Initial conditions dependence and initial conditions uncertainty in climate science

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Abstract

This paper examines initial conditions dependence and initial conditions uncertainty for climate projections and predictions. The first contribution is to provide a clear conceptual characterisation of predictions and projections. Concerning initial conditions dependence, projections are often described as experiments that do not depend on initial conditions. Although prominent, this claim has not been scrutinized much and can be interpreted differently. If interpreted as the claim that projections are not based on estimates of the actual initial conditions of the world or that what makes projections true are conditions in the world, this claim is true. However, what is often meant is that the simulations used to obtain projections are independent of initial conditions. This paper argues that evidence does not support this claim. Concerning initial conditions uncertainty, three kinds of initial conditions uncertainty are identified (two have received little attention from philosophers so far). The first (the one usually discussed) is the uncertainty associated with the spread of the ensemble simulations. The second arises because the theoretical initial ensemble cannot be used in calculations and has to be approximated by finitely many initial states. The third uncertainty arises because it is unclear how long the model should be run to obtain potential initial conditions at pre-industrial times. Overall, the discussion shows that initial conditions dependence and uncertainty in climate science are more complex and important issues than usually acknowledged.

Contents

1 Introduction

This paper investigates *initial conditions dependence* and *initial conditions uncertainty* in climate science. Initial conditions dependence refers to the dependence of simulation results on initial conditions. Initial conditions uncertainty refers to uncertainty arising because the initial conditions are not precisely known or because the calculations cannot be performed with the precise initial conditions. The question of initial conditions dependence and uncertainty arises for the two main types of forecasts performed in climate science, viz. predictions and projections. The first contribution of the paper will be to provide a clear conceptual characterisation of predictions and projections.

Climate *predictions* are claims about the *actual evolution of the climate system* given knowledge of the current state of the climate system (and an external forcing scenario). They are usually obtained by starting from an initial conditions ensemble representing the uncertainty in the *observations*. Then models are used to evolve this ensemble forward to obtain forecasts of the climate variables, assuming a certain external climate forcing scenario. (*Climate forcings* are the factors that affect the climate: they drive or "force" the climate system to change. Examples are variations in the energy output of the sun, greenhouse gases or volcanic eruptions. *External* forcings are forcings external to the climate system (as it is modelled), e.g., the variation in energy output of the sun). Climate *projections* are claims about the *response of the climate system to external forcing scenarios* (e.g. IPCC 2014, 953). They are usually obtained by starting from initial conditions ensembles that (in contrast to predictions) represent *possible (and not observation-based)* initial conditions of the climate system at pre-industrial times (where the system has at at least partially adjusted to the external forcings at pre-industrial times). Then models are used to evolve this ensemble forward to obtain a forecast of the climate variables (assuming a certain external forcing scenario). Predictions and projections are crucial: they provide the most important information about the future climate system and routinely inform policy decisions. Indeed, it seems no exaggeration to claim that the forecasts that have been most often shown to policy makers are projections.

Concerning *initial conditions dependence*, a widespread claim is that projections, unlike predictions, are independent of initial conditions. This paper will distinguish different interpretations of this independence claim. I will argue that projections are indeed not dependent on estimates of the actual initial conditions (because they are just based on potential initial conditions) and that because projections are claims, their their truth maker is the world and not initial conditions. However, importantly, it is often believed that simulations used to obtain projections deliver the same results, independent of the initial conditions (e.g. IPCC [2014], p. 958; Winsberg and Goodwin [2016]). I will argue that evidence does not support this belief. This issue has not received any attention in the philosophy of climate science.

When *initial conditions uncertainty* is discussed, it is usually pointed out that, just like for any other science, initial conditions are not precisely known. Hence there is uncertainty about climate simulations (e.g. Parker [2010]; Stainforth *et al.* [2007], p. 2148). This initial conditions uncertainty is usually regarded as less important than other forms of uncertainty such as model or parameter uncertainty (cf. Parker [2010]). This paper will argue that this initial conditions uncertainty is more severe than often acknowledged. Furthermore, this paper will distinguish two other kinds of initial conditions uncertainty (which have not been discussed in philosophy of climate science before). Namely: the uncertainty arising because the theoretical initial ensemble cannot be used in calculations and has to be approximated by finitely many initial states, and the uncertainty arising because it is unclear how long the model should be run to obtain initial conditions at pre-industrial times.

This paper proceeds as follows. First, a clear characterisation of projections and predictions will be provided (Section 2). Then Section 3 will discuss initial condition dependence and Section 4 initial conditions uncertainty. The conclusion will summarise the findings (Section 5).

2 Projections and Predictions

Climate science distinguishes between *predictions* and *projections* (IPCC [2014], Chapter 11). Both give rise to interesting philosophical questions concerning initial conditions dependence and initial conditions uncertainty (but there will be more discussion on climate projections as they raise more questions).

2.1 Predictions

Climate predictions are predictions in the sense ‘prediction’ is most commonly understood. Namely, they are *claims about the actual future evolution of the climate system given knowledge of the current conditions of the climate system* (and an external forcing scenario). They are obtained by starting from an *initial conditions ensemble* (a probability density over the space of all possible values of the climate variables, such as the surface temperature, the surface pressure etc) representing the uncertainty in the *observations* at time t_0. Suppose the aim is to make predictions at time t_1 under a given external forcing scenario. Then a model or class of models is considered. If one model is considered, the model is used to evolve the probability density forward to t_1 and as outcome this evolved ensemble is presented. If a class of models is considered, the model average of the evolved ensembles is presented (IPCC [2014], p. 1451; Meehl *et al.* [2014]; Taylor *et al.* [2012]). What we have described so far are *point predictions*, i.e. predictions at time t_1. Next to them often also *aggregate* predictions of the *average* values of the climate variables *over a certain time period* (e.g. over thirty years) are considered. One proceeds here as for point predictions but in the end presents the average of the evolved ensembles over the time period of interest.

An example is the point-prediction of the sea level pressure of the ocean on 1 January 2020, performed with the Community Climate System Model version 3 under the A1B emissions scenario (assuming a balanced emphasis on all energy sources) (Teng *et al.* [2011]). Here the observational uncertainty of the climate variables is reprsented by an initial conditions ensemble and this ensemble is evolved forward to predict the sea-level pressure of the ocean on 1 January 2020.

As natural as the concept of a prediction is, until recently climate scientists *were unable to make predictions*. It is only in the fifth assessment report (IPCC [2014], Chapter 11) that climate predictions were considered to be successful and thus presented. In general, the practice of climate prediction is still in its infancy (IPCC [2014], 958-966; Meehl *et al.* [2014]; Taylor *et al.* [2012]).

Why have climate predictions only been made now? There are several reasons. First and foremost, because climate models are at best only an approximation of the climate system, the states the model will evolve to after a while (model equilibrium states) will differ somewhat from the actual states the climate system evolves to after some time and that are observed (observed equilibrium states). So when climate models are initialized with observations, the simulations will be forced away from the model's equilibrium states to match the observations. They will then drift back to the model's equilibrium states, but this drifting back will be confounded with the climate evolution that is being predicted. Until recently climate scientists did not know how to disentangle the climate evolution and the drifting-back. Nowadays there are several methods to deal with this (including "bias correction methods" where the drifting-back is corrected and "anomaly initialization" where the anomalous component is added at the beginning to the equilibrium values of the model to minimize the drifting-back). There are also other reasons why performing predictions is difficult. Namely, good data, in particular about the ocean, are needed to initialize climate models, and they have have only become available recently (IPCC [2014], p. 965). Furthermore, initializing models with actual initial conditions ensembles is highly nontrivial and methods of initialization had to be developed (IPCC [2014], Chapter 11; Meehl *et al.* [2014]; Parker [2015]).

2.2 Projections

So until recently only projections were performed (and are still performed because the practice of climate predictions is in its infancy and projections provide a different kind of information).

What is a *projection*? Projections are claims about the *response of the climate system to external forcing scenarios* (cf. IPCC 2014, 953). Projections are also obtained with help of simulations. Indeed, the simulation performed are the same as for predictions except that the *initial conditions ensemble one starts with consists of states of a climate model that has at least partially adjusted to the external forcings at* t_0. A model has adjusted to the external forcings when there would not be any more changes to the climate variables apart from internal variability (*internal variability* refers to the variability of the climate variables due to natural internal processes within the climate system; known examples of internally generated variability include the El Nino Southern-Oscillation (ENSO) or the Atlantic Multidecadal Oscillation (AMO)).[1] Hence the initial conditions ensemble one starts with does *not* represent the observational uncertainty at t_0 (as for predictions) but the possible values of the climate system that has at least partially adjusted to the external forcings at t_0. Here t_0 has to be chosen in such a way that the actual climate system also has at least partially adjusted to the external forcings at t_0. In practice, t_0 is chosen to be 1850 or another point of time during the pre-industrial period.

Apart from this difference, the simulations performed are the same as those for predictions. That is, a time point t_1 in the future, an external forcing scenario and a class of models is considered. Each model is used to evolve the initial ensemble forward to t_1. As outcome of the projection what is presented are either these evolved ensembles for all models or a model average, i.e. an average of the evolved ensembles over all models. What we have described so far are *point projections*, i.e. forecasts at a certain time t_1. As for predictions, sometimes also *aggregate* projections are considered. One proceeds here as for point projections but in the end presents the average of the evolved ensembles over the time period of interest.

Why is the initial ensemble composed of possible states of the climate system that has at least partially adjusted to the external forcings at t_0? The theoretical reason is that some input is needed for climate models. Because the input cannot be actual observations (because of the difficulties of performing predictions), instead possible initial conditions are considered. Yet the possible initial conditions constitute an extremely wide set, which is restricted by only considering states of a climate system

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[1] Sometimes, this is also described by saying that the model is close or in equilibrium with the external forcings at t_0 (cf. Stouffer et al. [2004]).

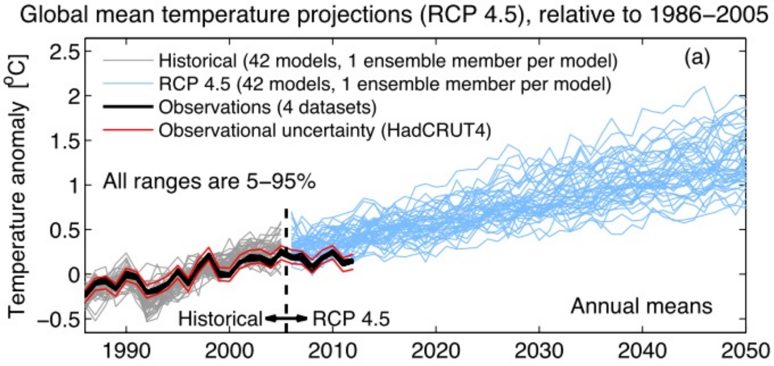

Figure 1

that has at least partially adjusted to the external forcings at t_0. The practical reason is that if initial states are chosen where the system has at least partially adjusted to the external forcings, then drifting-back to the equilibrium states can be avoided (cf. Subsection 2.1) (IPCC [2007], Section 8.2.7; IPPC [2014], 978; Stouffer [2004]).

To arrive at an ensemble of possible initial conditions of the climate system that has at least partially adjusted to the external forcings at t_0, climate models are initialized with current observations[2] and then are integrated backwards to pre-industrial times.[3] The model is run for a long time with pre-industrial forcings (between a few hundred to thousand years) to ensure that the system has at least partially adjusts to the pre-industrial external forcings (this is called the *spin-up* period). Once adjusted, an ensemble of possible initial conditions is generated from various points of the simulation.

An example is the projection of the global mean annual surface air temperature at 2050, performed with the CMIP5 (Coupled Model Intercomparison Project Phase 5) models under the RCP4.5 representative concentration pathway (where emissions peak around 2040 and then decline) (IPCC [2014], p. 981). This is an aggregate projection (annual forecast), and the outcome of these projections is a wide range of temperature simulation results, shown in light blue in Figure 1 (IPCC [2014], p. 981).

Now that we have introduced projections, let us discuss the two major intuitive characterisations of them. First, it is sometimes emphasised that projections are dependent on the external forcing scenario while predictions are not. For example:

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[2] Sometimes instead the input of the atmospheric variables is obtained from simulations, which are run for a long time to ensure that the atmospheric variables have adjusted to the present external forcings (Stouffer *et al.* [2004]).

[3] An alternative is to start under pre-industrial external forcing conditions and then perform even longer integrations (Stouffer *et al.* [2004]).

> A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized (IPCC [2014], p. 1451; see also Schmidt [2008], Slide 5).

From description given above it is clear that *both* predictions and projections depend on the emission/concentration/radiative forcing scenario. It is true, however, that for predictions usually short lead-times are considered and then they are approximately the same for all plausible emission/concentration/radiative forcing scenarios. Projections, on the other hand, are made both over shorter and longer time periods, and in the latter case they are strongly dependent on the emission/concentration/radiative forcing scenario (IPCC [2014], Chapters 11 and 12). Thus a charitable interpretation is that this first intuitive characterisation emphasises that *in contrast to climate projections, the external forcing scenario only has negligible influence on predictions.*

However, this *does not constitute the core difference* between projections and predictions. More specifically, from the description above it is clear that projections are not just like predictions, except that the prediction lead time is longer and hence the external forcings becomes more important. A prediction with a longer prediction lead time would still be a prediction. The fundamental difference is that predictions aim to estimate the actual evolution of the climate system based on current initial conditions, but projections aim to to estimate the reponse of the climate system to external forcings scenarios. The procedure of obtaining predictions and projections is the same, except that the *initial ensembles are interpreted differently* (as observed initial conditions for predictions; and as possible initial conditions where the system has at least partially adjusted to the external forcings for projections).

Second, projections are commonly characterised as *independent of initial conditions* (or at least that the influence of initial conditions is *negligible*), motivating the idea that projections are about the *forced response* of the system, i.e. the response of the system to the factors that affect the Earth's climate (Brandstator and Teng [2010]; Meehl *et al.* [2014], p. 251; Taylor *et al.* [2012], p. 487; Schmidt [2008], Slide 5). For instance, the IPCC ([2014], p. 958, see also p. 560) describes projections as:

> climate change experiments with models that do not depend on initial conditions but on the history and projection of climate forcings.

Clearly, projections about various different variables are performed (e.g., some projections just concern the temperature, some temperature and precipitation, many concern several climate variables). Note that what is claimed in the quotes is that all (or nearly all) projections are independent of initial conditions (i.e. a general claim about the concept of a projection is made). Let us now investigate this independence claim.

3 Initial Conditions Dependence

3.1 Projections

It is important to distinguish different interpretations of the independence claim. According to a *first* interpretation[4], what is meant is that projections, unlike predictions, are *not* based on estimates of *actual* initial conditions. This is true: as outlined above, projections are based on *potential* initial conditions at pre-industrial times. *Second*, projections are claims about the response of the climate system given a certain external forcings scenarios. Hence their truth makers are the world and do not include any initial conditions and can be said to be (in a sense) independent of initial conditions.[5]

Third, for projections the question arises how the *forced response of the climate system* is defined. When one looks at how projections are obtained, initial conditions ensembles (representing potential initial conditions of the climate system in equilibrium at pre-industrial times) are evolved forward to arrive at the evolved ensemble, which is identified with the forced response of the climate system. But then the forced response (independent of any details about initial conditions) is only well defined if the same evolved ensemble is obtained for all possible initial conditions ensembles. This claim that projections are independent of the details of the initial ensemble is the *third* interpretation of the independence claim. It is endorsed in several publications (e.g. Brandstator and Teng [2010]; IPCC [2014], p. 961) and will now be discussed.

Dynamical Conditions Justifying Independence of Initial Conditions?

Climate scientists often justify this claim by assuming that the *dynamics* of climate models is such that over time *all initial ensembles eventually approach the same probability distribution*, which is then identified with the forced response of the system (e.g. Brandstator and Teng [2010]; IPCC [2014], p. 961). In all discussion I have found this dynamical condition is stated intuitively and no formal definition is given. Given this, it is important to point out that the *corresponding formal condition is the one of having a time-dependent strong physical measusre.*

This condition will now be stated intuitively (for the formal definition see the Appendix). Time-dependent strong physical measures are defined for time-dependent

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[4] I am grateful to an anonymous referee for suggestion this interpretation.

[5] A referee urged me to include this interpretation.

climate models (the models used for projections depend on time; for instance, the incoming solar radiation, the greenhouse gas concentrations etc. change with time). Intuitively speaking, this condition expresses that for *any* arbitrary initial ensemble, if the ensemble is evolved forward for a *sufficiently long time*, the probability assigned to any set A at time t will approach the value $\mu_t^{SPM}(A)$. In other words, any arbitrary initial ensemble that is evolved forward eventually approaches the same probability μ_t^{SPM} (the time-dependent strong physical measure). When a model average is considered, of interest is whether each model has a time-dependent strong physical measure. If this is so, then also for any arbitrary initial ensemble, if the ensemble is evolved forward for a sufficiently long time, the probability assigned to any set A will approach the model average of the strong physical measures of the individual models. When aggregate forecasts over time are considered and the model has a time-dependent strong physical measure, for any initial ensemble, if the ensemble is evolved forward for a sufficiently long time, the probability assigned will be the average over the probabilities assigned by the time-dependent strong physical measure.[6]

Do climate models have time-dependent strong physical measures? Answering this question is very difficult because the dynamical properties of climate models are poorly understood. On the one hand, Brandstator and Teng ([2010]) find evidence for a strong physical measure for the upper ocean temperature (but note that for the upper ocean temperature initial conditions are expected to play less of an influence than for other variables (such as *all* the ocean variables)). Teng *et al.* ([2011]) is another study that finds evidence for a strong physical measure for the Atlantic overturning streamfunction. It cannot be excluded that for certain specific climate variables the models used for projections have strong physical measures (and the studies here might provide examples where this is the case).

Yet what matters is whether all (or nearly) models used for projections have strong physical measure. Evidence does not support this claim. In particular, if a system is independent of initial ensembles, it cannot have *several attractors* (several equilibrium states). Intuitively speaking, an attractor is a set where the model converges to after some time has passed (for some initial conditions) and this set is also often referred to as equilibrium state. If there are several attractors, the initial condition influences in which attractor the system ends up; then certain initial conditions ensembles evolve to one attractor and others to another attractor, contradicting the condition of a strong physical measure.

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[6] For time-independent models that are studied in classical dynamical systems theory the concept analogous to a time-dependent strong physical measure is mixing (cf. Werndl [2009]). However, mixing is not of interest in the context of climate projections because models used for projections are time-dependent (mixing is still of interest to climate science, namely when the behaviour of climate models under constant external forcings is studied).

Yet *several attractors were found for simple as well as complex* climate models. For example, the *ocean circulation* is associated with several equilibrium states (IPCC [2014], p. 433; IPCC [2007], p. 111; Stainforth *et al.* [2007], p. 2150). In particular, Manabe and Stouffer ([1999]) for a coupled ocean-atmosphere model found that the *ocean circulation* gives rise to two equilibria: a thermohaline circulation with sinking regions in the North Atlantic Ocean (resembling those of our Earth) and a reverse thermohaline ciculation with sinking in the circumpolar ocean of the southern hemisphere. There is also evidence for multiple equilibria of the *atmosphere-vegetation* system. For instance, Zeng and Neelin ([2000]) investigated the climate in Africa and found two equilibria: a desert-like and a forest-like state. Furthermore, Wang and Eltahir ([2000]) found two equilibria for a simple biosphere-atmosphere model: a wet equilibrium with a desert border at 17.5 and a dry equilibrium with a desert border at 16. Another relevant study is Conradie ([2015], pp. 110-119). He discovered several attractors for a low-resolution version of a CMIP5 climate model under the *RCP8.5 concentration pathway* for the global average surface air temperature, and the surface air temperature in the Southern Hemisphere, in the Antarctic, in the South of Southern Africa and in the Antarctic Circumpolar region.

In sum, that some climate models show several equilibrium states at least for some regions on Earth is plausible, and they could then also have a non-negligible effects on global variables. Further, having a strong physical measure is a very strong dynamical condition. In the absence of clear evidence for it, it has to be assumed otherwise. We conclude that *evidence does not support the claim that climate models have strong physical measures.*

Even if climate models had strong physical measures, this would not imply independence of initial conditions ensembles. For systems with a strong physical measure, the probability assigned to a set A by the evolved ensemble only relaxes to $\mu_t^{SPM}(A)$ *after some time* (see equation (2) in the Appendix). Hence there would only be independence if the convergence to the strong physical measure were quick enough and happened already for the standard prediction-lead times of interest. However, this is doubtful: Fraedrich [(1987)] argues that for climate systems predictability is only lost after about 10.000-15.000 (!) years. Daron and Stainforth ([2015]) and Selten *et al.* ([2004]) and Smith ([1987]) also argue that it is plausible that there is no convergence for prediction lead times of interest, and they underscore this with evidence from Lorenz's 1963 model and a community climate systems model.

Furthermore, even if climate models had strong physical measures, projections could not be independent of initial conditions ensembles. Why? The more an initial ensemble peaks around a certain value, the longer the convergence to the strong physical measure will need – otherwise the fundamental mathematical requirement of *continuity* would be violated (intuitively speaking, the dynamics of a climate model is continuous if it has no holes or sudden jumps). So given a certain fixed prediction lead time of interest, if the ensemble is sufficiently peaked around a certain value, there will be *no* convergence within the time period of interest. This problem can only be avoided if restrictions are placed on the ensembles that are allowed. However, since the ensembles just represent possible initial conditions, there are no principled reasons to exclude certain initial ensembles. This is also reflected in scientific practice, where there are no requirements that highly peaked ensembles are not allowed. This argument it strong because it shows that projections can for *no* climate variable of interest be independent of initial conditions ensembles.

We conclude that *even the condition of having a time-dependent strong physical measure cannot guarantee that projections are independent of initial ensembles.* Furthermore, it *does not make sense to look for stronger conditions* because otherwise continuity would be violated.[7]

What Projections Can and Cannot Provide

What are the implications of the above discussion for the kind of information projections provide? First, projections are often claimed to estimate the forced response of the system (independent of initial conditions). It is understandable that it would be attractive if such a forced response existed: we would then have a measure of what happens to the climate system when certain external forcings are applied, independent of internal variations and initial conditions. *However, as we have seen in the previous subsection, evidence does not support the independence of projections on initial ensembles. Thus projections cannot be taken to measure the forced response of the system (independent of initial conditions).*

Second, when seeing a graphical display of projections as in Figure 1, one might easily think that what is shown there are forecasts of the evolution of the climate system given the uncertainty in the present observations or the uncertainty in the observations in 1850s. However, as our discussion has made clear, this is not what projections provide us with – they do not provide us with forecasts based on observational input.

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[7] Note that dynamical systems theory is among the most important mathematical theories for climate science. In this field mixing (the time-independent analogue of a strong physical measure; cf. footnote 6) is a very prominent condition. This might partially explain why the idea that all initial ensembles smooth out to a certain probability measure features so prominently in climate scientists' thinking about projections.

Projections still provide very valuable information: they tell us about about *some of the possible paths of a climate system that started from initial conditions at a point of time where the system has at least partially adjusted to the external forcings (usually at pre-industrial times).* There is no requirement that for projections all possible initial conditions have to be included in the initial ensemble.[8] Therefore, projections only provide information about *some* but *not all* possible paths of the system that has at least partially adjusted to the external forcings at pre-industrial times.

There are already interpretations that emphasise that projections are possibilities. In particular, Stainforth *et al.* ([2007], p. 2155) argue that projections are "possibilities for future real-world climate". Betz ([2009]) and Katzav ([2014]) argue that climate projections and climate models describe possibilities. Parker ([2010]) interprets projections as a set of predictive outcomes that are plausible given the current knowledge, which is close to a view based on possibilities. However, neither Stainforth *et al.*'s nor Betz's nor Katzav's nor Parker's view is mainly motivated by considerations about initial conditions, but by concerns about model limitations and parametric uncertainty. Furthermore, neither of these views explicitly interprets projections as providing more specific possibilities, namely those of a climate system that had *at least partially adjusted to the external forcings at pre-industrial times.*

3.2 Predictions

The question whether the simulations used to obtain predictions are dependent on initial conditions also arises for predictions. As discussed in subsections 2.1 and 2.2, the simulations made for predictions and projections are very similar. The main difference lies in the interpretation of the initial conditions ensemble. Because of this similarity, the *arguments given in the previous subsection immediately show that evidence does not support that simulations used to obtain predictions are independent of initial ensembles.* This is in agreement with common belief: climate predictions are usually not claimed to be independent of initial ensembles, even by those who claim that projections are independent (cf. Brandstator and Teng [2010]; IPCC [2014], 960-962). The reason for this is that predictions are performed over very short time periods (not longer than 10-20 years). It is believed that over such short time spans, initial conditions are influential.

To obtain predictions, usually initial conditions *ensembles* are evolved forward. Sometimes, instead of initial condition ensembles, just *one initial condition* (representing the best guess of the current state of the climate variables) is used to arrive

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[8] Furthermore, climate models are not considered realistic enough so that they could provide information about all the possible paths of the climate system where the system has at least partially adjusted to the external forcings at pre-industrial times (cf. Thompson *et al.* [2016]).

at a forecast. In this case also the question of initial condition dependence arises, to which we now turn.[9]

Let us first consider point predictions of the climate variables at time t_1 based on one initial condition at t_0, or a model average of such predictions. Clearly, such predictions will depend on the initial condition.[10] Of real interest is therefore only the question whether *aggregate predictions* over time are independent of initial conditions. When several models are considered, the question is whether the model average of the aggregate predictions is independent.

For time-independent models, ergodicity is often invoked to formalize the condition that aggregate predictions are independent of initial conditions. Intuitively speaking, *ergodicity* expresses that aggregate predictions taken over infinite time periods equal the phase average over the dynamics (the formal definition can be found in the Appendix). Indeed, it can be shown that aggregate predictions taken over infinite time periods are the same for almost all initial conditions *if and only if* the system is ergodic (cf. Peterson 1983). When model averages are considered, the question is whether each model is ergodic.

Ergodicity is often invoked in climate science. For instance, Dymnikov and Gritsoun ([2001]), North *et al.* ([1981]) and von Storch and Zwiers ([2002], Section 11.2.8) assume that climate models are ergodic.[11] However, ergodicity is *of very limited relevance* for climate predictions because it is defined for time-independent dynamical systems and the models used for predictions are time-dependent. Still, it is interesting to ask whether climate models are ergodic because ergodicity is such a common assumption and because ergodicity is still relevant to climate science when trying to understand the behaviour of climate models under *constant* external forcings.

Answering this question is difficult because the dynamics of climate models is poorly understood. In general, *evidence does not support the claim that climate models under constant external conditions are ergodic.* Daron ([2012]), McGuffie and Henderson-Sellers ([2005]) and Schneider and Dickinson ([1974]) provide evidence against ergodicity. Peicai *et al.* ([2003]) view the climate system as a cascade of hierarchical sub-systems, implying that it is not ergodic. Also, the evidence of mul-

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[9] This question also arises for projections that are calculated on the basis of just one initial condition. Since the case of just one initial condition is more often considered, we comment on it here. Yet our discussion carries over to projections.

[10] They would not depend on initial conditions only if there were a fixed point to which all initial states converged. However, there is no evidence for this.

[11] Ergodicity is a crucial notion in measure-theoretic dynamical systems theory (also called ergodic theory), which is one of the most important matheamtical theories for climate science. This might partially explain why ergodicity figures prominently in climate scientists' thinking.

tiple attractors discussed above provides evidence against ergodicity (ergodic systems cannot have multiple attractors). Furthermore, even if climate models were ergodic, the assumption needed for ergodicity to imply independence, namely that aggregate predictions are approximately equal to averages taken over an infinite time period is doubtful. Evidence suggests that the climate system shows significant variability under constant external forcings. Thus distributions taken over relatively short periods such as thirty years will vary over time and hence cannot be identical to the infinite distribution (Dethloff *et al.* [1998]; Fraederich [1987]; Lovejoy [2015]; IPCC [2014], pp. 104 and 1103; Stouffer *et al.* [2004], p. 237).

On might hope that there is an analogous condition to ergodicity for *time-dependent dynamical systems*. However, this hope is *in vain*: there can be no such analogous condition because it cannot be guaranteed that averages taken over an infinite time period converge.

Finally, instead of ergodicity and distributions taken over infinite time periods, let us consider *aggregate predictions over finite time-periods* because these are calculated in practice. Is there evidence that they are independent of the initial conditions? The answer is *negative* because studies find that distributions taken over time periods such as thirty years will vary over time (Dethloff *et al.* [1998]; Fraederich [1987]; IPCC [2014], pp. 104 and 1103; Lovejoy [2015]; Stouffer *et al.* [2004]).

In conclusion, and this is an important contribution of the paper since ergodicity is sometimes invoked by climate scientists, *ergodicity cannot be appealed to* in order to argue that aggregate predictions based on single initial conditions are independent of initial conditions. Furthermore, *evidence does not support the claim that aggregate predictions based on single initial conditions are independent of initial conditions.*

4 Initial Conditions Uncertainty

4.1 Projections

Let us now turn to initial conditions uncertainty and first consider projections. Our main finding is that there are *three different types of initial conditions uncertainty.* In the context of projections, *initial conditions uncertainty is usually identified with the spread of the ensemble simulations*[12] (this is the *first* kind of initial conditions uncertainty). The underlying idea here is that projections are defined relative to ensembles of possible initial conditions that represent states where the system has at least partially adjusted to the external forcings. Thus the spread of the ensemble

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[12] The spread is also often referred to as internal variability.

results represents possible outcomes (and thus represents the uncertainty about the outcome). Let us now compare this initial conditions uncertainty to the influence of the external forcings and other uncertainties.

In the literature one often finds the claim that the forced response is more important in magnitude than initial conditions uncertainty (for common concentration pathways/emission scenarios) (cf. IPCC [2014], 1039-1040; Parker [2010]). Note that in practice, the forced response is usually estimated from the mean of the ensemble simulations. As argued above (Subsection 4.1), the notion of a forced response (independent of initial conditions) is ill defined because the simulations *depend* on the initial ensembles. Despite this, because it is so common, we will now compare the forced response and initial conditions uncertainty.

In general, initial conditions uncertainty depends on the variables considered and is more important on smaller scales. Studies that compared the magnitudes of the forced response and model uncertainty (for standard concentration pathways/emissions scenarios) found that over the first 10-40 years initial conditions uncertainty is most important for certain climate variables, and the second most important after model uncertainty for other variables (Cox and Stephenson [2007]; Hawkins and Sutton [2009]; Yip *et al.* [2011]). Over 40-60 years some studies found that initial conditions uncertainty decreases in influence (Cox and Stephenson [2007]; Hawkins and Sutton [2009]; Yip *et al.* [2011]). Other studies such as Selten *et al.* ([2004]), which considered larger initial ensembles than usual, found that initial conditions uncertainty is at least as important as the forced response over a sixty year time span for the global mean temperature. In general, for time spans longer than 60 years, the forced response is usually regarded as more important, but initial conditions uncertainty is still an important factor (Selten *et al.* [2004]). In sum: initial conditions uncertainty is more important or equally important than the forced response for the first 40-60 years (most climate projections are made on this time scale). The forced response is more important than initial conditions uncertainty only for longer prediction lead times.

Let us now compare this initial conditions uncertainty with other uncertainties. Cox and Stephenson ([2007]) for the decadal global mean temperature and Hawkins and Sutton ([2009]) for the decadal global mean temperature and the temperature of the British Isles found that the most important uncertainty is initial conditions uncertainty for the first 10-40 years. For longer prediction lead times they found that parameter and model uncertainty are more important. Because of such studies, initial conditions uncertainty has often been regarded as less important than other uncertainties (cf. Parker [2010]).

However, first, the first 10-40 years are very important (most climate projections are made on this scale). Second, recent studies have casted doubts on the above study results. The criticism is that these studies only implemented very few initial conditions and that the spread within the CMIP models (used in the studies) is very difficult to interpret because individual ensemble members have differing physics, dynamical cores, resolutions, initial conditions and the models are not independent. Therefore, to properly investigate initial conditions uncertainty, a large number of simulations with just one climate model is needed (Deser *et al.* [2012]; Kay *et al.* [2015]; Daron and Stainforth [2013]; Selten *et al.* [2004]).

Studies performed in this way highlight that *initial conditions uncertainty is more important than previously thought*. For instance, Deser *et al.* found that initial conditions uncertainty is more important than model uncertainty for annual-mean extratropical sea level pressure and precipitation trends during 2005–2060, and that internal variability is comparable to model uncertainty for temperature trends over North America, Eurasia and Antarctica during 2005–2060. They stress that initial conditions uncertainty has not been taken serious enough and that “given the inevitable competition between ensemble size and model resolution for a fixed level of computational resources, the former should not be sacrificed at the expense of the latter” (Deser *et al.* [2012], p. 545). Kay *et al.* ([2015]) find that initial conditions uncertainty can generate substantial spread in global trends for the period 1920-2100, and they even arrive at the result that for December to February surface air temperature the CMIP5 spread in many regions during 1979-2046 can be explained by initial conditions uncertainty *alone*. To conclude, the first kind of initial conditions uncertainty is more important than often thought.

Let us now turn to the second kind of initial conditions uncertainty. In the climate literature it is sometimes asked how many initial conditions are needed to *estimate the forced response* of the system (e.g. Deser *et al.* [2012]). Note that this question is *not* well-defined because there does not exist a forced response independent of the initial conditions (Section 3). What can be asked is what exactly the initial ensemble amounts to relative to which a certain projection is defined. One possibility is simply to say that a projection is defined relative to the ensemble of initial conditions that has *actually* been used in the simulations.

However, this is not how many climate scientists think about projections because they ask how many initial conditions are needed to reliable estimate the evolved ensemble for a projection. That is, projections are conceived as being defined relative to a *theoretical initial ensemble* (usually consisting of infinitely many points). Then there is *(a second kind of) initial conditions uncertainty because this theoretical initial ensemble cannot be used in calculations and has to be approximated by finitely many initial states.*

Then the crucial question arises how many initial conditions are needed to reliably estimate the evolved ensemble (Deser *et al.* [2012] can be interpreted along these lines; see also Daron and Stainforth [2013] and [2015]; Taylor *et al.* [2012]). Generally, the answer depends on the model, the theoretical initial ensemble as well as the prediction lead time, and there has been little research on this question. However, it is common practice to only consider very few initial states (often only 1-5 and rarely more than ten, CMIP5 requires a minimum of just three; cf. Taylor *et al.* [2012]; Daron and Stainforth [2013]).

The research that has been carried out is sobering and suggests that a *large number of initial conditions (and not just a few) are needed to reliably estimate projections.* For instance, Daron and Stainforth ([2013]) using a low-dimensional nonlinear system that exhibits behaviour similar to that of the atmosphere and ocean found that several hundred initial conditions are needed (see also Daron and Stainforth [2015]; Kay *et al.* [2014]). Similarly, Deser *et al.* ([2012]) perform simulations with one of the CMIP5 models, and argue that large initial conditions ensembles are needed. To conclude, *there is considerable initial conditions uncertainty of the second kind.*

The *third* kind of initial conditions uncertainty concerns the adjustment to the pre-industrial external forcings in the construction of initial ensembles. As outlined in Section 2, to produce initial ensembles, the model is integrated backwards to pre-industrial times; then it is run for a long time (between a few hundred or thousand years) to ensure that it adjusts to the pre-industrial external forcings. The model should adjust to the pre-industrial forcings, but there should also be some radiative imbalance present because some imbalance was actually present in 1850. There is uncertainty how long the model should be run with the pre-industrial forcings to achieve this because we do not know the radiative imbalance present in 1850 (Stouffer *et al.* [2004]; IPCC [2014], p. 607). Hence *there is initial conditions uncertainty because the simulations depend on the initial ensembles, and the initial ensembles depend on how long the model is run with the pre-industrial external forcings.*[13]

4.2 Predictions

Let us now ask whether the uncertainties arising for projections also arise for predictions. Because the adjustment procedure to obtain initial conditions is specific to projections, the third initial conditions uncertainty does *not* arise for predictions. However, analogues of the first and the second uncertainty do arise.

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[13] It is an interesting question how severe this uncertainty is, but I am not aware of any systematic studies exploring this issue.

Consider *first* initial conditions uncertainty as the spread of the ensemble simulations. For predictions this uncertainty is what is most commonly understood by initial conditions uncertainty: because the precise state of the climate variables is unknown, there is uncertainty and it is quantified by the predictions consistent with the observations (i.e. the spread of the ensemble simulations).[14] From the discussion on projections, because the prediction lead-times for predictions are usually short (not more than thirty years), it follows that *initial conditions uncertainty is crucial and is more important than the external forcings or other uncertainties.*

Let us turn to the *second* initial conditions uncertainty. For climate predictions the initial ensemble represents the observational uncertainty and it is usually represented by a density (of infinitely many states). In calculations it has to be *approximated* by finitely many points, and hence *there is uncertainty about the evolved ensemble (prediction).* How many initial conditions are needed to reliably estimate a prediction depends on the model, the initial ensemble and the prediction lead time, and there has been little research on this question. However, in practice only very few initial conditions are considered (rarely more than ten; CMIP5 requires just three – Taylor *et al.* [2012]). The research that has been carried out is sobering and suggests that *a large number of initial conditions are needed to reliably estimate preditions* (Daron and Stainforth [2013]; Daron and Stainforth [2015]; see also Kay *et al.* [2014]). Hence *there is considerable initial conditions uncertainty of the second kind.*

5 Conclusion

This paper examined initial conditions dependence and initial conditions uncertainty for climate projections and predictions. The first contribution was to provide a clear conceptual characterisation of predictions and projections.

Concerning initial conditions dependence, the main conclusions are as follows. First, climate projections are often described as independent of initial conditions – a claim that can be interpreted differently. If interpreted as the claim that projections are not based on estimates of the actual initial conditions of the world or that what makes projections true are conditions in the world, it is true. However, what is often meant is that the simulations used to obtain projections are independent of initial conditions ensembles. This claim has not been investigated much and this paper aimed to fill this gap (among others, by studying the dynamical condition of time-dependent physical measures). The conclusion is that evidence does not support this claim. Second and not surprisingly, evidence also suggests that climate predictions are dependent

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[14] This initial conditions uncertainty would disappear if climate predictions were *independent* of initial ensembles. However, there is no evidence for independence (cf. Subsection 3.2).

on the initial ensemble. In the extreme case of a prediction based on just one initial condition, one can ask whether aggregate predictions over time are independent of initial conditions. This paper has argued that this claim is not supported by evidence.

Concerning initial conditions uncertainty, the main contribution was to identify three kinds of initial conditions uncertainty. The first kind (the one usually discussed) arises for both climate projections and predictions and is the uncertainty associated with the spread of the ensemble simulations. It was stressed that this initial conditions uncertainty is larger than often acknowledged. The second kind arises because the theoretical initial ensemble (relative to which a projection or prediction is defined) cannot be used in calculations and has to be approximated by finitely many initial states. The third kind of initial conditions uncertainty only applies to projections and arises because it is unclear how long the model should be run with the pre-industrial external forcings to obtain initial conditions that represent states where the system has at least partially adjusted to the external forcings.

Overall, the discussion shows that initial conditions dependence and initial conditions uncertainty are more complex and important issues than usually acknowledged. Hopefully, this paper will contribute to raising awareness that this is so.

6 Appendix

Time-dependent Strong Physical Measures

First, formal definitions of time-dependent deterministic models[15] and attractors are needed. A (time-dependent) *deterministic model* is a triple $(X_M, \Sigma_{X_M}, T_M(x, t_0, t))$. The set X_M represents all possible values of the climate variables. Σ_{X_M} is a σ-algebra on X_M. $T_M(x, t_0, t) : X_M \times \mathbb{Z} \times \mathbb{Z} \to X_M$ is the dynamics, where $T_M(x, t_0, t) : X_M \times \mathbb{R} \times \mathbb{R} \to X_M$ is a measurable function such that $T_M(x, t_0, t_0) = x$ and $T_M(x, t_0, t+s) = T_M(T_M(x, t_0, t), t, s)$ for all t_0, t, s and x (cf. Kloeden and Rasmussen [2011]).[16]

A *pullback attractor* $\Omega \subseteq \mathbb{Z} \times X_M$ (where $\Omega(t) := \{x \in X_M \mid (t, x) \in \Omega\}$) with basin of attraction $U \subseteq X_M$ is an invariant set[17] where for all initial values $x \in U$

$$\lim_{t_0 \to -\infty} dist(T_M(x, t_0, t), \Omega(t)) = 0, \tag{1}$$

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[15] Climate science studies deterministic and stochastic models. We focus on deterministic models; but all the arguments of this paper have a stochastic counterpart.

[16] Climate science studies models where time varies in discrete steps ($t \in \mathbb{Z}$) and models where time is a continuous parameter ($t \in \mathbb{R}$). Because models used in practice are discrete, we focus on them. However, all our arguments have a continuous-time counterpart.

[17] That is, $\Omega(t) = T_M(\Omega(t_0), t_0, t)$ for all $t, t_0 \in \mathbb{Z}$.

where dist(x) measures the distance.

Time-dependent strong physical measures μ_t^Ω on $\Omega(t)$, $t \in \mathbb{Z}$, where Ω is a pullback attractor, are defined by the condition that for any t and t_0, any initial density p_{t_0} (relative to the Lebesgue measure λ) on X_M and for any set A (where $P_{t_0,t}$ is the density that arises when p_{t_0} is evolved forward from t_0 to t):

$$\lim_{t_0 \to -\infty} P_{t_0,t}(A) = \mu_t^\Omega(A), \tag{2}$$

whenever $\mu_t^\Omega(\delta A) = 0$ (δA denotes the boundary of A[18]) (cf. Buzzi [1999]).

6.1 Ergodicity

First, *time-independent* deterministic models need to be introduced. Formally, a *measure-preserving deterministic model* is a quadruple $(X_M, \Sigma_X, T_M(x,t), \mu)$ (where $t \in \mathbb{Z}$). X_M is the set of all possible states, Σ_X is a σ-algebra on X, $T_M(x,t) : X \times \mathbb{Z} \to X$ (the dynamics) is a bijective function that is measurable in (t, m) such that $T_M(x, t_1 + t_2) = T_M(T_M(x, t_2), t_2)$ for all t_1 and t_2. Finally, μ is a probability measure on X_M which is *invariant*, i.e. $\mu(T_M(A,t)) = \mu(A)$ for all A and all $t \in \mathbb{Z}$. Such time-independent model is *ergodic* iff

$$\lim_{r \to \infty} \frac{1}{r} \sum_{i=t_1+1}^{r+t_1} T_M(x,i) = \int_X T_M(x,1) d\mu \tag{3}$$

for almost all $x \in X_M$ and all t_1.[19]

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[18] This latter condition is fulfilled in all applications in climate science.

[19] The standard definition of ergodicity is that $\lim_{r \to \infty} \sum_{i=1}^{r} \frac{T_M(x,i)}{r} = \int_X T_M(x,1) d\mu$ for almost all x. It can be easily seen to be equivalent to our definition (which has the advantage of an immediate link to aggregate predictions).

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