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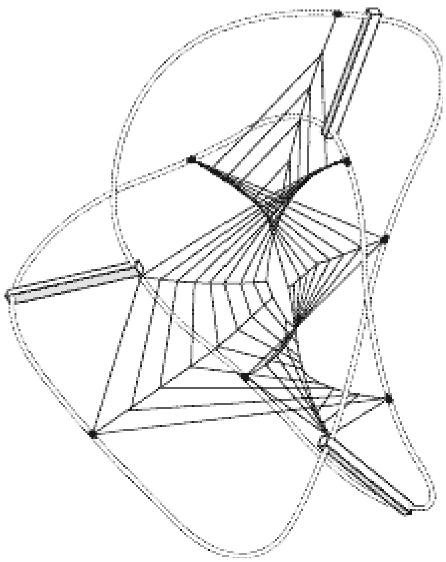

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What range of future scenarios should climate policy be based on? – Modal falsificationism and its limitations

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Abstract

Climate policy decisions are decisions under uncertainty and, therefore, based on a range of future climate scenarios, describing possible consequences of alternative policies. Accordingly, the methodology used to set up this scenario range becomes crucial. The preferred methodology of the International Panel on Climate Change will be characterised as "modal inductivism"; it suffers from severe shortcomings which disqualify it for scientific policy advice. Modal falsificationism, as a more sound alternative, would radically alter the way the climate scenario range is set up. Climate science's inability to find robust upper bounds for future temperature rise in line with modal falsificationism does not falsify that methodology, rather, this very fact prescribes even more drastic efforts to curb CO2 emissions than currently proposed.

Editor's Note

This paper contributes to the Contingency part of the project in the central area of climate change science and policy. The paper begins by making explicit and criticising a particular methodology, modal inductivism, that is used in climate change policy advice by the IPCC to predict future temperature change and sea level rises. Betz argues that modal inductivism, where possible scenarios are constructed based on what is well-known is problematic for various reasons. In particular, it underestimates the uncertainty in future temperature change. He argues instead for a modal falisificationism, where the emphasis is on ruling out scenarios as impossible. Betz then critically discusses the potential and limits of modal falsificationism in climate change modelling.

1 Introduction

Within the last decades, it has emerged as a consensus view among climate scientists that mankind is changing earth's climate by altering the composition of the atmosphere, in particular the concentration of greenhouse gases (GHGs) such as carbon dioxide (CO2), the main GHG, or methane (CH4).[1] It is equally well established that the atmospheric concentration of CO2 has reached levels unprecedented in the last 650.000 years: While 0.018–0.03 percent of the atmosphere was CO2 during the ice-age cycles—e. g. the CO2 concentration varied between 180 and 300 ppmv[2] (Siegenthaler et al., 2005)—, in 2005, the CO2 concentration equalled 379 ppmv (IPCC, 2007).

Although this represents sufficient ground to consider climate change a serious problem, climate policy decisions ultimately require some sort of foreknowledge: What will the consequences be if we continue business as usual? And what is going to happen if we reduce our GHG emissions? Conditional prediction of future climate change, more than any other type of scientific knowledge, is the most relevant policy information.[3]

The climate system, however, is not reliably predictable in a deterministic way—a fact widely acknowledged in the climate community and beyond.[4] Even robust probability forecasts are currently out of reach as we will see below. Therefore, reliable foreknowledge about the climate system is modal. Climate policy decisions are decisions under uncertainty, or ignorance (e.g. Knight, 1921; Ellsberg, 1961). They have to rely on ranges of future scenarios that project the *possible* consequences of alternative climate policies. These ranges of future climate scenarios represent one of the most important pieces of information in scientific climate policy advice, in particular in the reports of the International Panel on Climate Change (IPCC).

Hence, the question of how this scenario range should be constructed becomes a central issue in the methodology of scientific climate policy advice. It is not merely a question of interest to a philosopher of science. It is also of utmost political relevance since what turns out to be a rational climate policy—given normative evaluation of the possible consequences—

[1]E.g. Oreskes (2004) or Rahmstorf and Schellnhuber (2006).

[2]Parts per million volume.

[3]For the way different kinds of foreknowledge can rationally fuel a policy-decision compare also part III in Betz (2006).

[4]I quote from the Third Assessment Report of the International Panel on Climate Change: "The climate system is particularly challenging since it is known that components in the system are inherently chaotic; there are feedbacks that could potentially switch sign, and there are central processes that affect the system in a complicated, non-linear manner. These complex, chaotic, non-linear dynamics are an inherent aspect of the climate system. As the IPCC WG I Second Assessment Report [. . .] has previously noted, 'future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve 'surprises'. In particular, these arise from the non-linear, chaotic nature of the climate system'. " (IPCC, 2001, p. 773)

crucially depends on what future scenarios we consider as possible at all when deliberating climate policy measures.

This paper aims at shedding light on this issue by reconstructing and evaluating the methods currently employed to set up the future climate scenario range. Section 3 describes the methods used by the IPCC and their recent evolution. They will be summarised in the methodological principle of modal inductivism. This principle is evaluated in section 4—which will expose major problems. Thus, section 5 proposes modal falsificationism as an alternative methodology for setting up future scenario ranges. How this principle can be applied in scientific climate policy advice and where its limitations are to be found is discussed in section 6.

2 Modal inductivism as the preferred IPCC methodology

In this section, I will describe the methods the IPCC has used to set up the scenario range to be considered in climate policy, and how these methods have evolved in the last years. Moreover, I attempt to summarise the methodology in a fundamental principle.

I will distinguish two types of climate scenarios: global mean temperature scenarios which project the global average temperature change in the 21st century, and sea-level rise scenarios projecting global mean sea-level rise for the same period.

2.1 The IPCC's Third Assessment Report (TAR) 2001

The TAR (IPCC, 2001) set up the range of future temperature change scenarios as follows: Different global GHG-emission scenarios, systematically studied and grouped in separate IPCC reports[5], were translated into alternative developments of CO2-concentration in the 21st century. These alternative paths of CO2-concentration then served as boundary conditions for simulation runs with different complex climate models[6], so-called general circulation models (GCMs)[7], which calculated the future development of global mean temperature anomaly. Hence, a future climate scenario was obtained by combining an emission scenario with a certain climate model. Figure 1 depicts the range of temperature scenarios thus obtained, the bars on the right of the diagram indicate the range of simulation results for one

[5]The so-called SRES (Special Report on Emission Scenarios) scenarios (IPCC, 2000).

[6]Or, more specifically, a simple climate model which was tuned to different general circulation models.

[7]These are sometimes more precisely referred to as atmosphere-ocean general circulation models (AOGCMs) if the model couples a three-dimensional atmosphere with a three-dimensional ocean module.

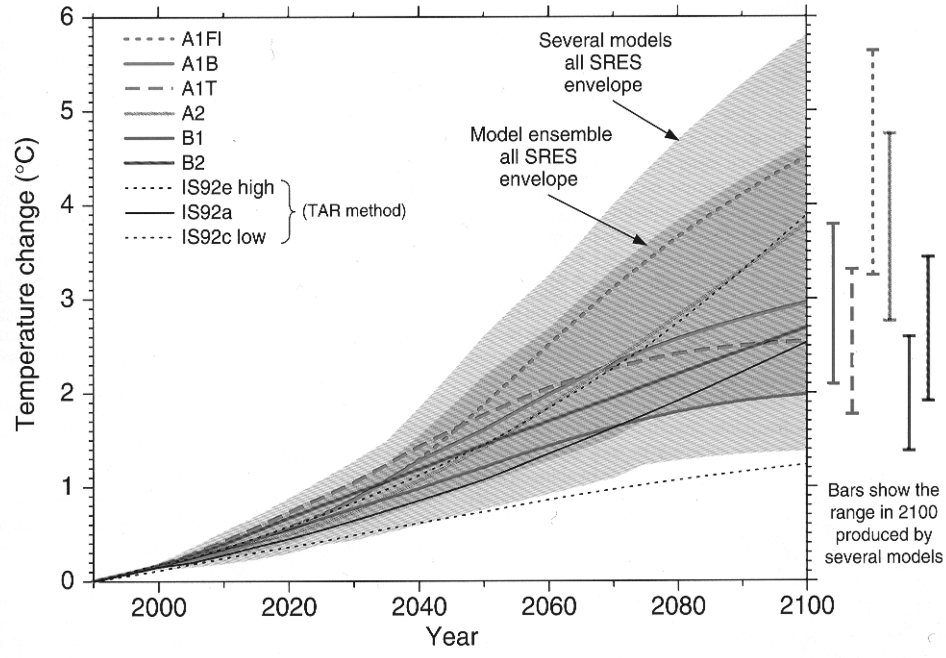


Figure 1: Future global warming scenarios of the TAR. The possible range of global mean temperature change in the 21st century is the envelope of predictions by several climate models given different emission scenarios. Source: IPCC (2001, p. 555).

and the same emission scenario, i.e. the uncertainty range due to the alternative climate models. This is the spectrum of future climate scenarios the TAR prominently displays as the range policy decisions should be based on.

While the construction of the sea-level rise range is very similar to the temperature case, there are some interesting distinctions. For the sea-level rise projections include, in addition to the explicitly modelled sea-level rise, contributions from glaciers and land ice-caps, or the thawing of permafrost. These contributions were not explicit variables in the GCMs, but were calculated separately based on the simulation results. Thus, a sea-level projection is obtained by combining an emission scenario, a climate model, and a set of assumptions about further contributing factors. The overall range in figure 2 shows the entire set of scenarios thus calculated. The bars on the right indicate the individual ranges of the different emission scenarios.

As a first point to note, general circulation models play a central role in this method. These complex models are the main tool for investigating the possible range of future climate change.

Secondly, real climate processes are only taken into account when setting up the scenario range this way if they are explicitly modelled in a GCM, or, regarding sea-level rise, at least roughly calculable. Processes which are not

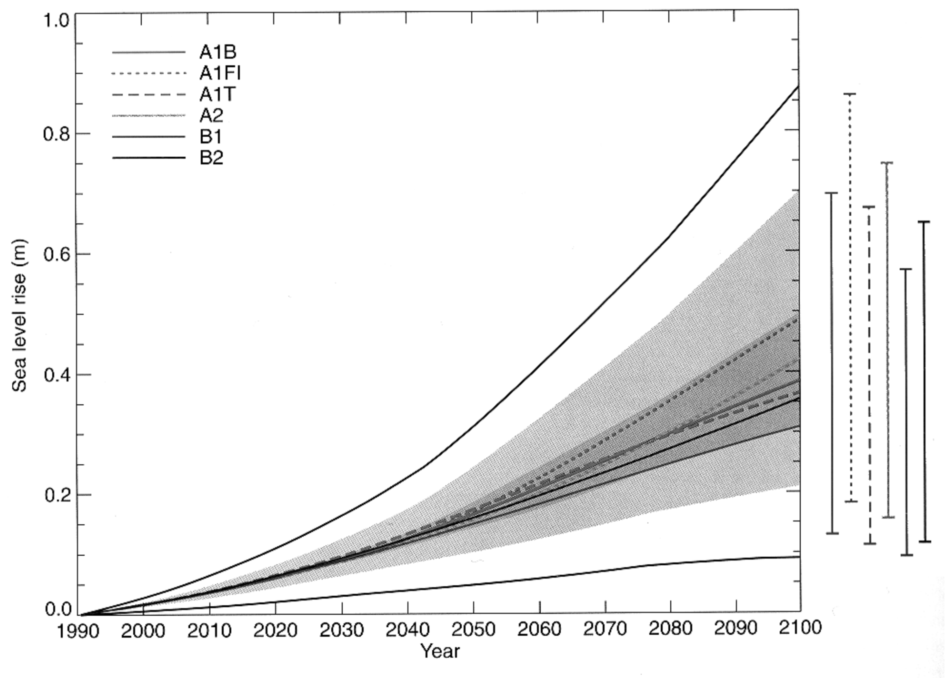


Figure 2: Future sea level rise scenarios of the TAR. The possible range of global sea level rise in the 21st century is the envelope of predictions by several climate models given different emission scenarios plus further contributions of factors not included in the GCMs. Source: IPCC (2001, p. 671).

modelled are ignored. This obviously holds for the temperature projections. But it is also true for the sea-level scenarios. Ice-dynamical changes in the Greenland and West Antarctic ice sheets, for instance, i.e. the acceleration of ice flow triggered by climate change, were so poorly understood that they were not even included in the calculation of the additional contribution to sea-level rise, let alone in the GCMs.

If we assume that the different emission scenarios and climate models are physically possible (i.e. consistent with our physical background knowledge), a model simulation with result R represents a positive proof that R is a possible future climate scenario. Therefore, the IPCC methods can be interpreted as an implementation of the following methodological principle:

Modal inductivism It is scientifically shown that a certain statement about the future is possibly true if and only if it is positively shown that this statement is compatible with our relevant background knowledge.

I will refer to this principle as modal inductivism.

2.2 2001-2007: the range of simulation-results explodes

Advances in computing power as well as innovative designs of climate simulation studies (distributing hundreds of simulations on desktop computers worldwide) enabled climate scientists to investigate ever more different versions of climate models.[8] Systematic variation of uncertain parameters led to an explosion of the climate scenario range in the years following the publication of the TAR. More specifically, these studies estimate the response of the climate system to a doubling of CO2-concentration, defined as "climate sensitivity". Accordingly, the uncertainty regarding climate sensitivity describes that part of the uncertainty regarding future climate change which is not due to uncertainty regarding future CO2-concentrations. The climateprediction.net study initiated by the British Hadley Centre may count as a milestone of this research. Stainforth et al. (2005) report that their model ensemble includes climate models exhibiting a climate sensitivity as high as 11 K (the range of climate sensitivity in the TAR is 2.0 - 5.1 K, IPCC, 2001, p. 560)! Stainforth et al. conclude:

> [Our] results demonstrate the wide range of behavior possible within a GCM and show that high sensitivities cannot yet be neglected as they were in the headline uncertainty ranges of the IPCC Third Assessment Report (for example, the 1.4-5.8 K range for 1990 to 2100 warming).

These results, the authors add, are not too surprising as

> [statistical] estimates of model response uncertainty, based on observations of recent climate change, admit climate sensitivities defined as the equilibrium response of global mean temperature to doubling levels of atmospheric carbon dioxide substantially greater than 5 K. But such strong responses are not used in ranges for future climate change because they have not been seen in general circulation models.

What is reiterated in this last sentence is nothing but the methodology of modal inductivism which makes GCMs the gold standard of climate change research.

If the IPCC keeps the methods it has used in the TAR to set up the future climate scenario range, that range would encompass a much wider spectrum of scenarios than in the TAR. So let us have a look at the 4AR which will be fully published mid-2007 but whose Summary for Policymakers (SPM) is already available.

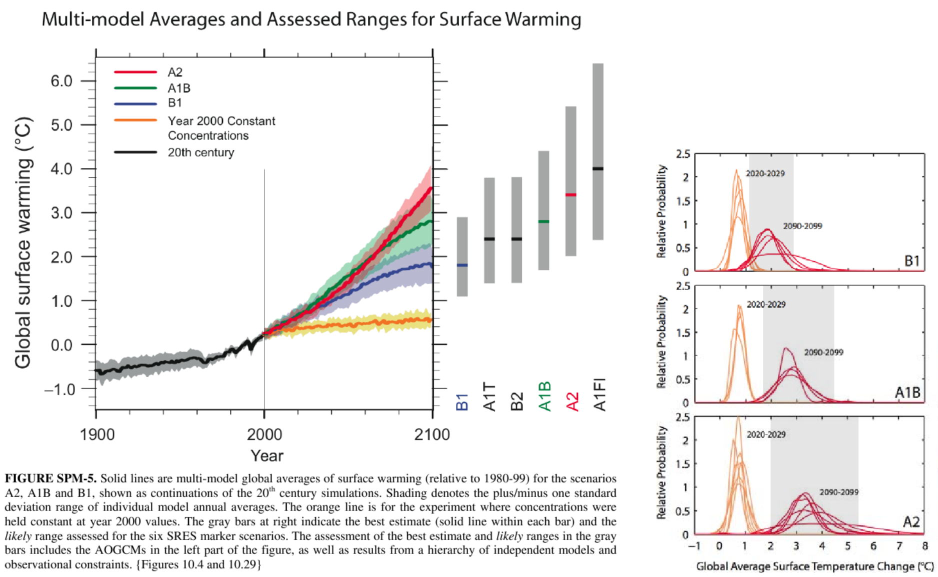
[8] See for instance http://www.climateprediction.net.

2.3 The IPCC's Fourth Assessment Report (4AR) 2007

Figure 3a shows the range of future temperature scenarios from the 4AR. Because the graph itself does not display the results from all emission scenarios, the range it indicates is slightly smaller than the corresponding range in the TAR (figure 1); but the bars at right, comprising all emission scenarios, span a slightly wider range than in the TAR, namely from 1.1 - 6.4 K. However, the scenario range does not include the extreme simulation results that have been obtained in recent climate research! The explanation for this lack is that the IPCC implements a modified methodology in its 4AR as it estimates only the "likely" range of temperature change, where the Summary for Policymakers defines "likely" as an assessed likelihood, using expert judgement, greater than 66%. From the description of figure 3a, it is not fully clear how this likelihood has been assessed and how exactly the range was set up. Does it represent the simulation results climate experts judge as realistic? Or are more sophisticated methods used to set up this interval? These questions will only be answered once the full report is published. Still, it is clear that the 4AR also uses probabilistic assessments of future climate change obtained with Bayesian methods. Figure 3b from the SPM displays probability density functions (pdfs) of temperature change as calculated in different studies. These pdfs are typically obtained by assigning prior pdfs to the parameters of a GCM which are then updated given observation in order to obtain a posterior probability for the parameters and, ultimately, climate sensitivity.[9] I have introduced a gray shading in 3b which demarks the intervals indicated by the bars in 3a: What the SPM does not explicitly reveal is how and on what methodological grounds the alternative, model-specific pdfs have been aggregated, and whether and how they have been used to obtain the likely ranges of future temperature change. Irrespective of this issue, the application of Bayesian methods to assess likely future climate change is highly problematic as the posterior pdfs, lacking sufficient observational constraint, significantly depend on the priors chosen. We shall return to this problem later.

So obviously, the IPCC has departed from pure modal inductivism in its 4AR. This allowed it to reiterate an only slightly modified scenario range compared to its previous reports. But has the IPCC entirely turned its back on modal inductivism? Not quite so, as being the result of a model simulation is in effect still a *necessary* condition for being considered as possible and thence being included in the scenario range. The IPCC has merely dropped the idea that being the result of a model simulation is also a sufficient condition. In sum, the IPCC still seems to implement what one can call weak modal inductivism, i.e. a methodology according to which a future scenario is considered as possible (in policy deliberations) only if it has been positively shown that it is possible.

[9] Compare, for instance, the study by Hegerl et al. (2006).



(a) (b)

Figure 3: Future global warming scenarios of the 4AR. Gray areas in panel (b) have been added by the author and indicate the 'likely ranges' from panel (a). Source: IPCC (2007, p. 14,15).

The SPM does not contain a diagram with sea-level scenarios but displays the ranges in a table. Table 1 shows the ranges, comparing them with the TAR assessment.

So, first of all, the 4AR provides a "model-based", not a "likely" range (as in the temperature case) of future sea-level rise scenarios: Regarding sea-level rise, the IPCC has fully implemented the methodology of modal inductivism (is this because no explosion of simulation results risked to blast the scenario range?). Moreover, the 4AR ranges are systematically tighter than the TAR ranges. The SPM explains that (i) 2090-2099 values instead of 2100 values are used and that (ii) the uncertainties are dealt with differently in the 4AR. Although a comprehensive analysis of the methods based on the full report is ultimately required, it seems likely that the IPCC has simply scrapped the additional contributions to sea-level rise not included in the GCMs. If so, the 4AR implements modal inductivism even more neatly then the TAR insofar as sea level scenarios are concerned.

3 Why modal inductivism is so problematic

The SPM itself openly addresses the problems modal inductivism faces:

> Models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of

SRES scenario	4AR "Model-based range excluding future rapid dynamical changes in ice flow" *m at 2090-2099 relative to 1980-1999*	TAR *m at 2100 relative to 1990*
B1	0.18 - 0.38	0.10 - 0.56
A1T	0.20 - 0.45	0.12 - 0.67
B2	0.20 - 0.43	0.12 - 0.65
A1B	0.21 - 0.48	0.13 - 0.70
A2	0.23 - 0.51	0.16 - 0.75
A1FI	0.26 - 0.59	0.18 - 0.86

Table 1: Comparison of sea-level rise scenarios of the IPCC's TAR and 4AR. Source: IPCC (2001, 2007)

> changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993-2003, but these flow rates could increase or decrease in the future. For example, if this contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios [shown in Table 1 above] would increase by 0.1 m to 0.2 m. (IPCC, 2007, p. 14f.)

In other words, because of a lack of knowledge, these processes are simply ignored when setting up the scenario range. This, the SPM acknowledges at least insofar as sea-level rise projections are concerned:

> Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise. (p. 15)

But is it correct to disregard potentially severe consequences and effects merely on the grounds that they are poorly understood? Hardly so, in any case not if the precautionary principle is applied as prescribed by the United Nations Framework Convention on Climate Change (UNFCCC)[10].

[10] Article 3, paragraph 1 of the UNFCCC reads

> The Parties should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.

These ideas thus translate into a first argument against modal inductivism[11]:

(1) Applying modal inductivism in climate policy advice (in order to set up the range of future scenarios) implies that potentially severe consequences and effects are disregarded merely on the grounds that they are poorly understood.
(2) Any methodology which implies that potentially severe consequences and effects are disregarded merely on the grounds that they are poorly understood is at odds with the precautionary principle.
(3) *Thus:* Applying modal inductivism in climate policy advice is at odds with the precautionary principle.
(4) The UNFCCC embraces the precautionary principle.
(5) Any methodology used in climate policy advice has to be in line with provisions of the UNFCCC.
(6) *Thus:* Modal inductivism must not be used in climate policy advice.

A second argument against modal inductivism arises independently of the precautionary principle in the light of observations we have made on that methodology so far. The IPCC admits in the SPM:

> Assessed upper ranges for temperature projections are larger than in the TAR [...] mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks. (IPCC, 2007, p. 14)

So by applying modal inductivism in the year 2007 we learn (ex post) that this very methodology was too restrictive in 2001. This is not just an unproblematic sort of self-correction since the diagnosis given for the overly restrictive range in 2001 applies in 2007 as well: the carbon cycle is still not fully understood. So can't we infer that, given the diagnosis of past failures, the methodology of modal inductivism is too restrictive and thence inappropriate today, too? Here is the argument:

(1) According to modal inductivism, i.e. by its own standards, modal inductivism underestimated the climate scenario range in 2001 because the carbon cycle and its interaction with the climate system was poorly understood.
(2) The carbon cycle, its interaction with the climate system as well as other processes in the climate system are still poorly understood.

[...]

[11] Generally, there is a risk of begging the question when arguing against modal inductivism, namely insofar other definitions of what is possible are used as a premiss; e.g. one cannot, without begging the question, assume in such an argument that dynamic changes in Greenland ice flow *are* possible (and infer that modal inductivism is inappropriate as it does not say so), because that very assumption presumes some other rule for what has to be considered as possible which conflicts with modal inductivism.

(3) *Thus:* It is likely that modal inductivism applied today will underestimate the climate scenario range (by its own standards), too.
(4) It is inappropriate to apply a methodology in climate policy advice which is likely to underestimate the future scenario range by its own standards.
(5) *Thus:* It is inappropriate to apply modal inductivism in climate policy advice today.

In sum, the methodology of modal inductivism—both in its pure as well as its weak version—cause a systematic underestimation of the uncertainties and the risks we face. Climate policy advice which is based on this methodology is biased and tends to play down the gravity of our situation. And that it might get even worse than the diagrams set up with modal inductivism suggest is a relevant policy information, for it affects decisions relating to our major climate policy questions:

Mitigation: How drastic should our efforts to prevent further climate change be? Specifically, to what extent should we reduce our GHG emissions?

Adaptation: How far reaching should our planning for future climate change be? Specifically, what kind of adaptation measures do we have to initiate today?

Assistance: How generous should our assistance to third countries be? Specifically, what kind of help to mitigate and adapt do developing countries need?

So modal inductivism gets a major policy information wrong. It should, therefore, not be applied in climate policy advice. But what are the alternatives? And, are they viable?

4 Modal falsificationism

The methodological principle of modal falsificationism represents an alternative to modal inductivism. It states:

Modal falsificationism It is scientifically shown that a certain statement about the future is possibly true as long as it is not shown that this statement is incompatible with our relevant background knowledge, i.e. as long as the possibility statement is not falsified.

Let me briefly pinpoint the analogy to classical inductivism and falsificationism, explaining the names chosen. Like classical inductivism, modal inductivism assumes the existence of an epistemic foundation: our background knowledge in general, instead of observation or empirical data. Starting from that basis, future scenarios, instead of hypotheses or theories, shall be positively inferred. Modal falsificationism, however, granting the existence of that basis, stipulates to invent arbitrary future scenarios, in a first step, before testing them, in a second step, systematically against the background knowledge. Only those creatively constructed future scenarios that have not been falsified shall be accepted (as possible).

The difference between modal inductivism and modal falsificationism can also be thought of as a difference regarding the allocation of burdens of proof. Assume it is contentious whether some scenario S should be considered as possible in policy deliberations or not. Then, according to modal inductivism, the burden of proof falls on the party that says S is possible whereas, according to modal falsificationism, the party denying that S is possible carries the burden of proof.

Modal falsificationism, in contrast to modal inductivism, does not conflict with the precautionary principle. Full scientific understanding or the ability to model a certain process or effect is not a precondition anymore for considering that process or effect in policy deliberations. Modal falsificationism is the more cautious and risk averse methodology.

Applying modal falsificationism in scientific climate policy advice has far reaching methodological consequences. Before the next section explores how a positive implementation of that principle might look like, here is a major negative consequence: According to modal falsification, GCMs have no role to play when setting up the range of future climate scenarios. The reason is simple: GCMs describe at most possible features, properties, and dynamics of our climate system. There is no GCM which could be labeled as the "true model" of our climate system. Whatever is deduced from a GCM has thence to be interpreted as a possibility-statement, too. But then it becomes logically impossible to infer from a GCM (together with observational data) that some statement about the future is inconsistent with our background knowledge, i.e. impossible. All one can infer is that the statement is possibly impossible—which does not suffice to exclude it from the scenario range according to modal falsificationism. The irrelevance of GCMs under modal falsificationism thence illustrates that any application of modal falsificationism must rely on robust models which do not merely represent possible worlds.

5 Applying modal falsificationism

If modal falsificationism, in order to be applicable, requires robust models and if GCMs are not robust, the question arises whether it has any chance of being implementable at all. In other words, are there any scenarios we can exclude from the future scenario range, i.e. show to be inconsistent with our background knowledge? This problem cannot be solved abstractly. In order to address it in this section, I will discuss on a case-by-case basis how modal falsification might work and what obstacles have to be overcome. I will consider sea-level rise scenarios first before moving on to temperature projections.

5.1 Sea-level rise scenarios

Can we falsify certain sea-level rise scenarios, i.e. demonstrate that they are impossible? The short answer is: yes. If the entire West Antarctic and Greenland ice sheets collapse, all ice caps and glaciers disappear and earth warms by 10 K until 2100, the sum of the individual contributions to sea-level rise would not exceed 6m (West Antarctic ice sheet)[12] + 8m (Greenland ice sheet)[13] + 1m (Glaciers and ice caps)[14] + 5m (thermal expansion)[15] = 20m. Any scenario projecting higher sea-level rise can be excluded as inconsistent with our background knowledge: there is simply no source where further rise could stem from.

This, of course, is a 'conservative estimate'. It lies one to two orders of magnitude above the IPCC's upper bound. So can we do better? Can we, say, exclude a sea-level rise of more than 2m for this century?

Very recently, Stefan Rahmstorf estimated the range of future sea-level rise (Rahmstorf, 2007). His reasoning, in spite of its simplicity, is remarkable because it does not rely on GCMs. So is Rahmstorf's method robust and does it represent an exemplification of modal falsificationism? We shall have a closer look at his argument.

1. The initial, as opposed to the long-run, equilibrium response of sea level to a given temperature increase is assumed to be proportional to that increase.

2. Sea-level rise in the 21st century is supposed to represent the short-term, initial response to global warming and can thus be approximated by the linear relationship.

3. The linearity hypothesis is tested for 1880-2001 data—and confirmed.

4. The proportionality factor is estimated given the data.

5. The simple linear model is used to generate sea-level rise scenarios on the basis of temperature rise projections. The scenario range obtained is significantly more elevated than the IPCC range (figure 4).

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[12]IPCC (2001, p. 678)

[13]IPCC (2001, p. 648), rounded up.

[14]IPCC (2001, p. 648), rounded up.

[15]This is a conservative upper boundary of a rather well-understood contributing factor, because (i) 21st century sea level rise will only be a fraction of long-term sea level rise, and (ii) no model-simulation, not even for extreme CO2- scenarios, yields 5m sea leve rise in the long run (IPCC, 2001, p. 676).

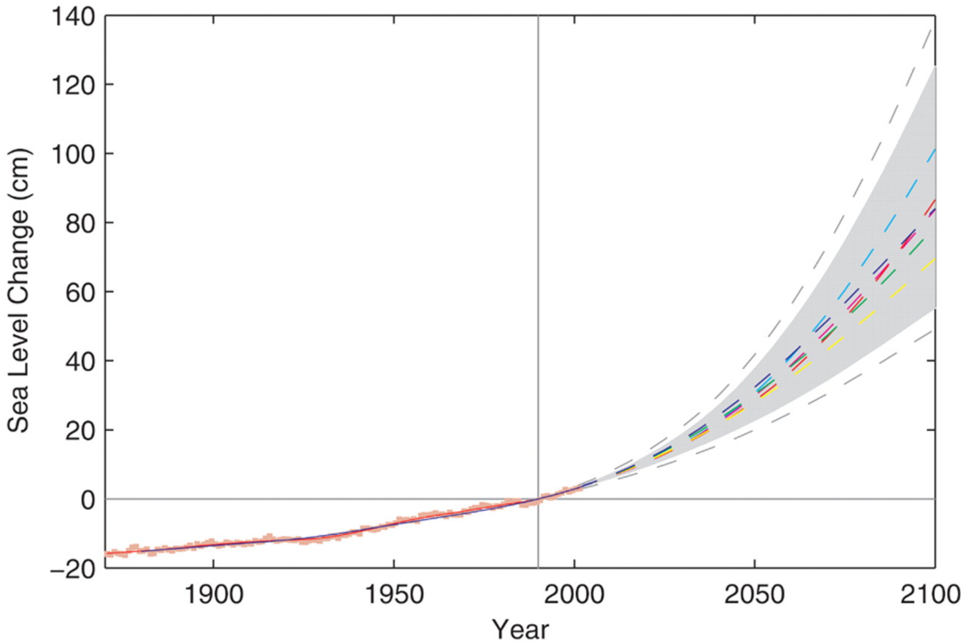

Figure 4: Future sea level rise scenarios obtained by a semi-empirical approach, based on a linear approximation. The boundary conditions are the same as in the IPCC projections. Source: Rahmstorf (2007).

As a first point to note, Rahmstorf's study shows that the GCM range is underestimating the future scenario range and thence represents a further argument against modal inductivism. But does it exemplify modal falsificationism, i.e. can we exclude sea-level rise higher than 1.4 m based on this reasoning? Rahmstorf himself is cautious and does not claim so:

> Given the dynamical response of ice sheets observed in recent decades and their growing contribution to overall sea-level rise, this approximation may not be robust. The ice sheets may respond more strongly to temperature in the 21st century than would be suggested by a linear fit to the 20th century data, if time-lagged positive feedbacks come into play (for example, bed lubrication, loss of buttressing ice shelves, and ocean warming at the grounding line of ice streams).

So by assuming linearity, Rahmstorf excludes certain processes and feedbacks on an ad hoc basis. This contradicts modal falsificationism.

Still, it could turn out that it is possible to modify Rahmstorf's semi-empirical approach in order to get an assessment of future sea-level rise in line with modal falsificationism, couldn't it? Again, one would have to estimate worst-cases for the individual contributions to sea-level rise. (i)

Maximal thermal expansion, being rather well understood, might be estimated by a linear approximation in spite of uncertainties in heat uptake by the ocean and expansion given a certain heat uptake. (ii) Regarding the ice caps and glaciers, one could assume that they are basically gone by 2100. (iii) As to the West Antarctic and Greenland ice sheets, one would have to assume the strongest possible feedbacks, yielding a non-linear relation between their contribution and temperature rise. Is that feasible? Leaving aside the question whether there is something like "the strongest possible feedback", we see that such an assessment still depends on an upper bound for temperature anomaly. So, can we estimate an upper bound for temperature anomaly in line with modal falsificationism?

5.2 Global mean temperature scenarios

In 3.2 I explained that climate sensitivity is the main parameter of our climate system which determines future global warming given a certain increase in GHG concentrations. Climate sensitivity, however, does not capture all uncertainties related to future temperature anomaly (e.g. uncertainties regarding carbon cycle feedbacks). Still, this section will focus on the question whether we can estimate an upper bound for climate sensitivity because if that were not the case, estimating an upper bound of future temperature rise would be equally impossible. I will present two promising methods to set up a climate sensitivity range in line with modal falsificationism and show why they ultimately fail. Then, I explore whether there is a general reason for this failure which proofs modal falsificationism inapplicable once and forever—which is not the case. Finally, I discuss what consequences we have to draw from our inability to establish upper bounds for climate sensitivity according to modal falsificationism.

1st method: palaeo-climate data. One way to estimate climate sensitivity without using GCMs is by relying on palaeo-climate data obtained from ice-cores drilled in Antarctica or Greenland (e.g. Lorius et al., 1990). These studies use energy balance models of the climate system that identify on a highly aggregated level the causally relevant factors for global temperature change, namely incoming solar radiation, aerosols, albedo (ratio of reflected solar radiation), GHG concentration. Using the palaeo-data, a statistical analysis can then be used to estimate the causal strengths ("amplitudes") of the different factors, or to reject certain hypotheses about the causal strength of GHGs as inconsistent with the robust model and the data.

Such an analysis assumes that the causal structure of the climate system today is basically the same as during the ice-age cycles. But isn't it possible that the statistical relationships have broken down? Specifically, the cloud formation and the cloud feedback could have been very different in glacial and inter-glacial periods several ten-thousand years ago than in the 20th and 21st century with its unprecedented rise in CO2-concentration. In other words: Nothing seems to guarantee that climate sensitivity is a constant whose current value we can measure given palaeo-data.

To show with GCM simulations that the causal structure of the climate system during the ice-age cycles *might* have been different from today's climate is consistent with our interpretation of GCMs as possibility statements. This is basically what Crucifix (2006) has done by showing that very different sets of assumptions, plugged into a GCM, can yield simulation results which are consistent with the palaeo-data.[16]

Yet another use of palaeo-data is made by Alley (2003) who claims that climate sensitivity might be higher than estimated by the range of current GCMs, arguing that abrupt and relatively rapid climate change is well documented by palaeo-data without being fully captured by GCMs. Although this is a further relevant piece of evidence piling up against modal inductivism, it is not to be confused with an implementation of modal falsificationism.

In sum, palaeo-data, in conjunction with robust climate models, has not been used to successfully exclude future climate scenarios as impossible so far.

2nd method: annual variation. The model used for this second method as implemented by Tsushima et al. (2005) is even more aggregate than the energy-balance model (including aerosols, albedo, etc.) mentioned above. The earth is seen from space as a blackbody whose temperature adjusts to a given external radiative forcing such that outgoing and incoming energy re-balance. To which extent an increase in earth's surface temperature increases the radiation at the top of the atmosphere is determined by some unspecified feedback process which can be described by a single parameter:

> The sensitivity of the climate is essentially controlled by the so-called feedback parameter, which is the rate of radiative damping of the unit anomaly of the global mean surface temperature due to the outgoing radiation from the top of the atmosphere (TOA). By dividing the radiative forcing of climate by the feedback parameter, one gets the radiatively forced, equilibrium response of global surface temperature. This implies that the stronger is the rate of the radiative damping, the smaller is its equilibrium response to a given radiative forcing. (Tsushima et al., 2005)

In other words, the smaller the feedback-parameter, i.e. the less radiation at the TOA increases with a given surface warming, the more the surface temperature has to increase in order to counter-balance a given radiative forcing and to restore equilibrium of incoming and outgoing radiation at the top of the atmosphere. Tsushima et al. (2005) use the annual variation of

[16] This example shows that GCMs do not become entirely worthless under modal falsificationism.

radiative forcing in order to estimate the feedback-parameter, and infer that the thus measured parameter describes the response of the climate system to the perturbation by GHGs.

A closer look reveals that the argument is basically an argument by analogy: Firstly, the response of the climate system to the annual variation (in radiative forcing) is similar to its response to a radiative forcing due to an increase in GHG concentration. This first premiss essentially assumes that the feedback parameter is a universal constant of the system. Secondly, based on (i) measurement of incoming solar radiation, (ii) satellite observation of earth's outgoing radiation, (iii) surface temperature data, we can estimate a confidence interval for the feedback parameter, or exclude certain extreme values. As climate sensitivity is proportional to the reciprocal value of the feedback parameter, this yields a demonstration that certain values of climate sensitivity can be rejected as inconsistent with our current background-knowledge (the aggregate model and the data).

This said, the similarity between the two methods is obvious. Both rely on highly aggregate methods, both assume that climate sensitivity/the feedback-parameter is a constant, both measure that parameter in a specific situation (ice age cycles/annual variation) and both infer from that measurement the response of the climate system to a future increase in GHG concentration. Like the first method, the second method hinges on the crucial assumption of structural similarity and like for method 1, GCMs show that this similarity might actually not hold:

> Since the pattern of the annual variation of surface temperature [...] differs greatly from that of the global warming simulated by a model, it is quite likely that the rate of the radiative damping of the global mean surface temperature anomaly is significantly different between the two. (Tsushima et al., 2005)

The cloud and albedo feedbacks, in particular, might differ significantly between annual variations of solar radiation and long-run variation of GHG concentration.[17]

So the second method fails to provide a robust exclusion of future scenarios in line with modal falsificationism, too.

5.3 Consequences of inability to falsify extreme scenarios

The similarity between these two methods and between their failure might suggest a general underlying reason for the failure of modal falsificationism.

[17] Accordingly, Tsushima et al. (2005) write that the "rate of radiative damping of local surface temperature anomaly is similar to the damping of the annual variation in global surface temperature under clear sky. Therefore, it is likely that the rate of the radiative damping of global surface temperature variation under clear sky is similar between the annual variation and global warming despite the difference in pattern. On the other hand, a similar statement may not be made for the albedo-, and cloud feedback."

Is there a universal cause which prevents us from deriving upper bounds for climate sensitivity and global mean temperature change? The following argument represents such a challenge to modal falsificationism:

(1) Future global mean temperature change causally depends on many detailed feedback processes in the climate system.
(2) *Thus:* Whether a certain future global mean temperature scenario is possible inferentially depends on how these feedback processes operate.
(3) *Thus:* We have to know how these feedback processes operate in order to know whether some future global mean temperature scenario is (im)possible.

One could even go further and argue from this last conclusion that aggregate models which characteristically disregard detailed processes in the climate system are ill-suited to exclude future temperature scenarios. Only models that capture the feedback processes can be used to robustly falsify such scenarios. But these are the GCMs which are (currently) inappropriate for modal falsificationism as shown above. We seem to face a dilemma.

Yet the challenging argument, in spite of rightly diagnosing the problem which caused the failure of the two methods discussed, is not valid. The inference step from (1) to (2) relies on the following general principle: If the evolution of some variable x causally depends on processes of type F, then whether a certain future development of x is (im)possible inferentially depends on how F-processes operate. This principle is invalidated by counterexamples like the following two. (1) The evolution of global sea level depends on many complicated feedback processes, in particular dynamical processes in the West Antarctic and Greenland ice sheets. Nevertheless, that a sea-level rise of 50m within the next 100 years is impossible is inferentially independent of the actual way these ice dynamical processes work; no matter how they operate, the 50m scenario is impossible as seen above. (2) Consider a system of mechanically coupled springs as depicted in figure 5. The future movement and positions of the weights attached to the springs causally depends on the precise nature of the springs and their couplings. That a position as depicted in figure 5c is impossible (given the system was in state 5b before and is properly shielded) is however inferentially independent of the properties of the springs and couplings; that purely follows from an energy-conservation reasoning.

So there is no a priori reason to think that we cannot limit the range of future scenarios in accordance with modal falsificationism. As a matter of fact, however, it is currently difficult to robustly falsify extreme temperature change scenarios and, as a consequence, sea-level rise scenarios.[18]

[18]Discussing the practicality of modal falsificationism, it is worth noting that it does not appear to be a primary aim of climate change research to robustly falsify extreme scenarios. In other words: modal falsificationism is currently hardly implemented. In-

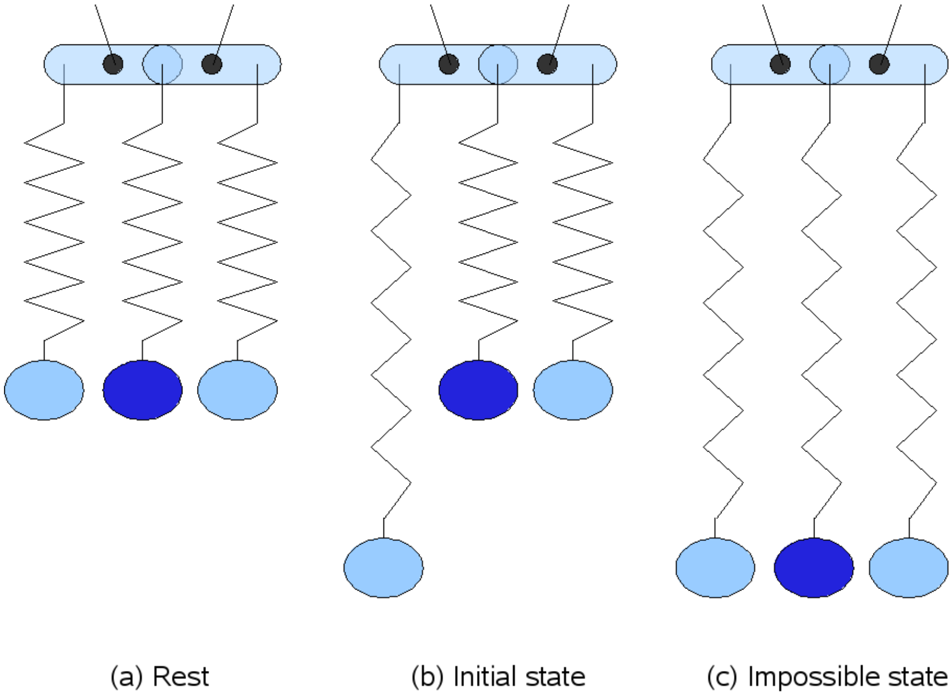

Figure 5: Three states of a system of coupled springs: (a) springs at rest, (b) some initial state of the system, (c) system state into which the system will not evolve from (b).

Although Frame et al. (2006) equate excluding future scenarios with falsifying model versions—operating cognitively in the framework of modal inductivism—, they correctly summarise our situation by stressing that, for the time being,

> [the] implication is that the risks associated with any stabilization or equilibrium-based [emission-] scenario remain critically dependent on subjective prior assumptions because of our inability to find directly observable quantities that scale with [climate] sensitivity. Thus any attempt to use [climate] sensitivity as a scientific and policy variable suffers from an inability to find a robust upper bound.

stead, research assigns GCMs a primary role or, insofar future climate change is assessed without relying on GCMs as in the studies discussed above, the aim is to provide 'best estimates' or 'likely ranges' rather than to robustly exclude worst cases. Thus, if climate research started to invest significant cognitive resources in implementing modal falsificationism, new methods for falsifying future scenarios might be developed. In any case, only once modal falsificationism has been tried can we make a final judgement regarding its practicality.

Remarkable, this is also a blunt rejection of a naïve application of Bayesianism in climate science which uncritically derives probability statements for policy advice that significantly depend on arbitrary prior probabilities—remarkably insofar as it is put forward by some of those researchers that helped to popularise Bayesianism in climatology in the first place. Frame et al. (2006) seem to assume—I add: rightly—that it would be downright irresponsible to make a scientific policy recommendation which affects the lives of billions of people, now and in the future, dependent on the arbitrary judgement, yes, on the taste of climate scientists. It is important to add that, in spite of their brilliance, there is no reason to belief that climate scientists are well calibrated estimators of the probabilities of future climate change for, unlike medical doctors or other experts, they have not been trained by being exposed to a sufficiently large sample of different changing climate systems.[19]

I argued that modal falsificationism is the correct methodology for preparing scientific climate policy advice. We then saw that it is currently impossible to significantly limit the range of future climate scenarios according to this methodology. What does this mean? Is this a scientific policy advice at all? Or is modal falsificationism itself falsified (by providing useless results)? Frame et al. (2006) propose an interesting argument related to these questions:

> The basic problem with sensitivity is that high sensitivities take a long time to come into equilibrium. This requires that forcings remain constant (or very nearly so) for a long time, possibly hundreds of years. This seems environmentally and economically unlikely.

Moreover:

> Fortunately, stabilization scenarios are not the only options available: indeed, the chances of future generations maintaining a specified concentration of CO2 indefinitely are probably very small. Other properties of the climate system are much better constrained by observations: for example, the normalized transient climate response (NTCR) which we define as the rate of warming in degrees per year divided by the fractional rate of CO2 increase per year. [. . .]
>
> NTCR turns out to be much more relevant than sensitivity for a scenario in which forcing reaches the equivalent of 550ppmv CO2 (double pre-industrial, though the same point holds for higher and lower peak forcings) and then declines by 10% over the ensuing 40 years, continuing to decline thereafter. [. . .]

[19]For a more detailed exposition of this argument see Betz (2007).

> Given the difficulties in determining climate sensitivity, we suggest that the climate policy community might begin to consider whether the UNFCCC should be interpreted a little differently. Since the ultimate objective of the Convention is to avoid dangerous climate change, and the commitment to stabilize future greenhouse gas concentrations does not preclude stabilization at near pre-industrial levels, 'stabilize' could be interpreted simply as 'bring back down' rather than as 'freeze' at a given elevated concentration in perpetuity [...].

Here is a possible reconstruction:

(1) We are currently not able to state a robust upper bound for climate sensitivity and long-term temperature projections.
(2) We can robustly estimate the range of short-term, transient climate response to CO2 increase.
(3) If climate policy aims at reducing GHG concentration to pre-industrial levels in the medium term instead of stabilising it at some higher value, transient climate response instead of climate sensitivity becomes the major relevant climate parameter.
(4) If we cannot robustly state an upper bound for parameter x but we can robustly assess parameter y and y (instead of x) becomes the major relevant parameter if policies aim at goal B (instead of goal A), then policies should aim at goal B (instead of goal A).
(5) *Thus:* International climate policy should aim at reducing GHG concentration to pre-industrial levels in the medium term.

Although I agree with the conclusion, the entire argument is crazy—which might indicate that this is not a fair reconstruction. Premiss (4) is patently absurd for it makes the goals our policies pursue dependent on our scientific knowledge. The mere fact that it is difficult to acquire a certain type of information is by no means a sufficient condition for changing (possibly radically) our policy goals.

Here is a more charitable interpretation of the line of reasoning, factoring in the precautionary approach[20] as a normative principle which drives the readjustment of policy measures in the light of uncertainty:

(1) We are currently not able to state a robust upper bound for climate sensitivity.
(2) Modal falsificationism: Scenarios have to be taken into account in policy deliberation unless they are falsified.
(3) *Thus:* Arbitrarily extreme scenarios regarding climate sensitivity have to be taken into account in climate policy deliberations.

[20] It is interpreted here in its strong version; see for different interpretations of the precautionary principle Morris (2000).

(4) If the scenario range climate policy is based on includes arbitrarily extreme scenarios regarding climate sensitivity, then a climate policy which aims at reducing GHG concentrations to a pre-industrial level in the medium term has the comparatively best worst-case.
(5) Precautionary principle (maximin rule): The climate policy with the comparatively best worst-case should be implemented.
(6) *Thus:* International climate policy should aim at reducing GHG concentration to pre-industrial levels in the medium term.

Note that the reduction of GHG concentration to pre-industrial levels in the medium term has the comparatively best worst case because it doesn't allow the climate system to fully adjust to a new (possibly very much warmer) equilibrium state but reestablishes the pre-industrial equilibrium. (Premiss (4) thus assumes that we can robustly rule out worst cases triggered by a quick reduction of GHG concentration to pre-industrial levels.)

Coming back to the critical questions raised above, our inability to robustly falsify extreme climate scenarios does not represent a falsification of modal falsificationism and is not a useless result at all; rather, it is itself a relevant policy information based on which, in the light of the precautionary principle, a rational climate policy decision can be taken. The corresponding policy recommendation, to reduce the GHG concentration to its pre-industrial level in the medium term, is significantly stronger and more far-reaching than the policy aims of recent reports such as the Stern Review (recommending stabilisation at 450-550 ppm CO2 equivalent[21]) or a policy paper by the German Advisory Council on Global Change (recommending stabilisation at 450 ppm CO2 equivalent[22]).

Although the principle of modal falsificationism and the precautionary principle figure as premisses in one and the same argument above, both can be clearly separated, and don't entail each other. Modal falsificationism, again, is a methodology for setting up the future scenario range under uncertainty. The precautionary principle is a decision principle under uncertainty. The former can, yet need not be combined with the latter. The argument above has shown that it is not impossible to justify a climate policy decision based on the (unbounded) scenario range we currently obtain when applying modal falsificationism: it is possible when we base our decision on the precautionary principle. It might, however, turn out to be impossible when we, or rather the democratically legitimised decision makers, decide to base their climate policies not on the precautionary approach but on some other principle.

[21] Stern (2007)
[22] WBGU (2007)

6 Concluding remarks on regional climate change and the Dappled World

This paper has strictly focused on global climate scenarios. Many climate policy decisions, however, require projections of climate change on a regional level. Here, in terms of our ability to robustly falsify future scenarios, things are even worse. The argument that detailed knowledge about climate processes is necessary to falsify regional climate scenarios seems to me much more plausible than the corresponding argument for global scenarios. Moreover, even if the range of global future scenarios were limited, these limits would not easily translate into limits for regional climate change which could turn out to be much more extreme than the global average. As a consequence, if the range of future global climate scenarios were significantly limited and if it were robustly shown that a stabilisation at 400 ppm would not trigger a global mean warming of more than 2 K, it could still be rational to aim at a GHG reduction to pre-industrial levels in the light of the uncertainty governing regional climate scenarios.

Modal falsificationism is a methodology for setting up the future range of scenarios. Yet it is more than that. It is, generally, a methodological framework for integrating diverse and scattered pieces of information and evidence, and deriving policy-relevant conclusion from this information. "Evidence for = evidence against." That is the slogan of modal falsificationism. A piece of information becomes 'evidence for use' (Cartwright, forthcoming), evidence for policy-making as soon as it is evidence against some future scenario, i.e. as soon as it can be used to falsify some possible consequences of a policy measure. Because different future scenarios might be falsified by very different, unrelated bits of information, modal falsificationism has the power to integrate evidence in a messy world.

As a last remark, the entire science of climate change exemplifies that a strong reductionist methodology is not only epistemically, but also morally wrong. As Cartwright (1999) argued in the Dappled World, by requiring inter-theoretic reduction, we impose artificial constraints on models and theories which might very well be empirically adequate and thus be able to yield policy relevant information.[23] Specifically, the very fact that a model of the climate system is conceptually different from detailed GCMs without being reducible to a precise thermodynamical description might represent its very strength since it allows the model to describe the system from an aggregate perspective which avoids messy details. If such a model is well tested, we might be able to use it to falsify certain future scenarios. I would even go further and claim that building these kind of non-reducible models which describe specific aspects of the climate system is required for limiting the range of future scenarios. The alternative, building models bottom-up,

[23] See also Feyerabend (1963) or Albert (1967, pp. 47ff.).

will only cause a further proliferation of GCMs that are currently not of great help in climate change assessment. Fortunately, climate science has generally accepted that climate models might be of very different shape, forming a whole "hierarchy" of models. It would be a great step forward if as many resources were spent on the development of robust, aggregate models as on increasing the sophistication of GCMs.

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