
2 The widening gap

The IPCC was established "to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts….Because of its scientific and intergovernmental nature, the IPCC embodies a unique opportunity to provide rigorous and balanced scientific information to decision makers" (www.ipcc.ch/organization/organization.shtml; IPCC 2006). The task is daunting. Scientists from many specialties must work together to synthesize scientific knowledge of an immensely complex system encompassing the climate, the economy and society. Given the difficulties, the IPCC has been extraordinarily successful in the task of synthesis and risk assessment. But that is not sufficient. To fulfill its mission, the IPCC must also communicate that knowledge effectively to diverse constituencies including policymakers, the media and the public.

Unfortunately, although scientific knowledge of climate change has improved dramatically since the founding of the IPCC, public understanding has fallen: "48% of Americans now believe that the seriousness of global warming is generally exaggerated, up from…31% in 1997" (Gallup 2010; Fig. 1). Public opinion in other nations follows roughly similar patterns (Leiserowitz 2007).

More disturbing, US public opinion is now strongly split along partisan lines. Republicans are much more likely than Democrats to deny that climate change is real or poses risks to human welfare (Gallup 2010). Leiserowitz et al. (2010) found 81% of Democrats agree that global warming is happening, but only 47% of Republicans; 68% of Democrats believe global warming is caused mostly by human activities, but only 33% of Republicans. These huge gaps are not disagreements about what should be done to the address risks of global warming, an issue outside the IPCC's mandate. They are disagreements about the scientific facts. Despite the efforts of the IPCC and scientific community, political ideology, not science, increasingly determines what people believe to be true about the physical world.

Some may argue that poor public understanding of climate change is unimportant because the audience for the work of the IPCC is policymakers, who are then expected to communicate with the public. This is incorrect. First, as shown below, highly educated adults with substantial training in Science, Technology, Engineering and Mathematics



"Thinking about what is said in the news, in your view is the seriousness of global warming generally exaggerated, generally correct, or is it generally underestimated?

Do you think that global warming will pose a serious threat to you or your way of life in your lifetime?

…which one of the following statements do you think is most accurate—most scientists believe that global warming is occurring, most scientists believe that global warming is NOT occurring, or most scientists are unsure about whether global warming is occurring or not?

Which of the following statements reflects your view of when the effects of global warming will begin to happen? They have already begun to happen, they will start happening with a few years, they will start happening within your lifetime, but they will affect future generations, (or) they will never happen.

…do you believe increases in the Earth's temperature over the last century are due more to the effects of pollution from human activities (or) natural changes in the environment that are not due to human activities?"

Fig. 1 US public opinion on climate change, as reported by Gallup, with IPCC assessment report publication years. The stolen so-called "Climategate" emails were made public in November 2009, just prior to the Copenhagen climate conference (December 2009). Presentation order for choices in the Gallup questions are rotated. See www.gallup.com/poll/126560/americans-global-warming-concerns-continue-drop.aspx

(STEM) suffer from systematic biases in judgment and decision-making and in assessing the dynamics of the climate-economy system. There is no reason to believe policymakers are immune to these problems. Second, whether policymakers seek to understand the science depends on whether the public values leaders who value science. Even if policymakers fully understood climate science, their ability to implement policies consistent with that knowledge, given societal goals, is constrained by the lack of grassroots political support. The public cannot be ignored.

However, when science conflicts with "common sense" people are unlikely to favor or adopt policies consistent with science (Fischhoff 2007, 2009; Morgan et al. 2001; Slovic 2000; Bostrom et al. 1994; Read et al. 1994). Strong scientific evidence documents the benefits of seat belts, motorcycle helmets, and childhood vaccinations, yet legislation mandating their use took decades. Citizen groups campaign actively against many of these policies, and compliance remains spotty. The connection between actions and outcomes in these cases is far simpler than the connection between GHG emissions, climate and human welfare.

Effective risk communication strategies begin with a deep understanding of the mental models of the relevant audience, as Morgan et al. (2001, 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."

What then are the mental models people hold about complex dynamic systems such as the climate and economy?

3 Scientific literacy

Studies consistently show low levels of reading comprehension, scientific literacy and numeracy among members of the public in the US and other nations (Kutner et al. 2007; Gonzales et al. 2009; Hartley et al. 2011). Most people, including most policymakers, legislators, and their advisors, have not been trained in STEM. Lacking basic scientific knowledge, policymakers and the public have difficulty understanding the IPCC's reports, including the *Summary for Policymakers* (SPM), a document intended for, well, policymakers and other nonscientists. To assess the readability of the SPM, I calculated the Gunning Fog index, a measure of the number of years of education required to understand a text. The Fog index for the AR4 SPM is nearly 17, indicating post-graduate training is needed to understand it.[1] That estimate certainly understates the problem. The Fog index considers only sentence and word length, while the SPM includes complex graphics, technical jargon ("anthropogenic GHG concentrations", "paleoclimatic", "climate-carbon cycle feedbacks"), chemical terms and formulae (perfluorocarbons, CO_2, CH_4) and unfamiliar units of measure (ppm, ppb, W/m^2, $GtCO_2$-eq/yr).

The problem is not just readability, but a huge gap between people's understanding of basic science and the explanations in the SPM. For example, Leiserowitz and Smith (2010) asked US adults how much various factors "affect the average global temperature of the earth," finding 56% chose "A lot" "Some" or "A little" for earthquakes, and 44% chose those options for the phases of the moon. Asked how much various items contribute to global warming, 76% chose "A lot" "Some" or "A little" for "Aerosol spray cans," only

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[1] The Gunning Fog index is given by $0.4(W/S)+100(W_3/W)$ where W is the number of words in the text, S is the number of sentences, and W_3 is the number of words of three or more syllables. Fog index calculated by www.editcentral.com/gwt1/EditCentral.html (result: 16.7) and www.online-utility.org/english/readability_test_and_improve.jsp (result: 16.9).

slightly less than the 80% choosing those options for “Burning fossil fuels for heat and electricity.”

4 Poor inquiry skills

The heuristics people commonly use in judgment and decision-making lead to a host of systematic errors and biases. The research is well known, so I provide only a brief survey (see, e.g., Kahneman et al. 1982; Plous 1993; Kahneman and Tversky 2000; Gilovic et al. 2002). We violate basic rules of probability and do not update our beliefs according to Bayes' rule. We underestimate uncertainty (overconfidence bias), assess desirable outcomes as more likely than undesirable outcomes (wishful thinking), and believe we can influence the outcome of random events (the illusion of control). We make different decisions based on the way the data are presented (framing) and when exposed to irrelevant information (anchoring). We credit our personal experience and salient information too highly and underweight more reliable but less visceral data such as scientific studies (availability bias, base rate fallacy). We are swayed by a host of persuasion techniques that exploit our emotions and our desire to avoid cognitive dissonance, to be liked, and to go with the crowd (Cialdini 2009).

More troubling, people generally do not reason in accordance with the principles of scientific method. We do not generate sufficient alternative explanations for a phenomenon, do not adequately control for confounding variables, and seek evidence consistent with prior beliefs rather than potential disconfirmation (confirmation bias). We revise beliefs and even memories after events so that we feel “we knew it all along” (hindsight bias). In constructing causal explanations, we tend to assume each effect has a single cause and infer causal relationships on the basis of covariation, proximity in time and space, and similarity (Einhorn and Hogarth 1986). Scientists and professionals, not only “ordinary” people, suffer from many of these judgmental biases (Cialdini 2009; Connolly et al. 2000; Gilovic et al. 2002; Tetlock 2005).

Our judgments are also strongly affected by unconscious processes. Risen and Critcher (2011) asked people to complete a survey under a variety of warm or cool conditions. People's belief in global warming was significantly higher in the warm conditions than the cool, while responses to items unrelated to heat were not affected. Li et al. (2011) found people in the US and Australia expressed more belief in and were more concerned about global warming if they perceived the temperature that day to be warmer than usual. Egan and Mullin (2011) integrated survey data with local weather conditions when participants completed the survey, finding “For each three-and-a-half degrees Fahrenheit that local temperature rises above normal, Americans become one percentage point more likely to agree that there is ‘solid evidence’ that the earth is getting warmer” (p. 2).

5 Mental models of complex systems

The judgmental errors and biases described above are particularly acute in complex dynamic systems. Whereas complex systems such as the climate and economy are dynamic, tightly coupled, governed by feedback, nonlinear, self-organizing, adaptive and evolving, our mental models tend to be static and narrow. We are often unaware of the delayed and distal impacts of our decisions, overemphasizing the local and short term. We don't understand the process of accumulation (stocks and flows), feedback, time delays, nonlinearity and other concepts necessary to understand the dynamics of complex systems such as the climate and economy (Sterman 1994). These errors have profound implications for risk communication.

5.1 Stocks and flows

The process of accumulation—stocks and the flows that alter them—is fundamental to understanding dynamics in general and the climate-economy system in particular. The stock of CO_2 in the atmosphere accumulates the flow of CO_2 emissions less the flow of CO_2 from the atmosphere to biomass and the ocean. The mass of the Greenland ice sheet accumulates snowfall less melting and calving. The stock of coal-fired power plants is increased by construction and reduced by decommissioning. And so on.

People should have good intuitive understanding of accumulation because stocks and flows are pervasive in everyday experience. Yet research shows that people's intuitive understanding of stocks and flows is poor in two ways that cause error in assessing climate dynamics. First, people have difficulty relating the flows into and out of a stock to the level of the stock, even in simple, familiar contexts such as bank accounts and bathtubs. Second, narrow mental model boundaries mean people are often unaware of the networks of stocks and flows in a system.

Poor understanding of accumulation leads to serious errors in reasoning about climate change. Sterman and Booth Sweeney (2007) gave graduate students at MIT a description of the relationships among GHG emissions and atmospheric concentrations excerpted from the SPM in the IPCC's Third Assessment Report. Participants were then asked to sketch the emissions trajectory required to stabilize atmospheric CO_2 by 2100 at various concentrations. To draw attention to the stock-flow structure, participants were first directed to estimate future net removal of CO_2 from the atmosphere (net CO_2 taken up by the oceans and biomass), then draw the emissions path needed to stabilize atmospheric CO_2. The dynamics are easily understood without knowledge of calculus or climate science using a bathtub analogy: atmospheric CO_2 rises when the inflow to the tub (emissions) exceeds the outflow (net removal), is unchanging when inflow equals outflow, and falls when outflow exceeds inflow. Yet, 84% violated these principles of accumulation. Most (63%) erroneously asserted that stabilizing emissions above net removal would stabilize atmospheric CO_2—analogous to arguing a bathtub continuously filled faster than it drains will never overflow. The false belief that stabilizing emissions would quickly stabilize the climate not only violates mass balance, one of the most basic laws of physics, but leads to complacency about the magnitude and urgency of emissions reductions required to mitigate climate change risk (Sterman 2008).

It might be argued that people understand the principles of accumulation but don't understand the carbon cycle or climate context. But the same errors arise in familiar settings such as bathtubs and bank accounts (Booth Sweeney and Sterman 2000; Sterman 2002; Cronin et al. 2009). Moreover, training in science does not prevent these errors. Three-fifths of the participants had degrees in STEM; most others were trained in economics. These individuals are demographically similar to, and many will become, influential leaders in business and government, though with more STEM training than most. Merely providing more information on the carbon cycle will not alter the false belief that stabilizing emissions would quickly stabilize the climate.

5.2 Time delays

People routinely ignore or underestimate time delays (Sterman 1989, 2000; Buehler et al. 2002). Underestimating time delays leads people to believe, wrongly, that it is prudent to "wait and see" whether a potential environmental risk will actually cause harm. Many citizens, including many who believe climate change poses serious risks, advocate a wait-and-see approach, reasoning that uncertainty about the causes and consequences of climate change means 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. To be a prudent response to the risks of climate change, wait-and-see policies require short delays in all the links of a long causal chain, stretching from the detection of adverse climate impacts to the implementation of mitigation policies to the resulting emissions reductions to changes in atmospheric GHG concentrations to radiative forcing to surface warming to changes in ice cover, sea level, weather patterns, agricultural productivity, habitat loss and species distribution, extinction rates, and other impacts. Contrary to the logic of "wait and see" there are long delays in every link of the chain.

More problematic, the short- and long-run impacts of policies are often different (Forrester 1969; Sterman 2000; Repenning and Sterman 2001). Such "Worse Before Better" and "Better Before Worse" behavior is common: restoring a depleted fishery requires cutting the catch today; credit card debt boosts consumption today but forces austerity when the bills come due. The tradeoff between short- and long-run responses is particularly difficult in the context of climate change because the lags are exceptionally long. Standard frameworks for intertemporal tradeoffs such as discounting are problematic because potentially catastrophic events sufficiently far in the future, such as sea level rise from the loss of the Greenland or West Antarctic ice sheets, are given essentially no weight even if discount rates are small. Further, people commonly exhibit inconsistent time preferences (Frederick et al. 2002). For example, people often prefer two candy bars in 101 days over one candy bar in 100 days, but prefer one bar today over two tomorrow, a violation of standard assumptions of rational decision theory. The preference for immediate gratification, which appears to have a neurological basis (McClure et al. 2004), often leads people to avoid actions with long-term benefits they themselves judge to be desirable, over and above the usual effects of discounting.

5.3 Misperceptions of feedback

The climate and economy are feedback rich systems. Understanding their dynamics and the likely impact of policies requires an ability to (1) recognize and (2) understand a diverse array of feedbacks, both positive and negative, and their (highly nonlinear) interactions. Few mental models, however, incorporate feedback processes. Axelrod's (1976) classic study of the mental models of political elites found few considered any feedback loops. Dörner (1980, 1996) found that people tend to think in single-strand causal series and had difficulty in systems with side effects and multiple causal pathways, much less feedback loops. Booth Sweeney and Sterman (2007) found limited recognition of feedback processes among both middle school students and their teachers in ecological and economic contexts.

Even when the concept of closed loops is explained, the concepts of positive and negative feedback are poorly understood. For most people, "positive feedback" means praise, while "negative feedback" is a euphemism for criticism. The confusion is not merely semantic, but arises from open-loop mental models. People routinely assume that positive (negative) feedback is good (bad) and have difficulty understanding that feedbacks can be either beneficial or harmful depending on one's values and on which way the loop is operating. Consider the familiar positive feedback of compound interest: The greater the outstanding balance on one's credit card, the higher the monthly interest, so (*ceteris paribus*) the greater the balance and the higher still the interest due. When debt is growing, that positive feedback is "bad" for the debtor but "good" for the card issuer (until the debtor defaults; a nonlinear regime shift). But if the debtor starts paying down the debt, the same positive feedback speeds elimination of the balance, a process the debtor finds pleasing, while it erodes the lender's profit. The confusion of positive/negative feedback with good/bad is particularly problematic in the context of climate change, where the negative feedbacks of black body radiation and CO_2 fertilization help limit warming, while positive climate-carbon cycle feedbacks worsen it.

Compounding the misperceptions of feedback in people's mental models, research also shows that people do not understand the behavior of even the simplest feedback systems. We tend to extrapolate linearly instead of exponentially even in obvious positive feedback systems (Wagenaar 1978; Wagenaar and Sagaria 1975). The phenomenon is readily demonstrated with the famous "paper folding" task. I begin with an ordinary sheet of copy paper, which I show participants is about 0.1 mm thick:

> Consider an ordinary sheet of paper like this one. Fold it in half. Fold the sheet in half again. The paper is still less than half a millimeter thick. If you were to fold the paper 40 more times, how thick would it be? Do not use a calculator. We are interested in your intuitive judgment. Along with your estimate, give the 95% upper and lower confidence bound for your estimate (that is, a range you are 95% sure includes the right answer. Your 95% confidence bound means you believe there is only a 5% chance the correct answer falls outside the upper and lower bounds you give).

	Lower Bound (95% sure it is between lower and upper bound)	**Your Estimate**	**Upper Bound** (95% sure it is between lower and upper bound)
42 Folds			

After 42 doublings the paper would be roughly 440,000 km (≈ 273,000 miles) thick, farther than the distance from the earth to the moon. Typical of results with diverse groups, the median estimate in a sample of 95 graduate students at the MIT Sloan School of Management was 0.05 m (less than two inches), and the mean, skewed by a few higher responses, was 134 km (≈ 83 miles). None of the confidence bounds included the correct value—we not only fail to understand exponential growth, but we are grossly overconfident in our judgments (Lichtenstein et al. 1982). Some students provided the correct formula but still failed to grasp its implications, such as the student who wrote, correctly, "0.1 mm*2^{42}", but gave an upper confidence bound of 1.2 km, less than three-quarters of a mile.

The feedbacks affecting climate dynamics interact nonlinearly, creating the possibility of thresholds and tipping points. Although the term "tipping point" has become a cliché, people generally do not understand nonlinearity or the dynamics of shifting feedback loop dominance (e.g., Paich and Sterman 1993). Worse, poor understanding of time delays, accumulation and feedbacks mean people often trigger tipping inadvertently even when they know a threshold exists. For example, participants in simulated fisheries frequently expand their fleets beyond the maximum sustainable yield, forcing the system over the tipping threshold into the regime in which smaller fish stocks reduce recruitment, leading to still lower stocks and the collapse of the fishery. Overshooting the tipping point persists in laboratory experiments even when the common pool resource problem (the Tragedy of the Commons) is eliminated by assigning perfect property rights (Moxnes 1998, 2004).

6 Policy recommendations

To improve the effectiveness of its reports and communications the IPCC should partner with social scientists, risk communication experts, and communication professionals. These experts should be engaged throughout the assessment process, not brought in at the end. Social scientists and risk communication experts should participate in working group meetings and plenary sessions so they can develop their understanding of climate science and so that climate scientists can develop their understanding of the relevant social science. Climate scientists will not become sociologists and psychologists, nor will social scientists become climatologists and economists. But sustained collaboration is required to overcome the silos that thwart communication across disciplinary boundaries. Taking the science and "throwing it over the wall" to communication specialists will fail.

The IPCC can also learn from the experience of other organizations whose scientific work is effective only to the extent it affects the beliefs and behaviors of policymakers and the public such as the Food and Drug Administration, Centers for Disease Control and Prevention, and National Hurricane Center. As an example, NSF and NOAA recently developed a program to improve hurricane risk communication (http://www.nsf.gov/pubs/2008/nsf08551/nsf08551.pdf).

6.1 Scientific literacy

Reports and other communications, particularly those intended for policymakers and the public, should be written in plain language, with minimal technical jargon. Proposed text and graphics should be tested by communication professionals with representative members of the relevant audiences—policymakers, business leaders, the media and the public at large—then revised and retested until they are both accurate and effective: "one should no more release an untested…[risk] communication than an untested drug" (Fischhoff 2009, p. 950). The process above differs substantially from current IPCC practice in which the SPM is developed from the working group reports by scientists and representatives of IPCC member states.

6.2 Poor inquiry skills

Fischhoff (2009) and Morgan et al. (2001) provide guidelines for improving risk communication in various contexts; Moser and Dilling (2004), Fischhoff (2007) and Weber and Stern (2011) apply them to climate change. These include attending to the impact of information framing and anchors (textual, numeric and graphical), to the availability and salience of examples and so on. They recommend focusing on the most important risks and people's deepest concerns, and on alerting people to ways their judgments may be biased by the way information is presented. Fischhoff (2009, p. 949) concludes that effective communication seeks to "complete mental models, bridging the gaps between expert and lay mental models," "ensure appropriate confidence in beliefs," and "provide information in the order of its expected impact on decisions." These guidelines are notably different from communications that contain a mass of detail in the name of precision or are organized by sectors or academic disciplines.

6.3 Mental models of complex systems

A number of techniques can help with the difficulties people have in understanding the structure and behavior of complex systems.

Stocks, flows and accumulation Pictures of bathtubs with tap and drain (or, better, animations and simulations, see below), help people recognize the presence of important accumulations and understand how the behavior of a stock is related to its flows (Sterman 2010). Such tub diagrams have been used effectively with business executives and other leaders (Sterman 2000, ch. 2). Simple diagrams portraying networks of stocks and the flows of material among them can help people expand the boundaries of their mental models by highlighting the stocks that constitute the sources and sinks for the flows affecting focal stocks such as the stock of CO_2 in the atmosphere (Figs. 2, 3 provide examples).

Time delays Decomposition is helpful in overcoming the tendency to underestimate time delays. People's perceptions about the delays in individual steps are likely to be more salient and accurate than their estimate of the overall delay (Sterman 2000, ch. 11). Scenarios and simulations should include delays in the response of the social and economic system, not only in biogeochemical processes. These include delays in the development and diffusion of scientific information, in opinion change, in the passage of legislation or negotiation of international agreements, in the implementation of such laws, in technological innovation and behavior change resulting from such laws, and in the gradual turnover of existing capital stocks.

Feedback Feedback processes can be represented effectively in the form of causal loop diagrams. Causal diagrams have a precise syntax (Sterman 2000, ch. 5) designed to enhance the ability of nonscientists to understand the feedback structure of complex systems and relate that structure to the likely behavior of the system (Fig. 4 shows some climate-economy examples). The terms "positive" and "negative" feedback should be avoided in communications aimed at policymakers and the public because these terms are conflated with "good" and "bad"; instead use the terms "reinforcing" and "balancing" feedback, respectively. Analogies with familiar systems such as thermostats and compound interest help explain unfamiliar processes such as the balancing CO_2 fertilization and reinforcing ice-albedo feedbacks. Simple diagrams showing a few feedbacks are better than comprehensive "spaghetti" diagrams.

6.4 Interactive learning through simulation

To fulfill its mission, the IPCC should develop a suite of interactive simulations and learning environments for policymakers and the public as an integral component of the next assessment report. Why? Effective risk communication must catalyze learning at a level deep enough to change entrenched mental models, attitudes and behaviors. Mere transmission of information in reports and presentations is not sufficient (Weber and Stern 2011).

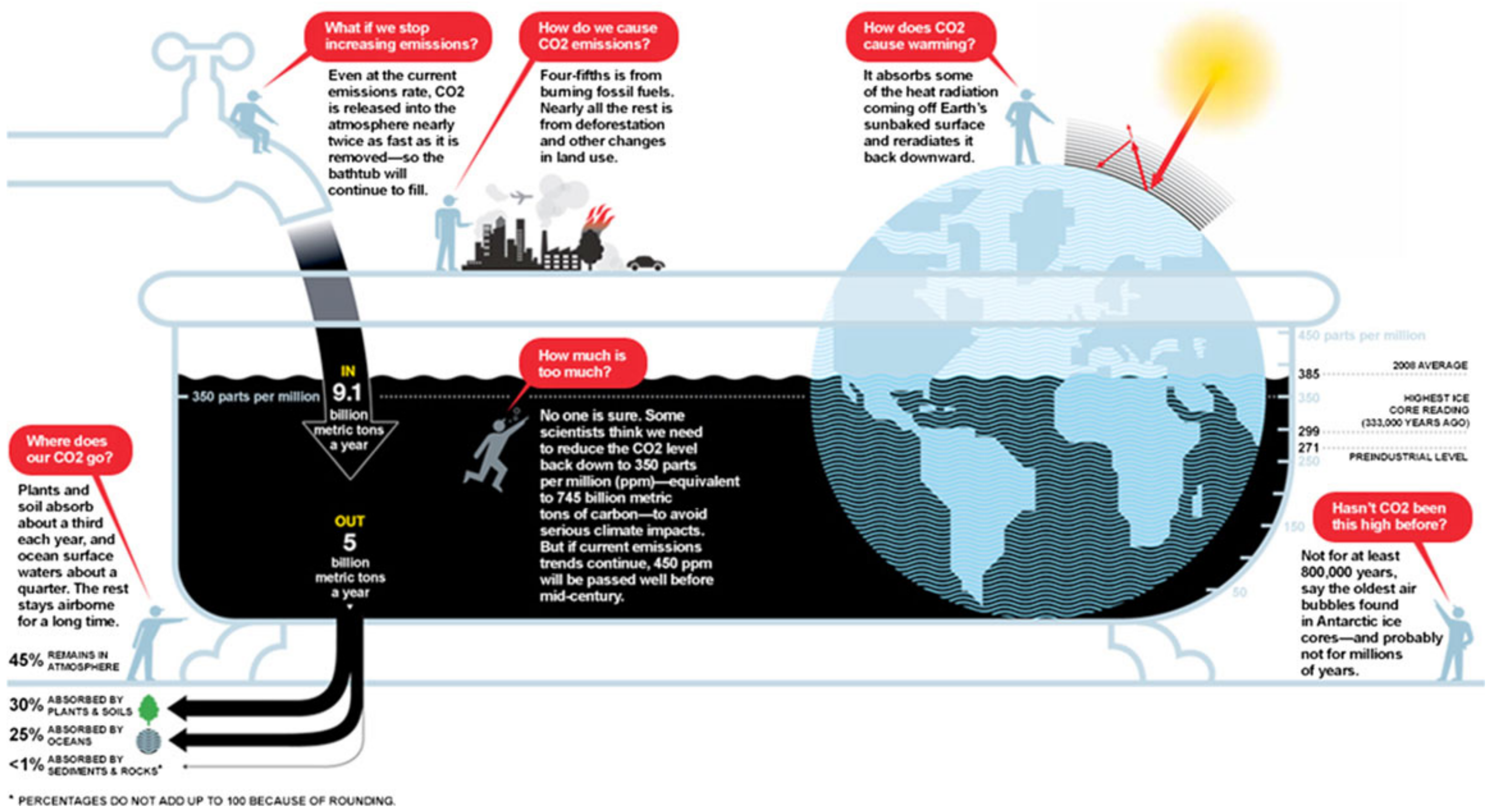

Fig. 2 Portraying stocks and flows: The "Carbon Bathtub" (Source: Graphic: Nigel Holmes. Sources: John Sterman, MIT; David Archer, Univ. of Chicago; Global Carbon Project. *National Geographic*, Dec. 2009; available at ngm.nationalgeographic.com/big-idea/05/carbon-bath)

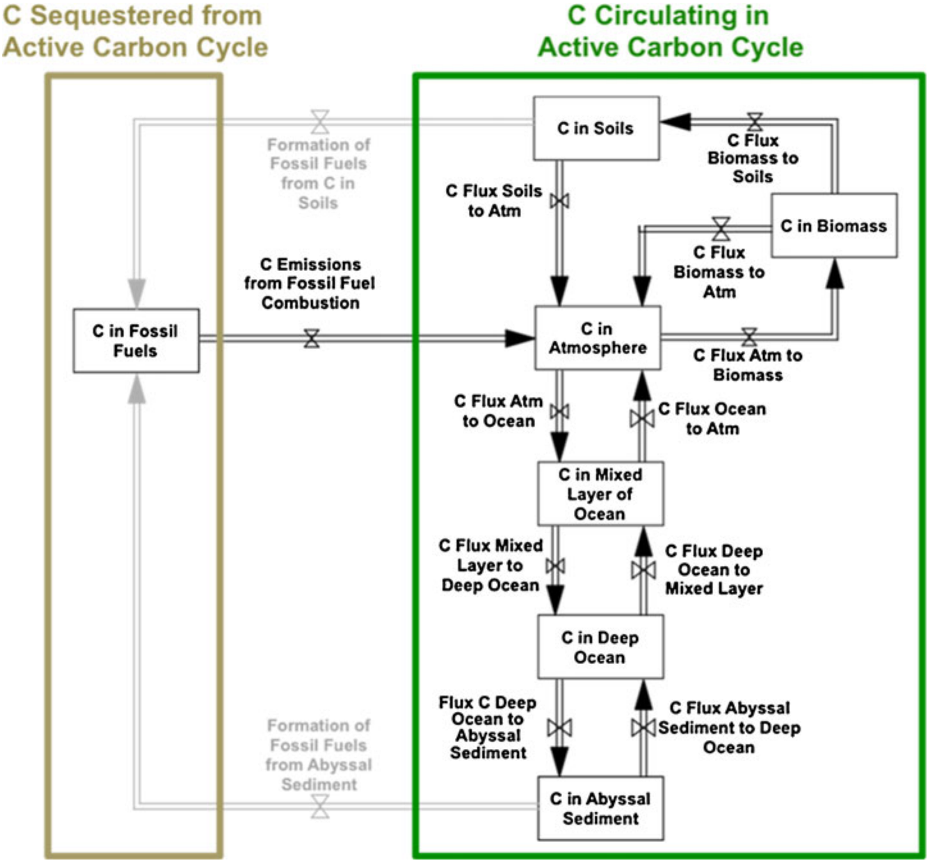

Fig. 3 Stock-flow diagram of the carbon cycle, useful after people understand the bathtub concept, to help them expand the boundaries of their mental models to include the sources and sinks for the flows of carbon into and out of the atmosphere. Boxes denote stocks, pipes and valves denote flows. Fossil fuel use injects carbon that has been sequestered for millions of years into the atmosphere, where it is taken up by biomass or dissolves in the ocean, but eventually cycles from these stocks back into the atmosphere. Flows showing the formation of fossil fuels from carbon in terrestrial soils and ocean sediments are shown in gray because these flows are, relative to human time scales, essentially zero. The diagram does not show flows of C associated with the formation and weathering of limestone and other rocks as these flows are, on human time scales, unchanging

There is no learning without feedback, without knowledge of the results of our actions. Scientists usually generate that feedback through controlled experimentation, an iterative process through which intuitions are challenged, hypotheses tested, insights generated, new experiments run. When experiments are impossible, as in the climate-economy system, scientists rely on models and simulations, which enable controlled experimentation in virtual worlds (Sterman 1994, Edwards 2010). Learning arises in the process of interacting with the models, hypothesizing how the system might respond to policies, being surprised, forming new hypotheses, testing these with new simulations and data from the real world. Paradoxically, however, scientists, having deepened their understanding through an iterative, interactive learning process, often turn around and tell the results to policymakers and the public through reports and presentations, expecting them to change their beliefs and behavior, then express surprise when these groups—excluded from the process, unable to

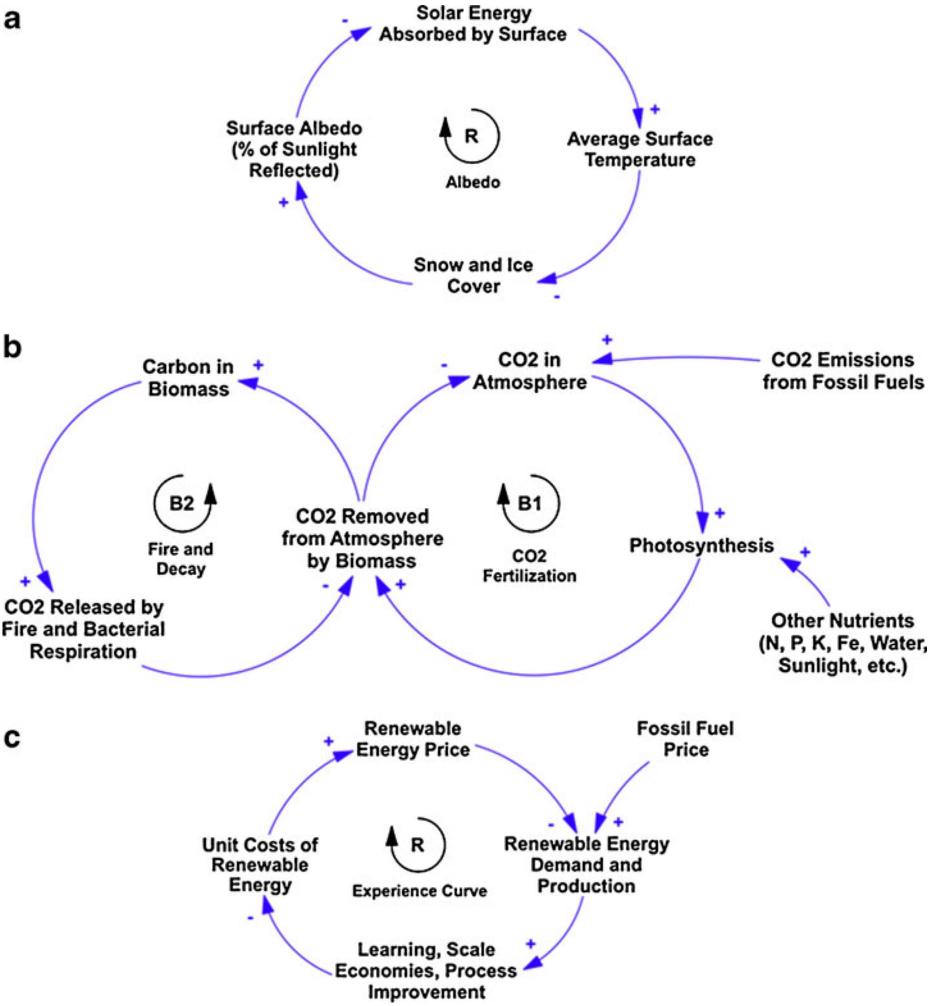

Fig. 4 Causal diagrams illustrating feedback processes. *Arrows* indicate causal influence; arrow polarity, e.g., x—>$^{+}$y, indicates an increase in x raises y above what it would have been otherwise; x—>$^{-}$y indicates an increase in x lowers y below what it would have been otherwise (Sterman 2000, ch. 5 provides formal definitions and examples). **a** Reinforcing (*positive*) ice-albedo feedback. For clarity, the diagram shows a single loop. **b** Balancing (*negative*) feedbacks around CO_2 fertilization. Diagram shows two loops to illustrate constraints on net CO_2 uptake by biomass. **c** Reinforcing feedback arising from learning curves and scale economies that lowers the price of low-carbon, renewable energy as the industry develops

assess the evidence on their own and presented with claims that conflict with deeply held beliefs—resist the message and challenge the authority of the experts.

Interactive, transparent simulations of the climate, rigorously grounded in and consistent with the best available science, are now available. To enable learning, the models must give people control over assumptions and scenarios, encourage wide-ranging sensitivity analysis, and run nearly instantly. Examples range from simple models to help people develop their understanding of stocks and flows (e.g., http://bit.ly/atmco2, http://bit.ly/stockflow, Moxnes and Saysel 2009) to more comprehensive models such as the C-LEARN and C-ROADS climate policy simulators (http://climateinteractive.org). These simulations are being used by a variety of policymakers and in interactive workshops for business leaders, educators and the public at large.

When experimentation is impossible, when the consequences of our decisions unfold over decades and centuries, that is, for climate change and many of the important issues we face, simulation becomes the main—perhaps the only—way we can discover *for ourselves* how complex systems work, what the impact of different policies might be, and thus integrate science into decision making.

References

Axelrod R (1976) The structure of decision: the cognitive maps of political elites. Princeton University Press, Princeton

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

Booth Sweeney L, Sterman J (2007) Thinking about systems: students' and their teachers' conceptions of natural and social systems. Syst Dynam Rev 23(2–3):285–312

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

Buehler R, Griffin D, Ross M (2002) Inside the planning fallacy: the causes and consequences of optimistic time predictions. In: Gilovich T, Griffin D, Kahneman D (eds) Heuristics and biases. Cambridge Univ. Press, Cambridge, pp 250–270

Cialdini R (2009) Influence: science and practice, 5th edn. Pearson, Boston

Connolly T, Arkes H, Hammond K (2000) Judgment and decision making, 2nd edn. Cambridge University Press, Cambridge

Cronin M, Gonzalez C, Sterman J (2009) Why don't well-educated adults understand accumulation? a challenge to researchers, educators, and citizens. Organ Behav Hum Decis Process 108(1):116–130

Dean C (2009) Am I making myself clear? A scientist's guide to talking to the public. Harvard University Press, Cambridge

Dörner D (1980) On the difficulties people have in dealing with complexity. Simulation & Games 11(1):87–106

Dörner D (1996) The logic of failure. Metropolitan Books/Henry Holt, New York

Ediwards P (2010) A vast machine. MIT Press, Cambridge

Egan P, Mullin M (2011) Turning personal experience into political attitudes: the effect of local weather on Americans' perceptions about global warming. Working paper, New York University, March; available at http://politics.as.nyu.edu/docs/IO/4819/egan_mullin_mar2011.pdf

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

Fischhoff B (2007) Non-persuasive communication about matters of greatest urgency: climate change. Environ Sci Technol 41:7204–7208

Fischhoff B (2009) Risk perception and communication. In: Detels R, Beaglehole R, Lansang M, Gulliford M (eds) Oxford textbook of public health, 5th edn. Oxford University Press, Oxford, pp 940–952

Forrester JW (1969) Urban dynamics. MIT Press, Cambridge

Frederick S, Loewenstein G, O'Donoghue T (2002) Time discounting and time preference: a critical review. J Econ Lit 40(2):351–401

Gallup (2010) Americans' global warming concerns continue to drop. Available at www.gallup.com/poll/126560/americans-global-warming-concerns-continue-drop.aspx

Gilovic T, Griffin D, Kahneman D (2002) Heuristics and biases: the psychology of intuitive judgment. Cambridge University Press, Cambridge

Gonzales P, Williams T, Jocelyn L, Roey S, Kastberg D, Brenwald S (2009) Highlights from TIMSS 2007: mathematics and science achievement of U.S. fourth- and eighth-grade students in an international context (NCES 2009–001 Revised). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. Washington, DC; available at nces.ed.gov/pubs2009/2009001.pdf

Hartley L, Wilke B, Schramm J et al (2011) College students' understanding of the carbon cycle: contrasting principle-based and informal reasoning. Bioscience 61:65–75

IPCC (2006) Principles governing IPCC work. Approved at the Fourteenth Session (Vienna, 1–3 October 1998) on 1 October 1998, amended at the 21st Session (Vienna, 3 and 6–7 November 2003) and at the 25th Session (Mauritius, 26–28 April 2006); available at http://www.ipcc.ch/pdf/ipcc-principles/ipcc-principles.pdf

IPCC (2007) Climate Change 2007: the physical science basis. Cambridge University Press, Cambridge UK; available at www.ipcc.ch

Kahneman D, Tversky A (2000) Choices, values and frames. Cambridge University Press, Cambridge

Kahneman D, Slovic P, Tversky A (1982) Judgment under uncertainty: heuristics and biases. Cambridge University Press, Cambridge

Kutner M, Greenberg E, Jin Y, Boyle B, Hsu Y, Dunleavy E (2007) Literacy in everyday life: results from the 2003 national assessment of adult literacy (NCES 2007–480). U.S. Department of Education. National Center for Education Statistics, Washington, DC; available at nces.ed.gov/Pubs2007/2007480.pdf

Leiserowitz A (2007) Public perception, opinion and understanding of climate change—current patterns, trends and limitations (UNDP, New York); available at hdr.undp.org/en/reports/global/hdr2007-2008/papers/leiserowitz_anthony.pdf

Leiserowitz A, Smith N (2010) Knowledge of climate change across global warming's six Americas. Yale University, New Haven CT: Yale Project on Climate Change Communication. Available at environment.yale.edu/climate/files/Knowledge_Across_Six_Americas.pdf

Leiserowitz A, Smith N, Marlon J (2010) Americans' knowledge of climate change. Yale University. New Haven, CT: Yale Project on Climate Change Communication; available at environment.yale.edu/climate/files/ClimateChangeKnowledge2010.pdf

Li Y, Johnson E, Zaval L (2011) Local warming: daily temperature change influences belief in global warming. Psychol Sci 22(4):454–459

Lichtenstein S, Fischhoff B, Phillips L (1982) Calibration of probabilities: the state of the art to 1980. In: Kahneman D, Slovic P, Tversky A (eds) Judgment under uncertainty: heuristics and biases. Cambridge University Press, Cambridge

McClure S, Laibson D, Loewenstein G, Cohen J (2004) Separate neural systems value immediate and delayed monetary rewards. Science 306:503–507

Morgan G, Fischhoff B, Bostrom A, Atman C (2001) Risk communication: a mental models approach. Cambridge Univ. Press, Cambridge

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

Moxnes E (1998) Not only the tragedy of the commons: misperceptions of bioeconomics. Manag Sci 44 (9):1234–1248

Moxnes E (2004) Misperceptions of basic dynamics: the case of renewable resource management. Syst Dynam Rev 20(2):139–162

Moxnes E, Saysel AK (2009) Misperceptions of global climate change: information policies. Clim Change 93(1–2):15–37

Olson R (2009) Don't be such a scientist. Island Press

Oreskes N, Conway E (2010) Merchants of doubt. Bloomsbury Press

Paich M, Sterman J (1993) Boom, bust, and failures to learn in experimental markets. Manag Sci 39 (12):1439–1458

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

Repenning N, Sterman J (2001) Nobody ever gets credit for fixing problems that never happened: creating and sustaining process improvement. Calif Manage Rev 43(4):64–88

Risen J, Critcher C (2011) Visceral fit: while in a visceral state, associated states of the world seem more likely. J Pers Soc Psychol 100(5):777–793

Slovic P (ed) (2000) The perception of risk. Earthscan, London

Sterman J (1989) Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. Manag Sci 35(3):321–339

Sterman J (1994) Learning in and about complex systems. Syst Dynam Rev 10(2–3):291–330

Sterman J (2000) Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill

Sterman J (2002) All models are wrong: reflections on becoming a systems scientist. Syst Dynam Rev 18(4):501–531

Sterman J (2008) Risk communication on climate: mental models and mass balance. Science 322:532–533

Sterman J (2010) Does formal system dynamics training improve people's understanding of accumulation? Syst Dynam Rev 26(4):316–334

Sterman J, Booth Sweeney L (2007) Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter. Clim Change 80(3–4):213–238

Tetlock P (2005) Expert political judgment. Princeton Univ. Press, Princeton

Wagenaar W (1978) Intuitive prediction of growth. In: Burkhardt D, Ittelson W (eds) Environmental assessment of socioeconomic systems. Plenum, New York

Wagenaar W, Sagaria S (1975) Misperception of exponential growth. Percept Psychophys 18:416–422

Weber E, Stern P (2011) Public understanding of climate change in the United States. Am Psychol 66(4):315–328