The Possibilistic Interpretation of Climate Model Ensembles

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Abstract: This paper examines an interpretation of climate model ensembles, according to which the model results from the ensemble represent a range of possibilities. We characterize this possibilistic interpretation (PI) and clarify how it differs from competing accounts. We then consider two related challenges – that models and model ensembles under the PI (i) have a merely apologetic function; and (ii) would be useless for inferential and policy-making practices currently pursued by the IPCC. We provide a conceptual basis for addressing (i), and in response to (ii) point out some potential uses of possibilistic climate model ensembles.

1. Introduction

In trying to gain knowledge of future climate change, the *Intergovernmental Panel on Climate Change* (IPCC) uses, amongst other resources, ensembles of climate models collected in the Coupled Model Intercomparison Project (CMIP). The models are global coupled ocean-atmosphere general circulation model (GCMs) that takes as input different forcing scenarios; they serve as the basis for projecting change in annual mean surface air temperature, typically from the late 20th century to the middle 21st century. The 5th IPCC Assessment Report, released in 2013, was based on CMIP5 which involved more than 50 models developed by around 20 modeling groups across the world (Taylor et al. 2011).[1]

The relevant model ensembles – which we will henceforth refer to as CMIPs – are *multi-model* ensembles. They consist of models that differ in mathematical structure and physical content rather than only in parameter values. Thus, the models in CMIPs are incompatible in the logical sense that some of the representational claims they make are inconsistent. Nevertheless, the use of these models is widely seen as complementary rather than mutually exclusive; this is often justified by the need to deal with scientific uncertainty and the inability to show that some model is superior to the others (Parker 2006). The fact that the models tend to yield different and contradictory results for the same forcing scenarios raises the question of how this *model spread* is to be interpreted and in what sense these models are complementary.

This paper examines one response to that question, which we will refer to as the *possibilistic interpretation* (PI) of climate model ensembles. This interpretation has been suggested by both climate scientists and philosophers, but it is currently unclear what this interpretation really amounts to and what it implies for the use of climate models. In this paper we aim to amend this. We first characterize PI and delineate it from alternative interpretations. Then we identify two challenges for PI and discuss how they might be met.

2. The Possibilistic Interpretation

Expressions of PI are found among both climate scientists and philosophers of science. As an example of the former, Stainforth, Allen et al. write:

> The model simulations are therefore taken as possibilities for future real-world climate and as such of potential value to society (2007, 2155).

A couple of years later, Knutti, Abramowitz et al. propose that

[1] CMIP6 began in 2013 and will consist of around 100 distinct climate models from 49 different modeling groups. It will be published with the IPCC's AR6, due 2022 (https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained).

ensembles can provide useful information about the spread of possible future climate change (2010, 5).

In additions to these more explicit instances of the PI, we also find it reflected in the distinction between *projection* and *prediction* that is used in the literature on climate modelling. A prediction aims to estimate the actual future of the climate system, based on observed current conditions, whereas projections attempt to estimate the system's response to external forcing scenarios, where these scenarios are interpreted as "possible initial conditions where the system has at least partially adjusted to the external forcings" at some pre-industrial point in time (Werndl 2019, 961). More simply put, as Bray and von Storch write, "projections (…) are a tool to describe *the range of possible developments*, some of which may be remote but cannot be excluded" (2009, 542). Notably, it seems to be evidence in favor of the PI that projections, not predictions, is what CMIPs have mainly been used for.

In the philosophical literature, the PI has been taken up by Betz (2009), who suggests that climate models are used to articulate previously undetected possibilities, and Katzav (2014), who argues that climate model assessment primarily aims to show that climate models and their output describe possibilities. Neither body of literature, however, analyses the concepts of possibility underlying the PI and their relevance for the climate modelling context. This paper aims to start remedying that.

From the textual evidence, we gather that PI involves two related claims. First, a claim about the *individual model projections*, stating that these represent genuine possible ways the world can turn out to be.[2] Sometimes also the models themselves, and the initial conditions inputted into the models, are seen as representing possibilities (see e.g. quotes by Stainforth and Werndl above). This goes some way to answer worries about apparent incompatibility between models in a CMIP: while *p* and *not-p* are logically incompatible, *possibly p* and *possibly not-p* are not. Interpreting CMIP members as representing possibilities thus might render them logically compatible. Second, the PI involves a claim about the *spread* exhibited by the ensemble, stating that the spread represents a somehow relevant *range* of possible scenarios. This latter part is evidenced in the quote from Knutti et al. above, and also in Stainforth, Downing et al.'s (2007, 2168) interpretation of model ensembles as providing "non-discountable envelopes" of future changes – i.e. a range of values that cannot be dismissed as impossible. This perspective strengthens the view that the use of CMIP models is complementary rather than mutually exclusive: claims about spread concern a CMIP as a whole, rather than any of its individual members.

We contrast the PI with two alternative interpretations: of ensembles as multiple-model idealizations (MMI), and as the sample space for a probability function. MMI assumes that all members of an ensemble aim to represent the same target, but that no single best model can be identified, due to the many different aims a scientific study of said target can have. Weisberg (2013) for example argues that different aims (e.g. prediction and explanation) requires prioritizing different desiderata in model construction, which sometimes trade off against one another. The CMIP spread is consequently interpreted as containing multiple models representing the same target, each with its own idealizing assumptions optimized with a different purpose in mind.[3]

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[2] "Genuine" here is meant to indicate that the possibility amounts to something more than mere technical feasibility in the sense that it is possible to generate the scenario given the modeling tools.

[3] Although we are not arguing for or against any of these interpretations, it is worth noting the models in CMIP are evidently used together to tackle the *same* issue (i.e. representing future climate) (Parker 2006, 356-7), and this is a challenge for the MMI interpretation. Note however that some PI proponents allow for multiple purposes of climate models, e.g. by distinguishing between their function as "prediction engines" and "prob[ing] possibilities" (Stainforth and Smith 2012).

The MMI interpretation conflicts with the PI in the following ways. First, the MMI assumes that all model results represent the same (actual) target, while the PI assumes that they represent multiple possibilities. Second, it does not follow from the fact that a model is instrumentally best for some purpose that it also represents a possible scenario; to the contrary, it might contain impossible idealizations that are nevertheless suitable for some purpose. There are strategies for handling idealizations under the PI (Betz 2015), but the point here is that the set of best models and the set of models capable of representing possible scenarios might overlap but need not coincide.

The other main contender is the probabilistic interpretation. On this view, the spread of model results is used to quantitatively specify the uncertainty of the outcome. Basically, the probability of an outcome is taken to be proportional to the fraction of the models which produce it: the more models agree on a result, the higher its probability (Frigg et al. 2015, 973). This can then be used to calculate a weighted average and integrated into a single projection. This is arguably an instance of what Parker (2006) calls integrative pluralism, where the results of logically incompatible models are integrated into a single representation of the uncertainty.

Interestingly, the probabilistic interpretation does not *conflict* with PI. To say that a projection has any probability larger than 0 is to assume that it is possible – probabilities are, in a sense, weighted possibilities (Bueno and Shalkowski 2015). Strictly speaking, the probabilistic interpretation presupposes that PI is right – i.e. that it represents scenarios that are *possible* and that the spread represents a *relevant range* of possible scenarios – but goes beyond PI in applying probabilities across the spread, in order to get an average. PI is "conceptually prior" (Staley 2020, 98) to the probabilistic interpretation, but is distinguished from it by its refusal to assign probabilities to the possibilities. It *merely* identifies possibilities.

The probabilistic interpretation is close to how many have actually interpreted CMIPs, including earlier IPCC reports. But at the same time, it is well-known in both the philosophical and the climate science literature that the probabilistic interpretation of CMIPs faces several challenges (see e.g. Stainforth, Allen et al. 2007; Knutti, Furrer et al. 2010; Parker 2011; Frigg et al. 2015). Among the central concerns are the fact that the models are not systematically or randomly sampled, that the uncertainty of the models cannot be quantified, and that attributing weights to individual models in the attempt to integrate them from an ensemble is hard to justify. Moreover, certain climate phenomena such as storm tracks or precipitation levels are represented as responding very differently to climate change in different models, and integrating these results into an average will lead to a washed-out response that is not really predicted by any of the models (Shepherd 2019).

In light of these problems, one faces the choice of either developing more adequate ways to treat the model ensembles probabilistically, or to fall back to the conceptually prior position, namely PI. An example of the former is Roussos et al. (2021) who propose supplementing probability distributions over ensembles with information about the confidence that they can support. But even with these improvements it is not clear that the models in CMIPs satisfy the necessary assumptions for a plausible probabilistic treatment – and proponents of PI would urge that they are not satisfied (cf. Roussos et al. 2021, 457). Indeed, PI is typically motivated in this negative sense – as a cautious fallback position in light of the lack of justification for more ambitious interpretations.

3. What can the possibilistic interpretation do for us?

An oft-cited reason for adopting PI is that it avoids the problems that beset alternatives, in particular the probabilistic interpretation. However, in light of that, two related challenges for PI present themselves.

First, one might worry that PI merely serves an *apologetic function*. Faced with problems of justifying more demanding model functions (e.g. predictions, actual explanations), it might seem that one can always justify the development of the model in question by asserting that it identifies a possibility. Yet as long as the semantics and evidential standards for the relevant possibility claims remain unspecified, anything might identify *some* possibility – such purported justifications would be pointless, amounting to little more than an apology for spurious modelling exercises.[4] If the PI lent itself to such apologetic (mis-)use, we would consider it not a viable option for understanding model ensemble practices. Therefore, it is crucial to specify criteria capable of separating spurious from genuine possibility claims made with CMIPs.

Second, there is an expectation that CMIPs can deliver information which can ground further scientific inferences as well as inform policy decision-making procedures currently practiced by the IPCC. Even if it can be shown that the models support genuine possibility claims (thus answering the apologetic worry), it remains a separate question whether this interpretation supports the standard practices that model ensembles are currently used for. Some proponents acknowledge that the PI "goes contrary to standard IPCC practice, which has as an important focus the use of climate models in order to establish confidence in claims about how the climate system actually is" (Katzav 2014, 237). Such an incompatibility of course can cut both ways: it might be that the PI is correct, and the practices must be adjusted. However, it would be a serious blow to the PI if worries like the following had traction: "If [the PI] was accepted, the IPCC process would not be seen as generating anything of decision relevance" (Roussos et al. 2021, 457). Therefore, it is crucial to specify the purposes the PI allows CMIP models to play in inferences and decision-making.

The two challenges are related in the sense that what purposes CMIPs might serve partly depends on what type of (genuine) possibility-information the model spread represents. Although we cannot give full treatment to these important issues here, we aim to show that there is a good conceptual basis available for friends of PI in addressing the apologetic challenge. We then use these insights in considering what purposes the CMIPs might serve under PI, proceeding from some recent proposals in the literature.

3.1 The Apologetic Challenge

Betz (2015) and Katzav (2014) both appear to recognize the threat from the apologetic function and try to delineate a substantial possibility notion ("serious" and "real" possibility, respectively) relevant to interpreting CMIPs. However, they both fail to note the distinction between *epistemic* and *objective* possibility, and its relevance. A claim of the form "*p* is possible" can mean different things. In particular, it can mean that (i) some features of the world *could* be such that *p* is/were/will be true (even if *p* is not true in the actual world); alternatively, it can mean that (ii) given an agent's limited knowledge, this agent cannot rule out that *p* is true in the actual world. These notions are widely known as objective and epistemic possibility, respectively.[5] They differ, firstly, in their semantics: the truth of "*p* is possible", epistemically interpreted, depends on the relation of *p* to the agent's corpus of knowledge; objectively interpreted, it depends on some feature(s) of the world, and is independent of humans' epistemic situation. While this distinction is widely understood conceptually, its relevance for philosophy of science is unfortunately often neglected (Sjölin Wirling and Grüne-Yanoff 2021a).

The PI's claim that individual projections from GCMs should be understood as descriptions of possible future climate states allows for both the epistemic and the objective

[4] For discussion and a defense of the possibilistic interpretation in the context of economic modelling, see Grüne-Yanoff and Verreault-Julien (2021).

[5] They can be combined, but retain their distinct characteristics (Sjölin Wirling and Grüne-Yanoff 2021a).

interpretation. Betz clearly has epistemic possibility in mind, whereas Katzav's notion, while harder to classify, has a more objective flavor. Our view is that the *projections* are best interpreted as representing possibilities in a sense that combines epistemic and objective conditions. This is because the variation amongst CMIP models is grounded in a mix of objective and epistemic sources of uncertainty (Shepherd 2019, 4-5). On the epistemic side, there is uncertainty about the climate system response to future climate forcing, expressed by substantially different model structures in the CMIP, each compatible with current scientific knowledge. Although (at best) only one of these representations is accurate, we don't know which one. This is to say, ensemble members are epistemically possible representations of the climate system. On the objective side, the climate system exhibits various natural internal processes, for example the El Nino Southern-Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO), whose dynamics drive a substantial internal variability of system. The actual system can develop into one of a multitude of possible, mutually exclusive states – and this is a property of the system itself and cannot be reduced to the limited knowledge of the observer.[6] Insofar as GCMs represents this internal variability, they involve an element of objective modality. Thus, the ensemble members incorporate both kinds of modality, and so will presumably the model results that they output.[7]

But it is important to keep the epistemic/objective distinction in mind in order to properly meet the challenge from the apologetic function, particularly when it comes to the evidential standards for showing that some *p* is indeed a possible future in the relevant sense. Given that objective and epistemic possibility claims are claims about different things, they also have different epistemologies. On the one hand, one is justified in accepting 'It is epistemically possible that *p*' if *p* is not ruled out by one's corpus of knowledge. On the other hand, in order to make a justified objective possibility claim, one needs to refer to evidence that plausibly indicates that so-and-so *is* a way the world could be. Consequently, while both possibility claims refer to the corpus of knowledge for justification purposes, ignorance functions as a direct justification of epistemic possibility, but plays no such function for objective possibility claims. This is relevant to evaluating whether GCMs indeed justify the kind of possibility claims relevant to climate science.

The distinction is also relevant to the notion of progress in CMIP design. It is often seen as desirable to "reduce uncertainty" and thereby reduce the model spread. Indeed, an increase of information, (and hence of knowledge) will imply a reduction of the range of *epistemic* possibilities in the CMIP. But for objective possibilities, this does not hold. Here, progress in knowledge is constituted by making the representation of invariance more accurate, which might imply either reduction or expansion of the range. Thus, it is not a general desideratum to reduce CMIP ranges.

In sum, it remains of course to work out more precise notion(s) of possibility relevant to climate projections, and to evaluate whether CIMP members plausibly deliver possibility information of the right kind, but we have gone some way here towards providing a conceptual basis for addressing apologetic worries. In particular, distinguishing between epistemic and objective possibility is important, and explicitly heeding the distinction will help avoid charges of relying on confused, mixed possibility concepts. Moreover, there is literature on the criteria for both kinds of possibility claims of which the PI can avail itself. The semantics of both concepts are relatively clear, and there seems to be at least a partial

[6] Some authors have explicitly defined emission scenarios as possible model states partially adjusted to external forcings at some historical point in time, and specified that models are *adjusted* in this sense "when there would not be any more changes to the climate variables *apart from internal variability"* (Werndl 2019, 959, our emphasis). The inclusion of objective possibilities then becomes a crucial feature of *projections*.

[7] Modality also comes in at the level of forcing scenarios conditionally on which the projections are made, but we focus on here on the models and the spread of model results with respect to a given scenario.

consensus for the evidential standard of epistemic possibility (for discussion, see Sjölin Wirling and Grüne-Yanoff 2021a). The evidential standards for modeling objective possibility are more controversial, but at least there are a discrete number of proposals that are seriously discussed in the literature (for an overview, see Sjölin Wirling and Grüne-Yanoff 2021b)

3.2 The Uselessness Worry

Assuming that GCMs can support genuine possibility claims, what uses can this information be put to? We consider here two different types of functions of CMIPs in current IPCC practices. First, many recognize that the model spread represents important information for policy decision-making (e.g. Knutti, Furrer et al. 2010, 2755; Roussos et al. 202, 443; Shepherd 2019). In particular, as Stainforth, Downing et al. (2007) put it, the spread informs us about a "non-discountable envelope", i.e. the range of possible outcomes that cannot be ruled out. We believe that CMIPs under the PI can represent this type of information, although attention needs to be paid to which modal concept is in play, as CMIPs can represent both epistemic and objective possibilities. Objective possibilities inform about the internal variability of the climate system (e.g. Deser et al. 2012); epistemic possibilities inform about the extent of ignorance about a climate system (Parker 2011; Staley 2020).

Under the probabilistic interpretation, CMIPs are employed for crucial roles in policy decision making. Such approaches essentially rely on the quantification of uncertainty not available in the PI, which has led some to conclude that CMIP under PI "would not be seen as generating anything of decision relevance" (Roussos et al. 2021, 457). We disagree. The qualitative description of different possibilities, both objective and epistemic, *can* provide substantial support for decision-making. Using decision rules akin to Maximin, those policy alternatives are considered robust that deliver acceptable results under a wide range of possible future states (Lempert 2013). This is for instance in line with the Storylines approach (e.g., Shepherd 2019). The Storylines approach stresses the importance for climate-related decision-making of contrasting and considering in detail a set of distinct, self-consistent possible trajectories, without probabilities attached. Proponents argue that this is in several respects an *improvement* of how uncertainty is represented to decision-makers, compared to the probabilistic interpretation, for instance because it avoids the risk of "missed warnings" and washed-out, implausible projections which does not correspond to any of the individually plausible model results that might be the upshot of averaging.[8]

That said, there are some further unresolved issues for PI in relation to this representative function. One concern is model idealization. As with all models, CMIPs members will be idealized representation of their targets – possibilities in this case, according to the PI. This has led some (e.g. Betz 2015) to worry how such models can support genuine possibility claims at all. We note that this is an issue specifically for the function of representing *epistemic* possibilities. Under the epistemic interpretation, any imputed model assumption in conflict with the current corpus of knowledge will count as an idealization. Under the objective interpretation, in contrast, only assumptions deemed impossible by the relevant standards will count as an idealization; others, contradicting the current state of the actual world, will count as counterfactual possibilities. Therefore, the function of providing objective possibilities is less threatened by model idealization than the function of providing epistemic possibilities (Sjölin Wirling and Grüne-Yanoff 2021a). This again emphasizes the relevance of keeping this distinction in sight. For an attempt at handling the issue see (Betz 2015).

Another concern is that CMIPs are "ensembles of opportunity". Since modeling groups are free to decide how to develop their model, this leads to many similarities between

[8] See also (Stainforth, Downing et al. 2007) on how non-discountable envelopes can inform policy decisions.

models, and a lack of the coordination perhaps required for (sufficient) diversity and exhaustiveness of the spread of possibilities. Without exhaustiveness, one cannot infer from a CMIP that what lies outside it is *not* possible or "discountable" (Stainforth, Downing et al. 2007, 2167), but a more serious problem is the lack of diversity, especially if this is desirable from a decision-making point of view. If explorations of ranges of possibility is a key function of CMIPs, this should presumably inform future construction of climate models and ensembles.

The second function for CMIP's we want to consider here is that of supporting further (theoretical) inferences. One example is the role that CMIPs play for model testing. Perhaps the simplest way to test a model is to make a prediction using the model and then see whether the observations match the prediction (Lloyd 2010). Such a procedure, however, must consider the internal variability ("climate noise") of the system: instead of giving only a point prediction, it should also provide the interval of expected stochastic noise. This is particularly important for climate systems with low signal-to-noise rations, e.g. ocean fluctuations (Deser et al. 2012). To correctly estimate and predict the magnitude of this noise requires drawing on substantially sized model ensembles representing objective possibilities (Shepherd 2019, see however Werndl 2019, 970 for a critical discussion of such minimal-size criteria). Thus, CMIPs under the PI serve important roles in testing model accuracy.

Furthermore, climate projections should specify not only internal variability but also systematic bias, arising from misspecified models employed in the observation process. Analysis of such systematic bias proceeds via specification of possible error scenarios: the range of epistemically possible models that would affect the value of a measured quantity (Staley 2020). Such an analysis is based on and cannot operate without a justified delineation of epistemically possible models. Again, CMIPs under the PI can play a substantial role for relevant inferences.

Finally, some authors have argued that obtaining the approximately same projection from a number of independently differing model construction provides confirmation of these model results (Lloyd 2010, Weisberg 2013). Such arguments typically appeal to variety of evidence arguments: it is because the same result obtains from a wide range of possible model constructions, that it increases confidence in the result. However, actual CMIP design – e.g. lack of independence and random, systematic sampling – present an obstacle to this type of robustness analysis (e.g. Parker 2011), just as it presents an obstacle to probabilistic treatment. This might also have been Levins' (1993, 553) worry, when he suggested that one's confidence in the robust model result depends on how much of the possibility space is covered.

Our discussion, while making no claim to completeness, suggests a couple of ways in which CMIPs, under the possibilistic interpretation, can be used for supporting decision making and for making various inferences. This, in our view, goes some way towards diffusing worry of uselessness.

4. Conclusions

The aim of this paper was to make some headway with respect to understanding and evaluating the possibilistic interpretation of climate model ensembles. After having specified more clearly the relation between the PI and other interpretations, we presented two related challenges for the PI: the apologetic worry and the uselessness worry. We then suggested in response to the former worry that the PI can likely be made viable but requires more careful delineation of the relevant notions of objective and epistemic possibility in order to obtain reliable standards of evidence, which is important for enabling evaluation of to what extent ensemble members *do* support possibility claims of the relevant kind. We also identified – against the charge of uselessness – two important functions that CMIPs can plausibly serve, given the type of information they provide under the PI. While (some of) these might require adjustment, they arguably remain sufficiently close to current IPCC practices and purposes to answer the uselessness worry.

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