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# Misperceptions of global climate change: information policies

**Erling Moxnes · Ali Kerem Saysel**

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**Abstract** Previous experimental studies have found that people generally misperceive the basic dynamics of renewable resources, and in particular the accumulation of greenhouse gases (GHGs) in the atmosphere. The purpose of the present laboratory experiment is to find out why people misperceive the dynamics of $CO_2$ accumulation and how misperceptions could be avoided. Using a simulator, 242 subjects were each asked to control total global emissions of $CO_2$ to reach a given target for the stock of $CO_2$ in the atmosphere. Consistent with previous investigations we find a strong tendency for people to overshoot the stated goal. Furthermore, our results point out that people need help to develop proper mental models of $CO_2$ accumulation and they need motivation to reconsider inappropriate decision heuristics. Based on these results and the literature on conceptual change a new information strategy is designed. To motivate, it imposes cognitive conflict; and to facilitate new understanding, it provides simple analogies. A new test shows promising learning effects. The results have important implications for the Intergovernmental Panel on Climate Change (IPCC), governments, and media covering the climatic change issue as well as for general education.

## 1 Introduction

Unlike many familiar tasks, the global climate cannot be properly controlled by reacting to recent changes in climate. Long delays between changes in emission

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E. Moxnes
System Dynamics Group, Department of Geography, University of Bergen,
Fosswinkelsgt. 6, 5007 Bergen, Norway
e-mail: erling.moxnes@ifi.uib.no

A. K. Saysel (✉)
Institute of Environmental Sciences, Boğaziçi University,
34342 Bebek, İstanbul, Turkey
e-mail: ali.saysel@boun.edu.tr

policies, emissions of GHGs, the atmospheric concentrations of GHGs, and finally temperatures and climate, imply that simply reacting to available information (feedback strategies) will lead to "overshooting behaviour." That is, if unacceptable problems occur, feedback policies will not prevent the problems from getting much worse before the policies start to have an effect. Therefore policies must be based on formal climate models.

Knowledge about the key relationships in the climate models is essential for the formation of proper mental models[1] among politicians and voters, who in democratic nations have much to say over public policies to control emissions of GHGs. Without a minimum of understanding of these relationships, lay people are invited to accept radical statements about the need to cut world emissions of for instance $CO_2$ by about 70%[2] just to stabilise the currently high level of $CO_2$ over the next hundred years. Most people are likely to dismiss or play down the importance of such radical information if it does not comply with their own understanding (mental models). Hence two very important questions are: do people have appropriate mental models of $CO_2$ accumulation and if not, how could their mental models be improved? These are the two questions that are addressed in this paper.

There are many aspect of the climate change problem that could be misperceived.[3] Our focus is on the dynamics of $CO_2$ accumulation. Numerous studies have found that people have great difficulties understanding and controlling dynamic systems (Sterman 1989; Funke 1991; Brehmer 1992; Rouwette et al. 2004). Of special interest are studies of renewable resources (Moxnes 1998a, 2004; Jensen 2005) that all have found overshooting tendencies even when the commons problem has been ruled out by the experimental design. Of particular relevance here is a study of global warming by Sterman and Booth Sweeney (2002) and an updated version of this study (Sterman and Sweeney 2007), the latter will be referred to as S&S. We build on the above studies in a set of laboratory experiments with novel treatment designs.

S&S found a strong tendency towards what they call pattern matching: when subjects were asked to increase the $CO_2$ concentration they increased global emissions, when they were asked to reduce the concentration they decreased emissions. In both cases emissions should have been reduced. This behaviour is consistent with a static mental model where the concentration is an algebraic function of emissions, for instance proportional. Moxnes (1998b) found strong indications that people tend to reason in accordance with static mental models when dealing with

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[1] A mental model is a person's mental representation of the structure of a system. It can range from a formal mathematical model which can be used to derive optimal policies to a simple classification which guides the choice among a repertoire of heuristics. See Doyle and Ford (1998).

[2] In IPCC's third Assessment Report (IPCC 2001a, p. 76), based on the two fast carbon cycle models Bern-CC and ISAM, alternative stable $CO_2$ concentration scenarios and their associated $CO_2$ emission trajectories are illustrated. A careful investigation of these graphs reveal that for any reasonably stable $CO_2$ concentration over the next 100 years, future $CO_2$ emissions have to be reduced to about one third or one fourth of the current rate.

[3] People misperceive causes and consequences of climate change and confuse the climate problem with, for instance, ozone depletion (Kempton 1991; Bell 1994; Bostrom et al. 1994; Read et al. 1994; Bord et al. 1998; Dunlap 1998; Groves and Pugh 1999; Meadows and Wiesenmayer 1999; Seacrest et al. 2000; Stamm et al. 2000). Also, people tend to build their expectations on climate extremes and own experiences rather than scientific models (Rebetez 1996; Shanahan and Good 2000; Palutikof et al. 2004).

renewable resources. However, mismanagement could also be caused by an inability to reason about behaviour. Whether the problem pertains to models or behaviour matters for information policies. To answer this question we use two treatments; one control task, and one identical task framed as a more easily visualisable and familiar air mattress. The test suggests that people have greater difficulties forming proper models of atmospheric $CO_2$ than of the more familiar task.

This means that one is faced with a problem of mental model change or conceptual change (Posner et al. 1982). In effect, people are confronted with a difficult problem similar in kind to what outstanding scientists have experienced before major breakthroughs. A priori, one should not expect everybody to form proper mental models without guidance (Kirschner et al. 2006). We test three information treatments. First we employ a balloon analogy to guide subjects in the $CO_2$ task. Analogies are used by scientists and in brainstorming and they are thought to help construct mental models and to provide “comfort and security” (Venville and Treagust 1996). Used in isolation, this analogy leads to no improvement. A likely reason is that the subjects are sufficiently confident in their own understanding that analogies seem redundant. The second information treatment is a phase diagram. While the phase diagram is a very efficient tool for researchers to analyse dynamic problems, our results show that the general public is not ready for this diagram. The third information treatment is outcome feedback about the $CO_2$ concentration. It leads to improved results. However, we argue that feedback about the $CO_2$ level may be of little importance in real life. On the other hand, insights from this treatment can be used to produce cognitive conflict (Limon 2001; Meadows and Wiesenmayer 1999) in terms of contradictory data to motivate subjects to consider analogies.

In the following we describe the experimental design, the underlying simulation model, the task of controlling global $CO_2$ emissions, and the different experimental hypotheses and treatments (between subject designs). Based on the obtained results, we construct a new information strategy which combines cognitive conflicts and analogies. A test of this strategy shows positive learning effects among 70 high school students. We point out implications for information policies of IPCC, governments, and media as well as for education in general.

## 2 The model

Although the world’s climate system is very complex, the dynamics of the most important greenhouse gas, $CO_2$, can be well approximated by a simple model (first order differential equation). The stock-and-flow diagram[4] in Fig. 1 illustrates the dynamics of anthropogenic $CO_2$. The stock of $CO_2$ in the atmosphere (rectangular box) increases by emissions (pipe with a valve) and decreases by absorption of terrestrial and ocean ecosystems. As long as the $CO_2$ emission rate (inflow) exceeds the absorption rate (outflow), the stock of $CO_2$ continues to increase. Only when the absorption rate equals the emission rate, the stock is stabilised. The arrow from the $CO_2$-stock to the absorption rate illustrates that the outflow depends on the stock ($CO_2$-concentration).

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[4] Diagram introduced by Forrester (1961).

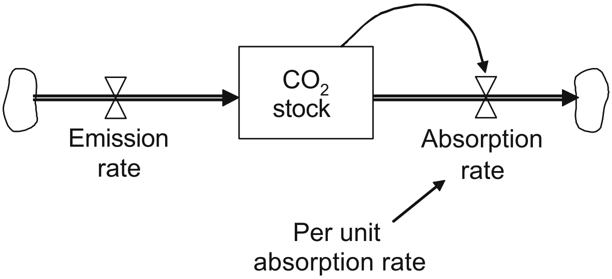

**Fig. 1** Stock-and-flow diagram of anthropogenic $CO_2$

The differential equation analogy of the stock-and-flow diagram is

$$\frac{\mathrm{d}S}{\mathrm{d}t} = E - aS \tag{1}$$

where $S$ is the stock of $CO_2$ measured in gigatons of carbon (GtC) *above* the pre-industrial level.[5] $E$ is anthropogenic carbon emissions in GtC per year and $a$ is the per unit absorption rate. This model gives a very good fit to historical data (1900 to 2000) for $a = 0.023$ per year (Moxnes and Saysel 2004). Saturation of sinks implies that $a$ will be reduced over time and we have chosen a value $a = 0.013$ per year (corresponding to a lifetime of 77 years for atmospheric $CO_2$). This $a$-value makes the model replicate well both a high and a low IPCC scenario, SRES B1 and IS92a for the period 2000–2100 (Moxnes and Saysel 2004).

## 3 Experimental design

### 3.1 The task

Figure 2 shows the simulator interface. The goal for the subjects is to reach a stable stock of anthropogenic $CO_2$ in the atmosphere of 300 GtC above the pre-industrial level in the period 2040 to 2100 (the new level corresponds to 437 ppmv).[6] The task is to decide on carbon emissions every 10th year from 2010 to 2100. The experiment starts in year 2000 with global annual carbon emissions of 8 GtC per year and an

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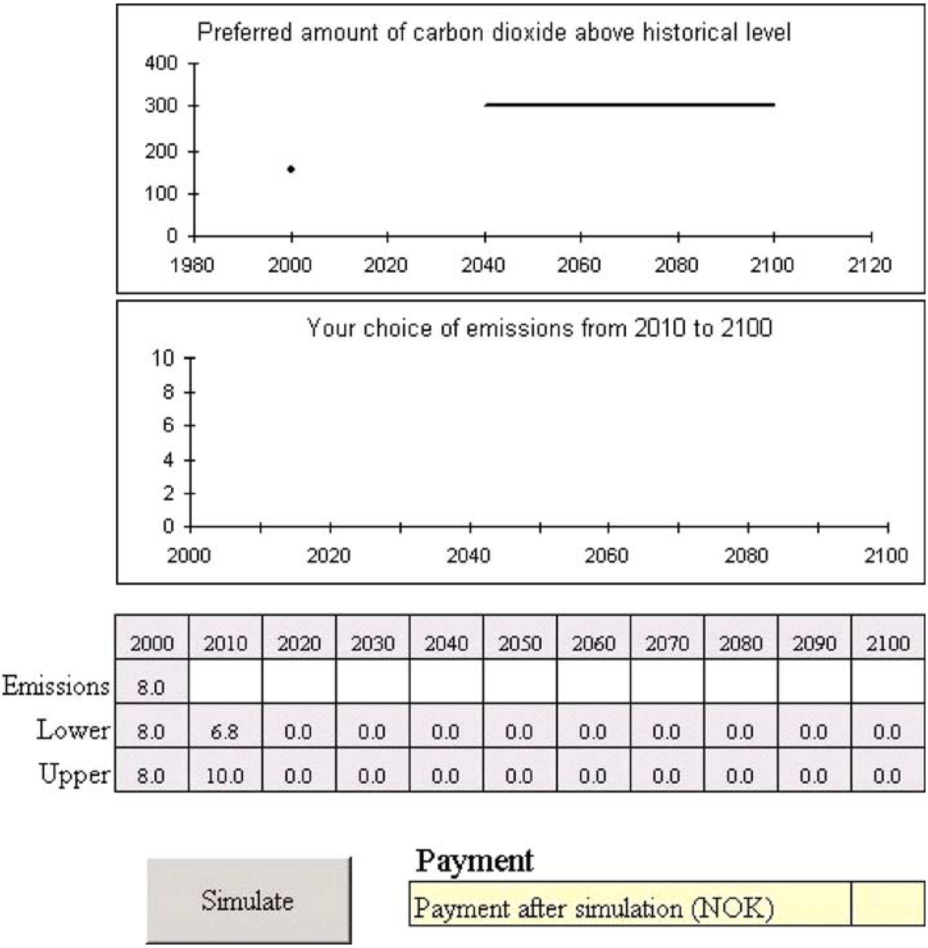
[5] 296 ppmv before year 1900. In the model, the conversion factor from ppmv to GtC is 2.13 as suggested by Clark (1982), p. 467.

[6] IPCC's "best-case" stabilization scenario sets the target for the $CO_2$ level very close to our choice, 450 ppmv by year 2050 (IPCC 2001a, p. 76). According to the 450 ppmv stabilization scenario, a moderate assumption on climate sensitivity implies temperature can increase by approximately 2°C by the end of twenty-first century. According to the carbon cycle models, this "best-case" scenario calls for a gradual decrease of emissions to 25% of today's emissions by the year 2100.



| | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Emissions | 8.0 | | | | | | | | | | |
| Lower | 8.0 | 6.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Upper | 8.0 | 10.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| | |
|---|---|
| Payment after simulation (NOK) | |

**Fig. 2** Simulator interface

atmospheric stock of anthropogenic $CO_2$ of 150 GtC.[7] The dot and the straight line in the graph show the starting point and the target for the stock. As the subjects enter their figures in the empty boxes, they see the resulting emission trajectory in the graph. The trajectory results from linear interpolation between each 10 year grid point. The scale along the $y$-axis changes automatically whenever emissions are set above 9.5 GtC per year. The initial axis stops at 10 GtC per year. This introduces a certain asymmetry which may bias the results in a downward direction, i.e. a conservative design with respect to the hypothesised overshoots.

To avoid unrealistic changes in emissions, the rate of change in carbon emissions over each 10 years period is restricted to the interval −15% to +25%. Any reduction

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[7] In SRES scenarios of (IPCC 2001a), the carbon emissions are close to 8 GtC per year in 2000. one hundred fifty gigatons C of $CO_2$ over the pre-industrial level corresponds to circa 366 ppmv, close to the 369 ppmv suggested by data (Keeling and Whorf 2002).

greater than 15% in a 10 year time period is likely to underestimate world economic growth, increasing energy requirements and the costs and time needed to increase energy efficiency. The 25% upper limit allows for increases due to world economic growth and movements towards a more fossil fuel intensive economy. Emissions outside the boundaries lead to error messages. If people are not normally conscious about such limitations on changes in emissions, our instructions may affect the results of the experiment in the direction of earlier and stronger curtailments, i.e. a conservative design.

After the subjects have entered emissions for *all* 10 year periods, they hit the simulate button and see the resulting stock of $CO_2$ and how much they have earned. Before the experiment starts, the subjects are told that their payoffs depend on how close they are to the target over the period 2040–2100. They also get to know that the maximum payoff corresponds to slightly more than a normal hourly wage for a student.

The instructions provided the subjects with a context and with full information about the structure and parameter values of the underlying simulation model, Appendix 1. During the experiment, subjects were allowed to use calculators and they had ample time to work on the problem. The participants were placed in cubicles. Privacy of the results was announced in the instructions in accordance with the precepts for laboratory experiments proposed by Smith (1982).

Given that subjects form appropriate mental models of the problem, only elementary math skills are needed to identify an approximately optimal emission trajectory. Here we illustrate how such a benchmark can be established by simple means. The subjects are told that the task is to stabilize the $CO_2$-stock at 300 GtC and that the per unit absorption rate is 0.013 per year. The stock is stabilized at this level only if the emission rate equals the absorption rate. When the stock is 300 GtC, the absorption and emission rates must be 300 GtC $\times$ 0.013 per year = 3.9 GtC per year. Thus a first rough benchmark policy is to gradually reduce the emissions from the initial rate of 8.0 to 3.9 GtC per year by 2040. This policy leads to the desired stock of 300 GtC in the long run.

However, to safeguard that the stock ends up close to 300 GtC already in 2040, one may fine tune by considering the net rate of change in the stock from 2000 to 2040. If for instance the emission rate is kept at 8 GtC per year for the first 10 years, and the absorption rate stays at about 2 GtC per year (ignoring that it increases somewhat with the stock), the increase in the stock over the first 10 year period is 60 GtC. If over the next 30 years (from 2010 to 2040) the emission rate is reduced linearly to 3.9 GtC per year, while the absorption rate increases linearly to the same level, the area of the triangle formed between emissions and absorptions equals 90 GtC. Altogether the two periods add circa 150 GtC to the initial level of 150 GtC and the goal of 300 GtC is reached by 2040. This example is a close approximation to the slowest possible emission reduction that is still sufficient to reach the goal by 2040. Therefore it serves as a conservative benchmark.

The design does not allow the subjects to reduce the stock of $CO_2$ much below the goal. If emissions are reduced at the maximum allowable speed in all periods, one ends up 49 GtC below the goal (average 2040 to 2100). Increasing emissions at the maximum speed leads to an excess of 850 GtC. Hence, in this regard the design is not symmetrical. If the subjects choose emissions at random, they will on average overshoot the goal considerably. This is not a weakness of the design, however, since

**Table 1** Distribution of subjects over groups and treatments

| | T0 | T1 | T2 | T3 | T4 | Total |
|---|---|---|---|---|---|---|
| MN | 15 | 16 | 13 | 13 | 15 | 72 |
| IST | 25 | 14 | 20 | 18 | 18 | 95 |
| HF | 18 | 18 | 16 | 16 | 7 | 75 |
| Total | 58 | 48 | 49 | 47 | 40 | 242 |

in reality an uninformed and random choice of emission strategy will also lead to an expected overshoot of a reasonable goal for the $CO_2$ concentration.

Since each subject has full command on the total global carbon emissions, the design rules out the commons problem as an explanatory factor of overshoots.

### 3.2 Subject groups

Three subject groups participated in the experiments. The first subject group, from Boğaziçi University – Istanbul, Turkey (IST), consisted of 95 students from engineering, economics and natural science departments (November and December 2002). The second group, from the University of Bergen, Norway (MN), consisted of 72 students from the Faculty of Mathematics and Natural Sciences (February 2003). The third group was 75 graduate students from the University of Bergen, Faculty of Arts (HF), who normally do not study mathematics and calculus and thus have a limited knowledge of these topics (April 2003). Altogether 242 subjects completed both the experiment and a post questionnaire. Table 1 shows the distribution over subject groups and treatments. To avoid learning effects, no subject participated more than once.

According to the post questionnaire there are only minor differences between the groups (Moxnes and Saysel 2004). The only difference that seems to have some importance for the results is the concern about the size of global $CO_2$ emissions.[8] On a scale from 0.0 to 1.0, IST (0.69) is significantly lower than both MN (0.85) and HF (0.90).

### 3.3 Treatments

The experiment has five treatments including the base treatment (Moxnes and Saysel 2004).

#### T0 The base treatment

Our experimental task is a stock and flow problem. In a laboratory investigation of the management of another renewable resource (lichen grazed by reindeer), Moxnes (1998b) found a strong tendency towards over-utilisation of the resource stock. He argued that the main reason for over-utilisation was that subjects tend to use a *static* mental model, where there is an algebraic relationship between the grazing rate and the stock. The correct dynamic model holds that the grazing rate *subtracts* from the lichen stock.

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[8] The statement that they responded to was: “The nations of the world should make stronger reductions in emissions of greenhouse gases than they currently plan to do.”

Based on his results, Moxnes speculated that the same misperception was likely to lead to overshooting emissions of greenhouse gases. This is exactly what S&S found when they asked subjects to choose emission trajectories to either increase or reduce the $CO_2$ stock. In both cases the appropriate response was to decrease emissions. When the goal increased over time, most subjects increased emissions. When the goal decreased, most subjects reduced emissions. Thus, S&S found strong evidence of what they call a *pattern matching heuristic*. Independent of the goal for the $CO_2$ concentration, this heuristic will lead to overshoots.

Our design is similar to the one for increasing $CO_2$ concentrations used by S&S with some noteworthy differences. First, their presentation of the task draws on presentations in IPCC documents about the real system. Thus they find that IPCC descriptions do not by themselves remove the tendency towards pattern matching. While S&S instructions make clear the stock and flow relationships, they are not explicit about residency times of $CO_2$ in the atmosphere, and they operate with different units for the $CO_2$ concentration and the flows. We ask the subjects to manage a completely described model with one unit for $CO_2$. Hence, our task should be simpler than that of S&S. Second, we mention explicitly that there are upper and lower limits for changes in emissions over future periods. This may lead to larger emission reductions in the short run than in S&S where this constraint is not explicit. Third, we motivate the subjects by monetary incentives. Normally, monetary incentives lead to better performances in experiments, although this effect may not be significant and not even positive for all kinds of experiments (Camerer and Hogarth 1999). S&S did not make use of monetary incentives but left that for further research.

Altogether we hypothesise that our design will lead to fewer cases of overshoots of the desired $CO_2$ stock than that found by S&S.

Alternatively, the differences are of minor importance and not sufficient to prevent overshoots.

### T1 Air mattress analogy

Both deficient mental models and inability or unwillingness to analyse models (predict consequences) can lead to mismanagement. The task in S&S was not designed to distinguish these causes. Here we want to investigate the role of mental models. According to Broadbent et al. (1986) this cannot be done reliably by a post questionnaire asking detailed questions about the system structure. This is because the underlying mental model that is used to guide decisions may not be compatible with fragmented knowledge that the subjects remember from the instructions. Postquestionnaires may also reflect lessons learnt in preceding tasks, and may not reflect how various models are combined in, for instance, anchoring and adjustment heuristics (Tversky and Kahneman 1974). This said, a post questionnaire in S&S does indicate that some people reason according to a static model.

The atmosphere with its $CO_2$ content is a quite unfamiliar and unobservable system to most people. A previous study by Brigham and Laios (1975) suggests that direct inspection of a physical system helps the construction of mental models. This observation inspires us to use an analogy to investigate the effect of visualisability or familiarity on performance and, implicitly, on the formation of mental models.

The analogy and the instruction are mathematically and numerically identical to T0. However, the task in T1 is to inflate a leaky air mattress and to stabilize the amount of air in the mattress over the next 40 to 100 min. To make the task sound practical, the subjects are told that after the next 40 min children will be jumping and playing on the mattress. Therefore the air pressure has to be stabilized at a desired level so that the children do not get hurt.

We hypothesize that treatment T1 will lead to fewer overshoots of the desired stock of air ($CO_2$) than T0.

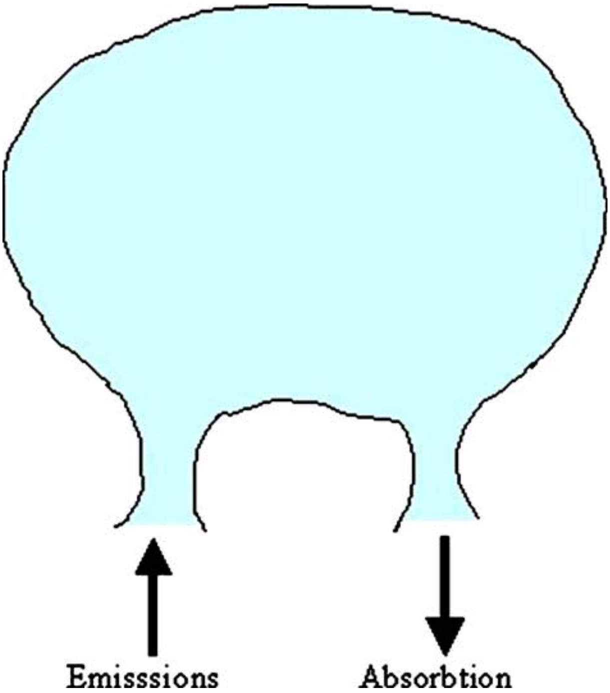
Alternatively there is no difference for two possible reasons. Either subjects are not able to formulate appropriate models even for the air mattress, or they form correct mental models but fail to see the implications for the pumping of air into the mattress (emissions).

### T2 Balloon analogy information

If people perform better with the air mattress framing than with the $CO_2$-framing, an air mattress or a balloon analogy could be used in information campaigns (Venville and Treagust 1996). To test this idea, the subjects were presented with the drawing in Fig. 3 and the following text.

> To help you get a good result, think of the carbon dioxide in the atmosphere as being in a big balloon with two openings. Through one opening are the emissions coming in, and through the other is carbon dioxide flowing out to plants and oceans (1.3% of the amount of carbon dioxide in the balloon each year). If more is flowing in than out, the amount of carbon dioxide in the balloon will increase. The size of the balloon will only decrease if emissions are made lower than what is flowing out.

**Fig. 3** Figure used in T2



For this treatment to have an effect, people must be better able to deal with the air mattress analogy in T1 (a balloon on the ground) than with the $CO_2$-problem, and they must understand, remember, and be willing to use the balloon analogy to structure their mental model of the $CO_2$-problem. The latter undertaking requires that the analogy is accepted as valid (compatible with the subjects' existing knowledge about $CO_2$ in the atmosphere and not in conflict with current mental models). Furthermore, the subjects must be motivated to reconsider their current mental models (they must understand that the analogy is not just redundant information, and they must not be overly confident in their present mental models).

We hypothesise that T2 will lead to fewer overshoots of the desired $CO_2$ stock than T0 and more overshoots than T1.

Alternatively the above conditions are not satisfied and there will be no difference between T2 and T0.

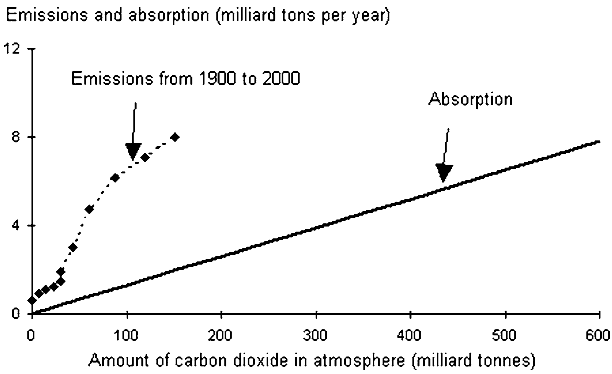
### T3 Emission and absorption rate information

Rather than building on an analogy, an information campaign could also make use of tools of analysis that are successfully used by researchers. Figure 4 and the following text shows how information about emission and absorption rates is given in T3.

> To help you get a good result, look at emissions relative to absorption. The figure above shows how absorption increases with the amount of carbon dioxide in the atmosphere (1.3 percent is absorbed each year). The figure also shows how emissions have increased from 1900 to 2000 (the black dots denote the situation in 1900, 1910, 1920 and so on). As long as emissions are larger than absorption, the amount of carbon dioxide in the atmosphere will increase. The concentration will only decrease if emissions are made lower than absorption.

The figure shown in T3 represents a phase diagram where the absorption rate is shown as a function of the stock, and the emission rate is to be determined by the subjects. The equilibrium emission rate of 3.9 GtC per year can be read directly from the absorption graph above the target stock level of 300 GtC. The need for reductions in emissions is easily seen. A quite similar phase diagram did have a positive effect on performance in Moxnes (1998b). As in this study we expect that some subjects will not read the graph correctly, in large measure because they do not have a proper stock-and-flow representation in mind (as in Fig. 1).

**Fig. 4** Figure used in T3



We hypothesise that T3 will lead to fewer overshoots of the desired $CO_2$ stock than T0.

Alternatively, the subjects are not motivated to consider the phase diagram (for the same reason as in T2) or the diagram is too complex to understand. In either case the treatment will have no positive effect.

### T4 Outcome feedback

The study by S&S differs from earlier investigations of stock and flow problems in that they do not allow for outcome feedback about the stock over time. Whenever systems are complex, ambiguous or influenced by unpredictable events, decision makers must rely on outcome feedback about the current state of the system. Feedback enables people to apply trial-and-error strategies and to correct for unexpected outcomes. Reliance on outcome feedback is a very natural process, and is long ago hypothesised to be a key element of human decision making (Forrester 1961). For instance, Moxnes (2004) found that one simple feedback rule explained virtually all outcomes of a laboratory experiment with a renewable resource. Only one parameter representing individual aggressiveness needed to be varied to span the range of outcomes.

To test the effect of outcome feedback, subjects in T4 received precise information on the stock of $CO_2$ every 10th year. Each time after having received new information they made a new decision about the emissions for the next 10 years. After a couple of 10 year periods the subjects start to receive compelling evidence that the $CO_2$ stock will overshoot the desired level. With high emissions in the first couple of decades, the limits on emission reductions become binding, and an overshoot can not be fully prevented.

We hypothesise that T4 will lead to fewer and particularly smaller overshoots of the desired $CO_2$ stock than T0.

## 4 Results

Performance is measured by the average stock of $CO_2$ over the period from 2040 to 2100 minus the target stock of 300 GtC, i.e. average overshoots of the goal. Table 2 summarises subject performance over groups and treatments. All combinations of groups and treatments show overshoots. For the reference case T0, the average overshoot is 154 GtC, 51% of the desired stock and 103% of the desired increase in the stock from the 2000 level.

**Table 2** Average overshoots of the $CO_2$ target (GtC)

| | T0 | T1 | T2 | T3 | T4 | All Ts |
|---|---|---|---|---|---|---|
| | Base | Mattress | Balloon | Rate | Feedback | |
| MN | 61 | 31 | 101[a] | 83 | 50[b] | 63[c] |
| IST | 229[c] | 14 | 157[b] | 128[b] | 45 | 128[c] |
| HF | 128[b] | 71[b] | 223[b] | 152[b] | 21[a] | 130[c] |
| All groups | 154[c] | 41[c] | 164[c] | 124[c] | 42[c] | 109[c] |

[a] Significantly different from zero at 5%-level

[b] Significantly different from zero at 1%-level

[c] Significantly different from zero at 0.1%-level

**Table 3** Median overshoots of the $CO_2$ target (GtC)

| | T0 | T1 | T2 | T3 | T4 | All Ts |
|---|---|---|---|---|---|---|
| MN | −3 | 2 | 41 | 22 | $36^b$ | $19^a$ |
| IST | $282^a$ | 14 | 61 | $71^b$ | 5 | $31^c$ |
| HF | 50 | 48 | $69^a$ | 106 | $20^a$ | $49^c$ |
| All groups | $50^a$ | 16 | $65^c$ | $61^b$ | $17^c$ | $33^c$ |

[a] Significantly different from zero (binomial sign test) at 5%-level

[b] Significantly different from zero (binomial sign test) at 1%-level

[c] Significantly different from zero (binomial sign test) at 0.1%-level

All averages over groups and over treatments are significantly greater than zero at low $p$ values. In 10 of 15 individual cells the overshoot is significantly greater than zero at the 5% level. The highest $p$ value in any group is 0.14 in cell MN-T0.

From the point of view of democratic decision making, it may be more interesting to look at the overshoots for the median subjects since the median overshoot may represent a compromise value. Table 3 shows a similar pattern to the averages. All groups and all treatments, except T1, come out with significant overshoots according to a binomial sign test. As expected, the sign test gives fewer significant overshoots for the individual cells, five out of fifteen, than the averages. The median overshoot for T0 is 50 GtC, which is 17% of the goal and 33% of the desired increase in the stock from the 2000 level.

We use a simple linear regression to test for differences in overshoots between treatments and groups. Table 4 shows that treatments T1 and T4 lead to significantly lower overshoots than the control treatment T0. Treatments T2 and T3 do not produce significant effects. The HF group has significantly higher overshoots than the MN group, while IST is not significantly different from MN. The effect of concern about climate change is in the expected direction but is not significant.[9] A Shapiro–Wilk test shows that the residuals are not normally distributed. Therefore we also perform tests that do not depend on normally distributed residuals.

A Kruskal–Wallis $H$ test suggests that average overshoots differ over all combinations of treatments and groups, $p = 0.036$. Kruskal–Wallis $H$ tests also show significant differences between treatments, $p = 0.03$, and between groups, $p = 0.05$. To compare pairs of treatments and of groups we use Mann–Whitney $U$ tests. We find that only T1 is significantly different from the control treatment T0, $p = 0.03$. For the other comparisons to T0 we find $p = 0.59$, $p = 0.88$ and $p = 0.17$ for, respectively, T2, T3, and T4. Thus, we no longer get the significant effect of T4 that we found in the regression. A major reason for this is a greater variation between groups in T0 than in the other treatments, as can be seen in Table 3. To reduce the variation we pool T0 with T2 and T3, both of which came out with insignificant effects of information treatments, as can be seen in Table 4. In this case both T1 and T4 come out as significantly different from the pooled treatments; $p$ values are respectively 0.004 and 0.05.

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[9] Ideally, T1 should not be included when testing the effect of Concern since there is no mentioning of climate change in that treatment, only in the post questionnaire. If T1 is excluded, however, the effect of Concern is not strengthened in the regression ($p = 0.17$).

**Table 4** Differences in overshoots from group MN and treatment T0 according to regression

| | T1 | T2 | T3 | T4 | HF | IST | Concern | Const. |
|---|---|---|---|---|---|---|---|---|
| Difference | −110 | 10 | −35 | −106 | 61 | 41 | −72 | 154 |
| *p* value | 0.001 | 0.74 | 0.27 | 0.001 | 0.02 | 0.12 | 0.13 | 0.000 |

Residuals are not normally distributed according to a Shapiro–Wilk test ($p < 0.001$).

Turning to differences between groups, the Mann–Whitney *U* test shows that both HF and IST differ from MN, both with $p = 0.03$. There is no difference between HF and IST, $p = 0.96$. The difference between MN and the two groups HF and IST is also consistent with a similar significant difference between these groups in the post questionnaire, where the participants were asked to identify the equilibrium emission rate at the desired $CO_2$ concentration. The percentages of correct answers were 44, 24, and 26 for MN, HF and IST, respectively.

From the questionnaire we also know the age and gender of the subjects as well as a measure of their general environmental knowledge. These variables came out with small and insignificant effects when included in the above regression. Since all our subjects were students, this test does not rule out that the results could be somewhat different for other groups.

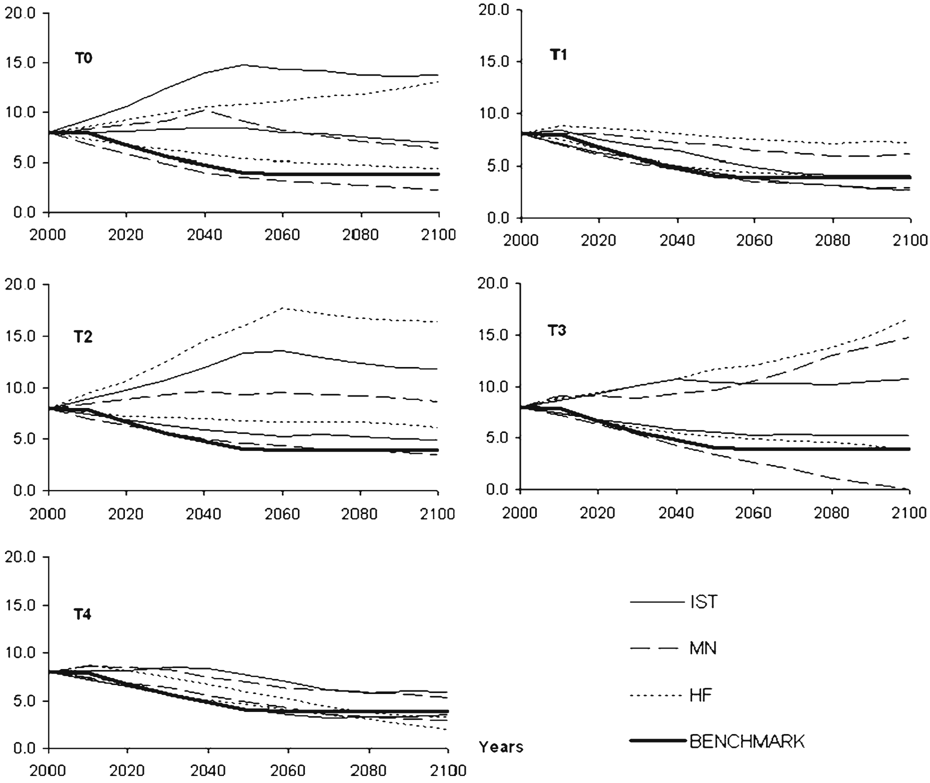

**Fig. 5** The benchmark emission path and 95% confidence intervals for average emissions over treatments and groups

To get a better sense of development over time, Fig. 5 shows 95% confidence intervals for average emissions for each treatment and subject group. The typical result is that the confidence intervals do not stretch below the benchmark path for emissions. Some of the confidence intervals show signs of pattern matching (emissions first rising with the desired stock of $CO_2$ and then stabilising with it), e.g. T0 for the IST group, and T2 for HF. In most cases there is no clear tendency towards strict pattern matching in the confidence intervals, even though data for individuals show many examples. Treatment T1 leaves very little room for pattern matching as a dominant strategy. In treatment T4, subjects do not start out significantly better than in the other treatments. However, as the subjects get compelling outcome feedback there is a sustained tendency for the $CO_2$ stock to decrease in the latter half of the century.

## 5 Discussion

### 5.1 The treatment results

We start by comparing our reference treatment T0 to the results obtained by S&S. In their case on average 42% of the subjects chose to reduce emissions (average over three treatments in the 400 ppm target case). In our case pooled results for T0 over all three groups show that 51% chose to reduce emissions.[10] The difference is not large and our reference treatment supports the results of S&S. The sum of design differences seems to be of little importance for the average subject.

If we concentrate on the MN group (with the presumably best skills in mathematics and the higher score on the equilibrium question), our study shows that 81% chose to reduce emissions with a slight median undershoot of the goal. This number is considerably higher than the percentage from the S&S study which also included students with mathematical skill. This indicates that for mathematically skilled subjects a simple and precise description helps their reasoning. Around the world the group of people skilled in mathematics is only a tiny minority. Still it may be an important group to the extent that its members serve as authorities or change agents, as suggested by the literature on diffusion of innovations (Rogers 1995).

The air mattress analogy in T1 had a highly significant and large positive effect on performance. The physical analogy was identical in structure and parameters to the original $CO_2$ problem in T0. Therefore, the difference in performance must be related to the subjects' ability to form appropriate mental models and not to the ability to predict behaviour and to control the system. The air mattress analogy is easier to visualise and presents itself as a stock and flow problem because of its physical appearance (Brigham and Laios 1975). The stock of $CO_2$ in different atmospheric layers around the world is a more abstract phenomenon that is less likely to present itself as a simple "one stock and two flows" problem. This is an important result because it points to the structuring of the problem, and the construction of mental models as major challenges.

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[10] Measured over the first 20 years to come close to the definition used by S&S.

In order for people to arrive at a “one stock and two flows” description, there are two challenges. First, subjects must overcome a tendency to assume that changes in one variable (here stock of $CO_2$) has one and only one cause (Plous 1993). Of the two rates, it is highly likely that it is the emission rate that receives the attention. After all, without anthropogenic emissions, there would be no debate about climatic change and no need for emission reductions. The absorption of anthropogenic $CO_2$ is caused by the stock of $CO_2$ in the atmosphere and is not in general seen as directly influenced by human activity. Thus the absorption rate may get less attention and its effect on the stock of $CO_2$ in the atmosphere may easily be neglected. The absorption rate needs more attention. Second, subjects must overcome a tendency to assume algebraic relationships (static models) or correlations between stock and flow relationships (Sterman 1989; Moxnes 1998b). Flows *add* to and *subtract* from stocks, stocks do not vary in proportion to flows. Only a static model justifies pattern matching.

The fact that most subjects in T1 chose to reduce rather than increase inflow of air (“emissions”) suggests that subjects do not use the pattern matching heuristic when they understand the system structure. However, we also note that very few of the subjects reduced the inflow of air sufficiently to avoid overshoots altogether. This indicates that many of those who reduce the inflow are also uncertain about what to do. Probably their responses represent compromises between two or more ideas, referred to by terms like “weak knowledge restructuring,” “assimilation” and “conceptual capture” in the conceptual change literature (Duit 2003). For instance, low but imprecise emission paths from a dynamic model may have been adjusted upwards to avoid “unrealistic” and “drastic” reductions, probably using an anchoring and adjustment heuristic (Tversky and Kahneman 1974).

In case reductions seemed uncomfortably drastic in T1, one should expect even greater effects for treatments framed as a $CO_2$ problem. Breaking an historical global trend for $CO_2$ emissions may seem both scary and undesirable, and thus may require a deep understanding and/or conviction. Thus, the entire difference between T0 and T1 may not be explained by differences in mental models. On the other hand, prior public information about climate change should have provided motivation for drastic emission reductions in T1. Since we cannot quantify these effects, a need for further research is revealed. The effects of information about the stock and flow nature will give a first indication about the need for such information.

The purpose of the balloon analogy, T2, was to strengthen the mental image of the $CO_2$-task as a “one stock and two flows” problem and to help understand behaviour by sentences explaining both structure and behaviour. We find no positive effect compared to T0, and a significant difference when comparing to T1 (Mann–Whitney $U$, $p = 0.007$). We hypothesised that the result of T2 should be between T0 and T1. No effect relative to T0 may seem surprising particularly in light of the large effect of T1. However, the result parallels that of (Moxnes 1998b), where a perfect “bathtub analogy” of a renewable resource problem had no effect on performance.[11]

One possible reason for differences between T1 and T2 could be that the balloon with an explicit outflow was a less effective analogy than a leaking air mattress on

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[11] Also when subjects get to work with and experience (less than perfect) analogous simulators, one observes limited transfer of knowledge (Bakken 1993; Jensen 2005).

the ground. A more likely reason is that in T1 the subjects worked directly with the analogy while in T2 the subjects could have seen the balloon analogy as excessive, redundant, and even partly misleading information. The motivation to consider the analogy could be missing as their existing mental models and heuristics seemed appropriate for the task.

The absorption rate information T3 shows that the initial emission rate is much higher than the initial absorption rate. It also makes it easy to find the equilibrium emission rate at the target stock of $CO_2$ (300 GtC). The lack of effect of T3 could be due to lacking motivation (as in T2) and it could also be caused by a limited ability to read the graph and to understand the relationship between the two rates and the stock of $CO_2$. The figure represents a phase diagram frequently used by experts analysing dynamic systems. For those who are familiar with this type of diagram, it takes no time and effort to see where the equilibrium point is and to see that the current emission rate is much too high. The experiment, however, demonstrates that this type of diagram is a poor pedagogical device, even with an accompanying text. For some people this result may seem obvious, for some experts in modelling it may come as a surprise.

In T4 the subjects benefited significantly from outcome feedback about the stock of $CO_2$. The feedback provided motivation to change strategy, and may have caused the needed cognitive conflict to question own mental models. Unfortunately, there are reasons to believe that feedback about the $CO_2$ concentration have a limited potential for preventing future overshoots. True, feedback about $CO_2$ gives earlier signals than delayed effects on surface temperatures – $CO_2$ concentration represents the “thermostat setting” for temperature. However, $CO_2$ is not likely to get the same media and public attention as climate episodes. Furthermore, while the experiment lasts for less than an hour, climate change takes place over decades. Therefore the effect of feedback will require that the target is kept in mind and does not drift with new information.

On the other hand, T4 suggests that “feedback” about historical data could be collected and organised for people to test their mental models. Of particular value are periods where emissions have decreased or stayed constant while the atmospheric $CO_2$ concentration has increased steadily. Such data contradict the static model and produces the cognitive conflict needed for people to question the pattern matching heuristic (Limon 2001; Meadows and Wiesenmayer 1999). Such historical feedback information may be what is needed to motivate people to consider and learn from analogies and other types of information.

### 5.2 Concern and emission reductions

It may seem surprising that subjects seriously concerned with the climate change problem did not choose sufficiently strong emission reductions to reach the stated goal for the experiment. While 86% of the subjects expressed that nations should make stronger reductions in greenhouse gas emissions, only 51% chose to reduce emissions in the experiment, and only a small minority reduced the emissions sufficiently to reach the stated goal. Hence it seems people’s concerns are not coming out of an appropriate understanding of the dynamics of the problem; they must rely on other types of information. Such information is likely to modify attitudes and aggressiveness of strategies, while mental models are preserved (Moxnes 2004). We also note that there seems to be a synergy between education and concerns about climate.[12]

## 5.3 Comments about current information strategies

IPCC reports (for example, IPCC 2001a, p. 76 and IPCC 2001b, p.4) illustrate alternative emission trajectories that may lead to climate stabilization. But they never speak about the discrepancy between the emission and absorption rates even though this is implicit in all the climate models. One reason may be the current uncertainty in our understanding of the carbon absorption processes. However, as long as one has historical time-series data for the stock of $CO_2$ and emission rates, one can produce quite reliable estimates of the aggregate historical absorption rates.

Media coverage tends to focus on the current and future impacts rather than basic greenhouse dynamics as illustrated by two articles on climate change in prominent popular science journals. National Geographic Magazine (September 2004) covers climate change in one hundred pages. This coverage considers impacts of climate change on various ecosystems and biota. Increasing atmospheric $CO_2$ concentrations are covered in a single page[13] without any verbal or graphical description of GHG emissions and absorptions. New Scientist (February 12 2005), provides a comprehensive overview focusing on impacts rather than basic dynamics. The article includes a bar graph illustrating target $CO_2$ stabilization levels versus cumulative amount of carbon that can be emitted, based on different assumptions about future global carbon absorption levels (p. 9). The time dimension is not included and it is impossible to discern the dynamics of the accumulation process.

Stern et al. (2006) is explicit about the fact that $CO_2$ accumulates in the atmosphere. The executive summary states: "Stabilisation – at whatever level – requires that annual emissions be brought down to the level that balances the Earth's natural capacity to remove greenhouse gases from the atmosphere. The longer the emissions remain above this level, the higher the final stabilisation level." (p. xi). This is the best and most precise expression of the "one stock and two flows" problem we have found. However, in light of T2 where we presented a similar explanation, it is no longer obvious that this text is very effective.

## 5.4 Implications for information strategies

In democracies politicians need considerable popular support to enact apparently costly policies to prevent uncertain, but potentially severe future consequences. Therefore it is in the population's self interest to be well informed. Our investigation and previous studies suggest that with the current level of knowledge, people may come to vote for policies that lead to different outcomes than what they prefer. Based

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[12] Regressing the average stock of $CO_2$ on Concern for each of the three groups, we obtain the following coefficients for Concern −258 ($p = 0.01$), −130 ($p = 0.10$), and +173 ($p = 0.24$) for, respectively, MN, IST, and HF.

[13] Page 104 in the Turkish edition.

on our findings and the literature on conceptual change, we propose the following information strategy:

1. Use the following historical data to challenge static mental models and pattern matching heuristics. From 1979 to 1985, the world emission rate of $CO_2$ did not increase. Still, the stock grew: anthropogenic $CO_2$ concentration increased steadily from 84 to 103 GtC (the same pattern was observed in the period from 1991 to 1994). The cognitive conflict should create an interest in explanations.
2. To explain the accumulation process, an inner tube surrounding the earth could serve as an effective analogy. As long as air (or $CO_2$) is pumped into the inner tube, it will continue to increase in size.
3. Introduce yet another cognitive conflict to provoke thoughts about the absorption rate. This could be done simply by asking the following question: Do emissions have to be zero to prevent further increases in the GHG concentration? After having reached the desired size of the inner tube, what would justify further pumping?
4. To solve this conflict one could add a leakage to the inner tube. At the desired size, pumping cannot exceed the leakage rate. It follows that the leakage rate is the single most important measure to know in order to identify the pumping rate that stabilises the size of the inner tube. Similarly the absorption rate for $CO_2$, or the expected future absorption rate, is the single most important quantity to know when targets for emissions are to be set.
5. Finally, one should point out the exact future emission rates that follow from a proper dynamic model. In other words, one should give away the correct answer. We could not do this in our experiment since we needed to check the subjects' understanding. Important to note, it is probably not sufficient to give away the "correct answer." People get conflicting advice from multiple sources that are of varying quality. Therefore people need arguments and a deeper understanding to judge the advice they receive. This is particularly important when it is the "correct" advice that deviates most radically from what seems intuitively appropriate.

To test this information strategy (points 1 to 4) we ran an additional experiment. A control group got a simplified version of T0 while a second group in addition received the information treatment. An English translation of the questionnaire is shown in Appendix 2. Seventy high school students participated in the full factorial study (50 science students (23 control and 27 information) and 20 non-science students (9 control and 11 information). A score of 0.0 was used to code answers where emissions clearly increased over time (pattern matching type). A score of 1.0 coded clearly decreasing emissions (consistent with a proper dynamic model). All but eight subjects gave answers that fell in these two categories. The remaining eight fell in-between and were rated with a score of 0.5.

The average scores are shown in Table 5. The main impression is that the scores improve with science background (+0.47) and with the information treatment (+0.25). The combined effect is to improve the results from a very poor score of 0.11 to an impressive score of 0.83. Analysis of variance shows that the effects of science background ($p = 0.00004$) and information ($p = 0.02$) are both significant. The effect of science background is consistent with the better performance in the MN group. The interaction term is small and insignificant.

**Table 5** Average scores in additional experiment

| | Control | Information |
|---|---|---|
| Non-science students | 0.11 | 0.36 |
| Science students | 0.59 | 0.83 |

The new experiment shows that students' understanding of a small, yet complex dynamic model can be improved considerably by a few minutes intervention combining cognitive conflicts and analogies. The low score for non-science students combined with the fact that several of them were helped by the information treatment suggest that there is a need for and also an improvement potential of better general education in dynamic systems.

## 6 Conclusion

Observed misperceptions of the accumulation of $CO_2$ are likely to have severe consequences for climate policies around the world. Even people who know that $CO_2$ or GHG emissions can lead to climate change and who think that political actions are needed, may come to favour policies that fall short of reaching their intended goals. The perception problem seems strongly linked to an inability to form appropriate mental models of $CO_2$ accumulation. Current information in media and even from the IPCC are not likely to be very effective in correcting erroneous mental models, nor were our attempts at using a balloon analogy and a more technical phase diagram. Based on our findings and the literature on conceptual change we proposed and tested a revised information strategy where we provoked cognitive conflict and used analogies to solve the conflicts. This strategy did lead to improved understanding. Of vital importance in this strategy seems to be the comparison of current emissions with reliable measures of current or expected future absorption rates.

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## Appendix 1: Instructions for the base treatment (T0)

*Please, do not touch the PC before you have read the instructions.*

Burning of for example oil, gas, and coal leads to emissions of carbon dioxide and to higher concentrations of carbon dioxide in the atmosphere. The scientific community thinks that this higher concentration will lead to increasing temperatures and to climate change. The more climate change, the larger problems and costs for humans on this planet. On the other hand, reductions in energy use to limit emissions also lead to problems and costs for humans. Thus, somewhere between a too high and a too low concentration of carbon dioxide, there will be a preferred concentration which leads to the lowest total costs to humans. The challenge is to control the size of world emissions so that the concentration stabilises at the preferred level. This is the task you face, managing a simulator of atmospheric carbon dioxide.

The simulator is very simple. It keeps track of the amount of carbon dioxide that is above the level that was considered normal historically (before 1900). This amount of carbon dioxide is increased by human emissions and it is reduced by uptake of carbon dioxide in plants and oceans. To be precise, each year, 1.3% of this amount of carbon dioxide is absorbed by plants and oceans and thus leaves the atmosphere. Although very simple, this simulator produces almost the same development of carbon dioxide over the next century as the most advanced scientific models.

Historically, human emissions of carbon dioxide increased from close to zero in 1900 to 8.0 milliard tons per year in 2000. Due to these emissions, the amount of carbon dioxide above the historical level has increased from nearly zero in 1900 to 150 milliard tons in 2000. The numbers for 2000 define the starting point for the simulator. (In the simulator, red dot on the first graph points to this starting concentration). The preferred atmospheric concentration is 300 milliard tons, the double of the concentration in 2000. You should try to reach this goal by 2040 and keep the concentration at the preferred level the entire period from 2040 to 2100. If you stabilise the concentration at exactly 300 milliard tons you will earn NOK 120. If you on average deviate by 50 milliard tons in this period, you will receive NOK 80. The further you are away from the preferred level, the less you get paid.

The simulator works as follows. You enter your choice of the yearly emission rate for each 10th year from 2010 to 2100 in the boxes named “Emissions.” The graph shows what your choice of emission rate looks like for the entire period. You can change the numbers until you obtain the development you want. When you are pleased with the result, you click on the button called “Simulate”. The simulator will calculate the resulting concentration of carbon dioxide, and you will see how much you have earned. Remember, when you hit “Simulate” you can no longer make changes in the emission rate. To earn as much as possible, it is important that you take time to think about what to do before you click on “Simulate.”

Note that there are lower and upper limits for changes in the emissions. You are not allowed to reduce emissions by more than 15% in any 10 years period. This may seem a small amount, however, when one remembers that world economic growth leads to higher needs for energy and emissions, a 15% reduction is a strong reduction. The upper limit of a 25% increase allows for both normal economic growth and some extra growth in emissions. If you set any emission rate outside the upper and lower limits, you get an error message.

To get your payment you must write down each and every decision you make in the decision form. When the game is over no longer touch the PC, write your payoff and sign your name on the form. After that, raise your hand and ask for the questionnaire. After filling in the questionnaire, approach the experiment leader to get your payment. Each participant will be paid privately to maintain anonymity.

Good luck, and thanks for participating!

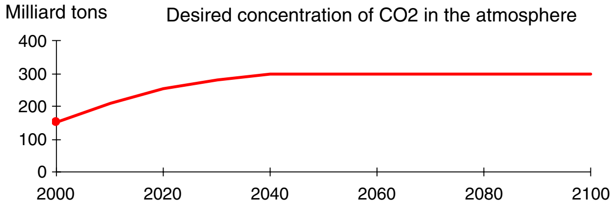
## Appendix 2: Instructions for the additional experiment

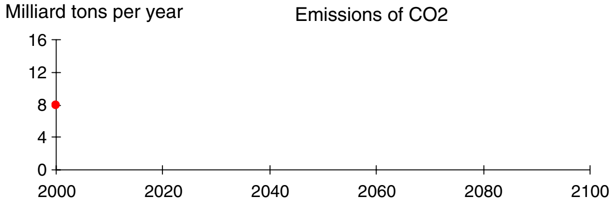
Below are the instructions to the second experiment translated from Norwegian to English. The information and the control treatments differed in that the latter did not have any text after the second graph.

How large emissions of carbon dioxide ($CO_2$)?

In 2000 the concentration of $CO_2$ in the atmosphere was 150 milliard tons carbon higher than in the year 1900. This task is about this extra amount of $CO_2$ caused by human activities. Assume that the world's nations agree to let this concentration increase to 300 milliard tons by 2040 and then stay constant thereafter, see the first figure.

*Your task is to draw, in the next figure, how yearly world emissions of $CO_2$ must develop to reach this goal.* The emissions start at 8 milliard tons per year in 2000. Also note that each year 1.3% of the $CO_2$ concentration goes back to plants and oceans.





It may seem natural to think that the concentration of $CO_2$ changes in pace with the emissions. However, this is contradictory to historical observations. From 1979 to 1985 world emissions of $CO_2$ did not increase, still the concentration in the atmosphere continued to increase. How can this be explained?

Picture $CO_2$ in the atmosphere as the air in a bicycle's inner tube. As long as air is pumped into the tube, it will continue to grow; even when one is pumping at a constant speed. Does this mean that the emissions of $CO_2$ have to be reduced to zero for the concentration to stop growing?

The answer is no. Imagine that there is a hole in the tube where some air leaks out all the time. Then it is sufficient to reduce the pumping until the air that flows in just replaces what is leaking out. Therefore, to stop the growth in the concentration of

$CO_2$, the yearly emissions must over time be reduced to the size of the "leakage" to plants and oceans. This "leakage" increases in pace with the concentration from 1.95 in 2000 to 3.9 milliard tons per year when the desired concentration of 300 milliard tons is reached.

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