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Philosophy of climate change: models, problems and uncertainties

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Abstract

The objective of this article is to show the problems in the philosophy of science that climate change researchers are faced. The topic of the theoretical load of observation appears within the field as an indispensability of theoretical models in the detection and attribution of climate change. The empirical underdetermination of the models is accompanied by an uncertainty of values in both instrumental series and secondary data, and a structural uncertainty related to the specification of the couplings and radiative forcings. The realism of global models is also examined in connection with their calibration and climate projections.

Keywords: Global warming; Climate models; Uncertainties; Scientific realism.

1. Introduction

1.1. *Climate change*

Climate change is a multifaceted problem. It has a scientific face, an economic face, political one, and even another philosophical one, which intersects with epistemology. As a scientific problem, it is a multidisciplinary issue, because climatologists, meteorologists, physicists, mathematicians, computer programmers, geologists, biologists, among others get involved. The reason for this polydisciplinarity is that the so-called global climate is a complex system, and according to the Intergovernmental Panel on Climate Change (IPCC), the system made up of five subsystems: the atmosphere, the hydrosphere, the lithosphere, the cryosphere and the biosphere (IPCC, 2013a). Consequently, rather than one climate change science or climate science, there is a plurality of sciences involved in climate change

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research. They are the sciences of the Earth system: climatology, meteorology, oceanography, geology, ecology, etc.

The rise of Earth sciences occurred during the Cold War, when the United States and the former Soviet Union struggled to control both space and the deep sea. The Earth or, rather, certain parts of the planet, such as the atmosphere, were brought to the laboratory (Pogdorny, 2005). However, despite the label making a fortune in the 1980s promoted by NASA, there is no unified science of the Earth system, but rather a variety of sciences that study different interconnected aspects of the global environment (Alvarez Munoz, 2004).

The objective of this article is to highlight the epistemological problems that climate change scientists are encountered. Next, in the second section, the question of how to define climate and in the third we briefly outline the consensus of the scientific community on anthropogenic global warming are introduced. Then, the problems raised by the concept of global average temperature is analyzed and a first source of uncertainty: the values of the instrumental series are collected. Subsequently, while studying past global temperature variations, the uncertainty of values associated with proxy data are examined.

After studying the detection of climate change, its attribution is discussed. Thus, in the next part, the estimate of the radiative forcings and, especially, of the greenhouse effect due to carbon dioxide are reconstructed. Then, when describing global climate models, how they are used to make causal inferences are explained. In the eighth section, the problems related to climate projection, focusing in particular on deterministic chaos and the question of how to assign probabilities to model ensembles are considered. In the final section, we examine how the calibration of model parameters makes their verification or falsification difficult, resulting in structural uncertainty inherent to climate models.

2. Definition of climate

While weather changes hour by hour, climate is the average state, that is, the most frequent, least anomalous state of the atmosphere over a place over thirty years. It is the distribution of meteorological weather over that location during that interval of years (IPCC, 2013a). However, it is worth nothing the conventionalism that hovers over the definition of climate; because, although geographers traditionally preferred longer periods, meteorologists and climatologists agreed on base periods of thirty years and, lately, some researchers propose even shorter periods. This standard was adopted by the World Meteorological Organization (WMO) (founded in 1950) based on historical practices dating back to the first half of the 20th century. But the reference to a base period of thirty years was established because the first time that was recommended, only data corresponding to that number of years was available (WMO, 2011).

Faced with this empiricist definition, climate scientists currently use another, in which the climate is no longer the statistical distribution of the observed meteorological conditions, but the attractor-in the sense of the mathematical theory of dynamical systems-of the climate model under study (Parker, 2018; Werndl, 2016). This theoretical definition avoids the conventionalism associated with the empiricist definition, but it has not been imposed in the scientific community, because its direct reference is not the observation of a specific place but a mathematical model.

3. Consensus on anthropogenic global warming

The theory of climate change basically consists of the conjunction of two hypotheses that have a different degree of corroboration: a) there is global warming of the Earth, and b) the dominant cause of global warming is the greenhouse effect caused by carbon dioxide emissions and other gases of anthropogenic origin (Fleming and Fourier, 1999).

The IPCC, in its fifth and final assessment report (AR5), has stated that warming of the climate system is unequivocal and estimates global warming from 1880 to 2012 at 0.85 ºC. Furthermore, it specifies that in the northern hemisphere it is likely that the period of 1983-2012 was the warmest 30-year period of the last 1,400 years (IPCC, 2013b).

In Figure 1, the evolution of the global average temperature is seen. It is observed that the rate of warming of the planet since the end of the Little Ice Age, at the end of the 19th century, has not been constant. Between 1940 and 1975, warming slowed, giving way to a slight cooling. But, since 1980, the rate of warming has significantly accelerated. However, between 1998 and 2012 this pace slowed down again as a fact, that is difficult to reproduce and explain by climate models.

Now, everything about climate change depends on dynamic or statistical models, both theoretical models to know how global models are built to reproduce observations and make predictions; and data models to know how observations are modeled. The data make the global models, but the data models also make the data, since there is no raw data and climate records are periodically reanalyzed using various techniques such as data assimilation, analysis, reanalysis. The theoretical burden of observation is one of the most present topics of the philosophy of science in the climate change: “there is no such thing as an observation separate from modeling” (Edwards, 2010). Both the detection and attribution of climate change fundamentally depend on the use of models, but this methodology is not free of epistemological problems. Studying the issues that arise in the detection of climate change and, in particular, how that temperature is defined globally that the experts talk about, is essential.

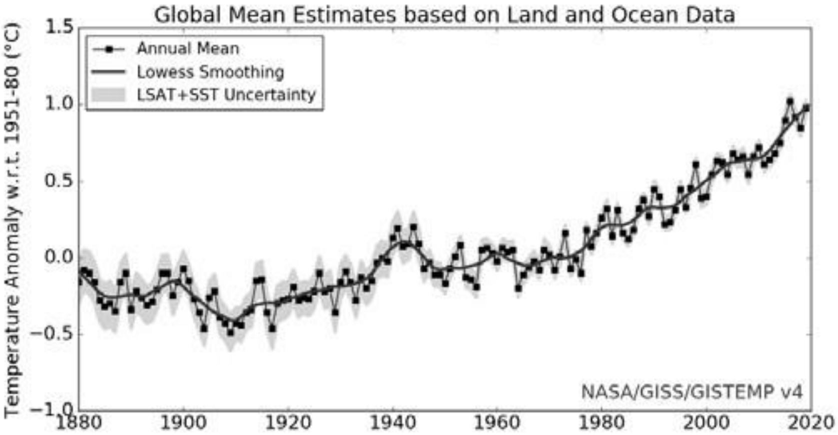

Figure 1. Reconstruction of global average temperature. Left: Temperature anomaly with respect to the period 1951-1980 in ºC. Above: Global mean temperature estimated from land and ocean data. Inside: Annual average; Smoothed series; Total uncertainty (Total uncertainty over land and sea). Source: NASA GISS https://data.giss.nasa.gov/gistemp/graphs_v4/

4. Global mean temperature and uncertainty in instrumental series

While the local temperature in a certain place, like the weather, is observed and measured, the global temperature of the planet, like the climate, is the result of a calculation, a statistical estimate, since the temperature is more than in a discrete number of places and times. There is no such thing as a global thermometer that could be put on the Earth to know its precise temperature, because the planet is not in thermodynamic equilibrium. Therefore, global temperature is the result of an average that can be calculated in different ways from the data provided by weather stations, sounding balloons, marine buoys and satellites (Essex *et al*., 2007).

Generally, the average temperature of a specific place is calculated in the following way: the maximum and minimum of each day are added, dividing by two, obtaining the average temperature of the day; this protocol is repeated for each day of the year and, finally, the average of all these temperatures is calculated (WMO, 2011). However, not all States do or have done so: in the former Soviet Union, for example, the average daily temperature was calculated by adding the temperatures at 1, 7 a.m. and 1, 7 p.m., dividing by continued by four (Edwards, 2010).

There is also a problem of quantity and quality with the starting data: there has not always been a well-distributed spatially and temporally distributed network of meteorological stations. Actually, the use of sounding balloons became widespread after 1950 and that of climate satellites after 1980. In fact, only the records of a thousand stations in the world cover the entire 20th century, and all of them are located on land and in the northern hemisphere, mostly near European and North American cities. Due to their location, many of the stations are subject to the heat island effect of cities. This and other biases such as changes in instrumentation or location, force the instrumental series to be homogenized, eliminating anomalous data and adjusting the rest. However, the homogenization and interpolation procedures are not univocal. As an example of the tensions caused in data processing, the announcement by NASA's Goddard Institute for Space Studies (GISS) in 2010 that 2009 had been the second planet's warmest year on record that was questioned by the Hadley Center of the United Kingdom Meteorological Office (Schmidt, 2010).

In short, the mesh of observatories with which the variation in global temperature has been calculated throughout the last century is poor and poorly distributed, since the southern hemisphere and the oceans are generally not covered. Climate scientists have a first source of uncertainty in values. While in his pioneering article Stewart Callendar (1938) took into account data from about 200 stations to reconstruct the evolution of global temperature. Brohan *et al*. (2006) considered 4,349, a figure that Richard A. Muller has increased to 36,866 (Rohde *et al*., 2013), in order to more accurately estimate the temperature curve between 1850 and 1950, where there was more uncertainty.

5. Uncertainty in proxy data

Considering the construction of this estimator of the Earth's climate called global temperature to be satisfactory and relying on other physical indicators such as volume of glaciers, and snow cover. During the last century, scientists wonder about global warming of almost one degree Celsius which is abnormal. To do this, they turn to paleoclimatology, which studies the climatic variations of the Earth throughout its history.

Variability is one of the essential characteristics of global temperature, which changes continuously as a consequence of various factors such as volcanic eruptions or the El Niño phenomenon. Looking carefully at the graph of the evolution of global temperature from 1880 to 2020 (Figure 1), it can be seen how global temperature has fallen and risen, and that the current period of warming began approximately in 1975, just when it ended. a period of cooling that began in 1940. During the Cold War, a fraction of the scientific community was considering the theory of global cooling. Some scientists claimed that human activity, by increasing atmospheric pollution, was making the air thicker, which made it difficult for solar radiation to reach.

During the first third of the 20th century there was another period of warming, since warming as a trend is not something recent, but rather began in the 19th century, as a consequence of the end of the Small Ice Age as a product of a solar minimum and high volcanic activities, which lasted from the 15th century until the 19th century. This stage, in turn, put an end to the Medieval Warm Period, coinciding with a maximum solar radiation. Further back is the climatic optimum of the Holocene, a warm period that began around 7500 BC. and lasted until 2500 BC., when a gradual cooling began that did not end until the Medieval Warm Period (Marcott *et al*., 2013).

At certain points in the planet's geological history, the global average temperature has fluctuated abruptly (IPCC, 2013a). However, the brevity of the instrumental meteorological series, which do not go back beyond 1850, requires the use of proxy data or climatic data extracted indirectly to establish climatic trends, such as the analysis of fossil air trapped in core bubbles of ice, the dating of lake sediments or the study of tree rings. The problem is that scientists find themselves here with a reinforced uncertainty of values.

Reconstructing past temperatures from proxy data is not always reliable, as highlighted by the hockey stick controversy of Mann *et al*. (1998), a graph where it seemed as if nothing relevant had happened during the last millennium until the warming of the 20th century. However, several groups published critical studies that qualified the graph (McIntyre and McKitrick, 2003; Von Storch *et al*., 2004). Currently, the IPCC (2013b) recognizes that between the years 950 and 1250, temperature values were as warm in some regions as at the end of the 20th century. It has gone from the hockey stick of the 2001 report to the spaghetti plate of the 2013 report (Frank *et al*., 2010). Today, multiple temperature reconstructions are available in the northern hemisphere using different proxies. However, paleoclimatologists continue to work to reduce the uncertainty in secular temperature variations, as well as to extend their spatial validity.

6. Greenhouse effect and estimation of climate forcing

After having studied the detection of climate change in the present and in the past, it should be going to analyze how its attribution is carried out. To do this, it must look at carbon dioxide, a greenhouse gas (GHG), which retains part of the energy that the Earth's surface emits as a result of having been heated by the Sun, analogically recreating what happens in a common greenhouse.

In 1824, Joseph Fourier surmised that some gases contribute to warming the atmosphere. In 1861, John Tyndall identified some of these gases in the laboratory, such as water vapor or CO_2. In 1896 the Swedish scientist Svante Arrhenius published an article on the influence of CO_2 on surface temperature (Edwards, 2010), but it was Callendar (1938) who proposed the connection between warming and anthropogenic CO_2. Based on the temperature and CO_2 measurements that was gathered, Callendar hypothesized that artificial production of carbon dioxide influenced temperature, but his research was received as a coincidence, given that the measurements he had were mostly from seasons per season. above the 45º N parallel.

Now, in the case with temperature, scientists have measurements of the CO_2 concentration in the present, seek to compare them with measurements of CO_2 concentration in the past, to find out if they deviate from normal. However, estimating CO_2 levels prior to the 20th century is not easy, since it requires the use of proxies, which again creates uncertainty in values. Thanks to the geological strata, it is known that there is currently less CO_2 in the atmosphere than at other times in the Earth's history, such as the initial Eocene, when there were concentrations higher than 1000 ppm and temperatures higher than today (IPCC, 2013a). It is also known that the current CO_2 concentration exceeds the range that has been maintained for the last 800,000 years (IPCC, 2013a).

Considering now the effect on temperature, carbon dioxide is by no means the main greenhouse gas, which is water vapor (responsible for at least 60%). Scientists distinguish between the natural greenhouse effect which makes the Earth habitable; and the artificial greenhouse effect, induced by man as a consequence of the industrial emission of CO_2, methane, nitrous oxide and other gases.

Climate dynamics are much more complex than stating that CO_2 increases and temperatures rise. The variability of CO_2 levels hardly explains the increase in temperatures between 1920 and 1940, when there were low levels, much less the cooling produced between 1940 and 1975, when there was a notable growth in emissions of human origin. Furthermore, paleoclimatic studies show that temperature does not strictly follow CO_2 levels: in multiple reconstructions at geological scales, peaks in temperature occur about 800-1300 years before peaks in CO_2 concentration (Stott *et al*., 2007).

Apart from GHGs, climate scientists consider that behind the rise in global temperature there may be other factors, both natural and human, between which there may be complex feedbacks. On the one hand, natural factors such as solar activity. There is a strong influence of solar cycles on the Earth's climate and solar forcing has at some point been as influential as forcing induced by GHGs. The Sun's activity has been unusually high during the 20th century, which may be behind the warming before 1940, but, at most, only 30% of the warming observed since 1975 (Solanki and Krivova, 2003). On the other hand, processes of human origin, not directly related to GHG emissions, such as the heat generated by the urbanization of continents or changes in land use, can also contribute significantly to warming (Kalnay and Cai, 2003).

Similarly, just as there are natural factors that tend to cool the planet for example, volcanic activity, there are also human factors for this issue. One is the so-called global dimming, a phenomenon that refers to the gradual reduction in the amount of sunlight that reaches the Earth's surface since the 1940s, and is caused by the increase in suspended particles such as carbon and sulfates. The effects of aerosols are still not well understood. Although they appear to directly cool the global climate, and masking the action of GHGs, they can also contribute to its warming; for example, when dust is deposited on snow, its albedo changes. In fact, “uncertainty about forcing due to aerosols remains the dominant contribution to the global uncertainty about net anthropogenic forcing” (IPCC, 2013b).

But how do all these factors (GHG, solar irradiation, aerosols, among others) and their radiative forcings come together in the global climate? What is the combination of these factors that explains the observed global warming? The attribution of climate change indispensably depends on the use of climate models.

7. Global model and climate change attribution

The effort to mathematically model the climate came to fruition during the Cold War, coinciding with the development of the first computers in a military context. Slowly, a hierarchy of climate models was built, from the simplest (the energy balance models of M. Budyko and W. Sellers) to the most sophisticated, which try to cover the entire Earth's surface. The first general circulation models were proposed by Norman Phillips, and improved by Suki Manabe and Richard Wetherald in the 1960s. These atmospheric models, used first in weather prediction and then in climate studies, gradually incorporated additional couplings and forcings.

In current coupled global climate models, the planet's climate is represented by a system of differential equations with several ingredients:

1) The equations that reflect the evolution of climatic variables according to physical laws (Navier-Stokes equations, conservation principles, etc.) and that describe the movement of a compressible and stratified fluid on a rotating rough sphere;
2) The equations that collect the exchange processes between the atmosphere and the oceans, the continents or the ice cover,
3) Certain equations that represent processes of great influence on the climate, such as evaporation or convection, but that are they occur at a very small spatial scale compared to global climate processes.

Given its extreme complexity, the system of equations has no explicit analytical solution, and its resolution can only be approached approximately by numerical methods, with the help of supercomputers. To do this, the atmosphere must be cut into parallelepipeds, about 100-150km on each side, and atmospheric processes such as convection or cloud formation, which occur at a scale smaller than that of the grid, must be represented by the artificial introduction of parameters, which emulate these phenomena. Otherwise, if the spatial resolution were increased to avoid these cumbersome parameterizations, the computation time would skyrocket. In the international scientific community there are about thirty models of the global terrestrial climate.

These climate models are the key to attributing the detected climate change, because they are aimed at jointly evaluating the natural and human factors that affect the climate, their forcing (positive or negative) on the evolution of global temperature. Once the models manage to reproduce the observational series of global average temperature, CO_2 concentration. Among other aspects, between 1880 and the present, scientists study whether anthropogenic forcings are strictly necessary. When the models are left to run, acting only on natural factors (solar irradiation, volcanic activity, etc.), they do not reproduce the evolution of global temperature up to the present. On the other hand, when both types of forcing are allowed to act together, weighted in a certain way, global warming is reproduced acceptably. The balance of all natural and anthropogenic forcing would explain the 0.85 ºC increase in the planet's global temperature (Figure 2).

The anthropogenic attribution of climate change is fundamentally based on this methodology with models, because attribution of observed changes is not possible without some kind of model of the relationship between external climate drivers and observable variables. A world cannot be observed in which either anthropogenic or natural forcing is absent, so some kind of model is needed to set up and evaluate quantitative hypotheses (IPCC, 2013a).

However, the statistical evidence found with the discovery of the cause or reasons that operate behind it must not be confused, since causal attribution requires complementing the statistical association found with the specification of the underlying physical-chemical mechanisms. Correlation does not imply causality. It is the philosophical problem of causal inference or, more precisely, of the inference of the most probable cause, a refinement of the inference of the best explanation, since this kind of theoretical inference involves an existential component (Cartwright, 1999).

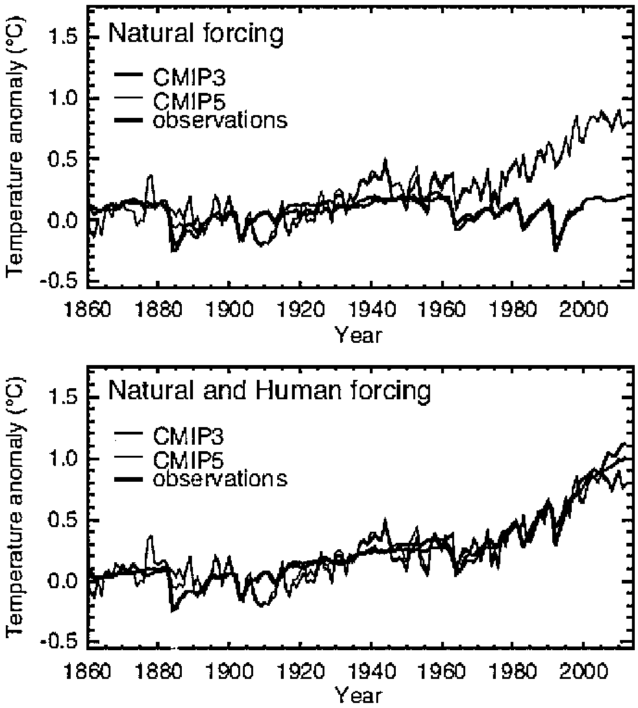

Figure 2. Climate change attribution. Left: Temperature anomaly (ºC) Above inside: Natural forcing; and the series are: CMIP3 (the models participating in phase 3 of the Coupled Model Intercomparison Project, 2006), CMIP5 (the models participating in phase 5 of the Coupled Model Intercomparison Project, 2014) and observations. Down inside: Natural and human forcing; and the series are the aforementioned Source: IPCC (2013a)

In a study by Haghroosta (2019), in the case of tropical cyclones' prediction, two different methods were applied. The results of two hydrodynamical and statistival models were compared. The study results showed that while various complicated models in the world have been set up and run, they cannot exactly predict the typhoon path or intensity, and reliable forecasting is still a difficulty. Despite high accuracy in weather predictions, there is an ambiguity in all forecasts.

Climate scientists, without prejudice to the still incomplete knowledge of all interaction mechanisms for example aerosols, provide other fingerprints of anthropogenic climate change. They tried to reinforce their causal argument, such as the cooling of the atmosphere in layers high and its warming in lower layers, or that the warming is more pronounced at night than during the day (Katzav, 2013).

8. Chaos and uncertainty in the predictability of global climate

Climate models are not only used to reproduce the evolution of global temperature or other climate variables from the past to the present. They are also used to predict their future evolution, finding another source of uncertainty: deterministic chaos. In 1963, Edward

Lorenz warned that the atmosphere determines a non-linear system with a chaotic regime, which curtailed Charney's aspiration that by adding more and more degrees of freedom the models would stabilize (Madrid Casado, 2011).

In chaotic systems, the present determines the future, but an approximation of the present does not approximately determine the future. Small differences in the initial conditions or in the model formulation result in different evolutions. Even in the absence of external forcing, drastic changes can be experienced. Thus, the observed hiatus in the rate of rise in global average temperature between 1998 and 2012, which the models cannot reproduce, is attributed to internal climate variability (IPCC, 2013b). In Figure 3 it can be seen how the majority of models do not reproduce the 1998-2012 hiatus, leaving the observed series (in thick black line) below them, and also how small differences in the initial conditions or in the model formulation produce trajectories that lead to significantly different predictions for global temperature in 2050.

Every climate model depends, on the one hand, on the initial conditions (current climate values) and, on the other, on the boundary conditions, that is, on the specification of the couplings of the atmosphere with the ocean or continents. Initial conditions are of greatest importance in weather forecasting and short-term climate prediction (on the scale of a few decades), defining what is called an initial value problem. In contrast, boundary conditions dominate medium or long-term climate prediction and define a boundary or boundary problem.

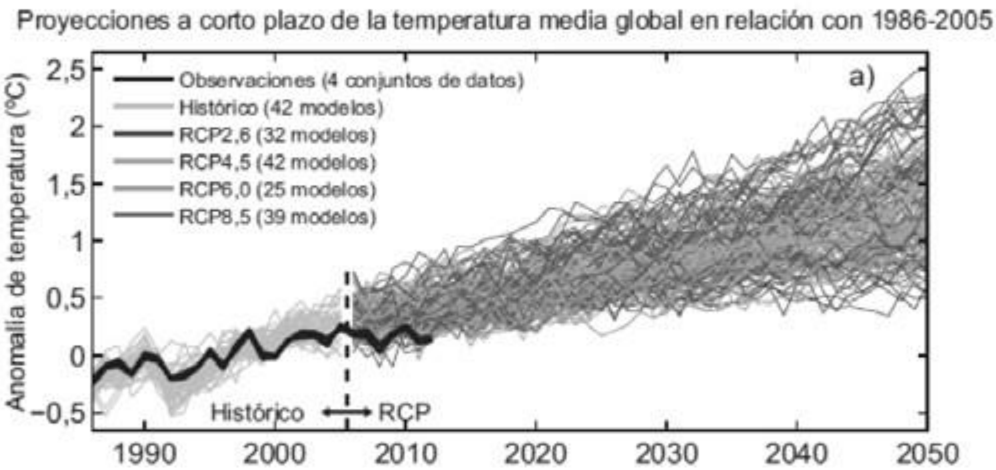

Figure 3. Global average temperature projections Source: IPCC (2013b)

For Palmer (2005), deterministic chaos would affect meteorological prediction (which depends significantly on the initial conditions) more than climatological prediction, since in the latter the time or specific state of the atmosphere at 50 o 100 years (i.e., a particular trajectory), but the climate, that is, the statistical distribution of meteorological states after those years or, to put it with the alternative definition mentioned in the second section, the shape of the attractor of the dynamical system climate (which is supposed to be similar to the real one).

The problem is that chaos is not reduced to sensitivity with respect to initial conditions, because it can also appear as a consequence of the propagation of computational errors, as well as perturbations in the model parameters (a small difference between the value of the model parameter and the actual value of the parameter may cause divergent predictions). While we associate the chaos linked to initial conditions with the butterfly effect, some authors propose associating the chaos linked to small changes in the structure of the model with a supposed hawkmoth effect. The butterfly effect would be to the initial conditions what the moth effect is to the structure of the model. But has it been proven that small variations in the specification of climate models lead to large changes in the final predictions? Are climate models sensitively dependent on the detail of their structure? Is there structural instability in climate models? This is an open topic. While philosophers of science linked to the London School of Economics respond affirmatively (Frigg *et al.*, 2014), basing themselves on the non-linear nature of these models, others do so in a negative way, indicating that they cannot be generalized and must be go case by case, studying model by model (Nabergall *et al.*, 2019; Winsberg, 2018; Thompson, 2013).

To try to control the chaos, ensemble prediction is used, a technique designed by Palmer (2005) and Kalnay (2003), among others, which consists of using sets of different initial conditions or different climate models at the same time. Running a model with variations in initial conditions is often used in weather prediction. The use of multiple models seeks to minimize, however, the error in determining the boundary conditions and parameters, since this type of error is the decisive one in climate prediction. Sometimes, both procedures are used simultaneously. Building a global ensemble prediction system, which takes into account the uncertainty in both the initial conditions and the boundary conditions. Using multi-model ensembles, the IPCC (2013b) predicts that by the end of this century a warming between 0.91 and 5.41 ºC is expected (the most pessimistic prediction), with it being likely that it will exceed 1.5 ºC, compared to pre-industrial levels (1850-1900).

The results of the different models are not identical and the disparity reflects the degree of uncertainty in the knowledge of the future of the global climate, since the greater the agreement between models, the less uncertainty. When two-thirds of the available models agree on a result, that result is said to be robust (Lloyd, 2009). Thus, while predictions of increases in global temperature and precipitation or the evolution of Arctic ice are robust, predictions of regional variations in temperature and precipitation, the evolution of Antarctic ice or the increase in the frequency of events extremes are not as robust (Gettelman and Rood, 2016).

Another example of robust prediction is provided by the estimation of climate sensitivity, that is, the change in temperature in response to a doubling of the CO_2 concentration. AR5 has established that more than two-thirds of climate models determine climate sensitivity to be between 1.5 and 4.5ºC, although that range has remained virtually unchanged since Charney and his team's estimate in 1979, as a consequence of ignorance of the effect of aerosols and cloud formation processes on a hotter planet.

Now, the results produced by computer models are basically simulations with an important component of uncertainty that must be evaluated. AR5 provides a binary treatment of uncertainty in quantitative and qualitative terms, probability and confidence, respectively. For example: “in the Northern Hemisphere, the period 1983-2012 is likely to have been the warmest thirty-year period in the last 1400 years (medium confidence)" (IPCC, 2013b). This means that this result has an evidence-based probability of at least 66% and is issued, with that probability, with a mean assessment of scientific agreement or consensus regarding it. According to the IPCC (2013b), confidence in the validity of a result (quantified probabilistically) is given qualitatively and takes into account the available evidence and the level of agreement.

The problem is that probability and confidence do not always appear clearly differentiated, because for the IPCC the probability of a result, which is expressed quantitatively, is the result of the statistical analysis of observations, the results of the models or the expert's judgment. But, with the latter, the IPCC confuses probability and confidence, that is, when numerical probabilities can be assigned using statistical methods and when they reside in expert judgment, just like confidence (Curry and Webster, 2011). There is, therefore, difficulty in making a common interpretation of the notion of probability used by the IPCC.

That 90% of the (twenty-odd) global climate models predict a certain outcome cannot be confused with the probability of the outcome being 0.9 (offering a picture of false precision). This percentage does not mean that the frequency of occurrence of the event in reality is 9 out of 10, but rather that it occurs in 9 out of 10 simulations executed by the set of models. Because an ensemble of models does not constitute a simple random sample extracted from a hypothetical space of all possible model structures (which would at least allow us to speak, in the frequentist interpretation, of 90% confidence). The different simulations of the same model, in which the initial conditions or parameters are perturbed, are not independent of each other. Nor are the different global models independent of each other, because, although developed by different teams, they usually share modules (Knutti, 2008).

Despite this, in multi-model ensembles the average of the different model results is calculated, without considering how many simulations each model contributes or how interdependent they are (IPCC, 2013a). The range of results cannot be taken, therefore, as an exploration of all possible outcomes (Knutti, 2010).

If the set of models is not independent of each other, the robustness of a result lacks a priori epistemological value, since the agreement between models may be caused more by their mutual dependence than by the truth of the result. At their core, climate scientists work with opportunity ensembles, which incorporate all available models assuming that the different models are sufficiently different from each other to explore the uncertainties associated not only with the initial conditions but also with the parameters and measurements. boundary conditions (Santos Burguete, 2018).

In short, the assignment of probabilities, following the principle that the greater the coincidence between simulations, the less uncertainty in the prediction, determines in the best of cases an objective Bayesian probability. However, when expert judgment is also introduced into the quantification, a subjective Bayesian probability is obtained, which values a belief. It is, therefore, "an informal application of Bayesian concepts" (Schmidt and Sherwood, 2015), without exactly considering priors and likelihoods or calculating posterior distributions.

Prudently, since 2001 the IPCC prefers to use the term projection rather than prediction to refer to the results of the simulations, given that each simulation essentially depends on a series of assumptions that define a scenario, relative to how the amount of the contributions will evolve. GHG emissions depending on the world economy or population. The projections are predictions conditioned on scenarios that characterize the evolution of some radiative forcings. To the uncertainty in the observation of the initial conditions and the uncertainty in the implementation of the boundary conditions and model parameters, the uncertainty associated with the scenarios is added for the long-term climate projection, at the end of the century. While the uncertainty in the initial conditions dominates in the short term, the uncertainty associated with the scenarios dominates in the long term, while the uncertainty in the boundary conditions and parameters operates at any time scale (Santos Burguete, 2018).

Finally, another source of uncertainty related to climate models and prediction has to do with the spatial variable rather than the temporal variable which are referring to regional-not global-projections of climate change.

The approximate resolution of the model in a reasonable computing time requires the consideration of a spatial mesh that is not excessively fine, with the artificiality that this entails (an area like the Iberian Peninsula, for example, is covered by little more than five dozen cells). When the models are left to run, it is assumed that the global values of the future state of the climate system will be similar to the mean values returned by the models, but it cannot be guaranteed that the local values coincide, as a consequence of chaos and other sources of uncertainty. These inadequacies make regional analysis of climate change and its impacts difficult.

To reduce the uncertainty associated with regional projections, scientists use two sets of downscaling techniques. Dynamic downscaling operates by increasing the spatial resolution of global models. For its part, statistical downscaling combines the predictions of global dynamic models with the use of empirical or semi-empirical statistical models: using the global model, the future value of a global variable is predicted and, subsequently, using the statistical model, it is estimated, from that value, the future value of the local variable under study, based on the statistical relationship between both in the present, although this methodology depends on the accessible statistical data being representative and the estimation not involving excessive extrapolation (Gettelman and Rood, 2016).

9. Calibration and evaluation of climate models

The uncertainties inherent in the models' representation of different climate processes—such as couplings and forcings—can be grouped under the heading structural uncertainty. Although they reproduce the climate trends of the evaluation period (1880-today), the models may not correctly represent climate dynamics. Regarding the truth that can be attributed to climate models, scientists are faced with the debate on scientific realism.

Any verification or validation of the structure of the models is inherently partial, at the risk of falling into the fallacy of the affirmation of the consequent, because if the model M implies the result H and H is observed, the truth of M cannot be concluded. (Oreskes *et al.*, 1994). From the fact that the model reproduces fractions of past climates or some forecast is confirmed, it cannot be concluded that the equations faithfully represent the real climate, because more than one model can produce these outputs, in the same way that more than one curve can pass by a series of given points. It is the problem of the empirical underdetermination of the models. Various models may be empirically equivalent but logically incompatible, because they represent certain physical processes in different ways.

Furthermore, it is possible that the success is due to a false reason, error compensation, or parameter calibration. Leaving aside the circumstance that the model can be correct due to error cancellation (which sooner or later would be discovered when testing the model under different conditions), we are going to focus on the delicate problem of calibration (tuning) of the model parameters. Climate scientists adjust the parameters with the observed series, so that data from the 20th century are used both to calibrate the model and to confirm it, in what appears to be a "double counting" exercise (Frigg *et al.*, 2020). This is an unsatisfactory procedure but functional to a certain extent, since it forces empirical adaptation.

It is worth asking, then, to what extent the empirical adequacy of the models is due to the correct representation of climatic processes or to the ad hoc adjustment of their parameters: "Agreement with observations is often (and maybe misleadingly) used to demonstrate progress even if it might partly result from tuning or compensating errors" (Knutti, 2010).

Parameter calibration can mask fundamental problems in the model structure. For example, adjustment to the amplitude of warming observed during the 20th century can be made either by adjusting the climate sensitivity or by adjusting the radiative forcing. In the first option, if climate sensitivity is increased, future global warming may be overestimated. In contrast, in the second option, if the total radiative forcing is increased, future warming may be underestimated (Hourdin *et al*., 2017).

This drawback, together with the fact that climate models present a diffuse modularity (the different modules - for the circulation of the atmosphere, the dynamics of the oceans, etc. - work intertwined), means, for Lenhard and Winsberg (2010), that the Holism permeates climate science (an example is provided by the aforementioned calibration of global temperature increases during the 20th century). According to Duhem-Quine's thesis, scientists can tweak the models at different points to save the phenomena, but they cannot know in principle in which module the fault lies.

As a result of this, the IPCC chooses to talk more about the evaluation of models than about their validation or verification, that is, their direct confrontation with reality. This evaluation consists of a comparison between the available models, with respect to the simulation of the pre-industrial era or the current era, the estimation of climate sensitivity and projections for the 21st century. But, as Edwards (2010) pointed out "the relatively greater agreement among climate models used in the IPCC reports could conceivably be due to questionable parameterization and tuning practices", although certainly "the models that plausibly reproduce the past, universally display significant warming "under increasing greenhouse gas concentrations, consistent with our physical understanding" (IPCC, 2013a).

The limitations of falsificationism put forward by some climate scientists when they philosophize about their work are thus confirmed: "If a prediction produced by a model is shown to be in conflict with measurements, then the model itself can be said to have been falsified" (Randall and Wielicki, 1997). Climate models are not subjected to severe empirical tests that could refute them, but rather are routinely patched in an attempt to reproduce recalcitrant observations, a circumstance that some working scientists recognize (Schmidt and Sherwood, 2015).

Climate models are loaded with data, but data, as we saw, that in turn depend on models: the data make the models and the models make the data (Edwards, 2010). Models are built with data, but, bidirectionally, the data is interpreted thanks to the models. The image that emerges from this symbiosis fits, in our opinion, with the circularist image of scientific activity described by Bueno (1992), Hacking (1992) or Pickering (1995), where models, observations and instruments of measurement are mutually coupled, in a dialectic of resistance-accommodation.

But, even when the models are consistent with all present climate data, it must be assumed that the equations and parameterizations can be extrapolated beyond the evaluation range. There is no guarantee-only confidence-that they will agree with future data (Schmidt and Sherwood, 2015). The fundamental reason for this pessimistic induction is, in our opinion, that the application of the strongest arguments in favor of scientific realism, which are related to intervention and experimental practice (as this occurs in sections of physics, chemistry or molecular biology), is prohibited in the field of climate change sciences.

The tools available to climatologists to study global climate are mainly mathematical modeling and simulation using supercomputers, which defines the science of climate change as a science of models, theoretical and observational rather than practical and experimental (more similar, in this sense, to cosmology than to solid state physics). Climate models are, in essence, tools to try to understand the climate, explaining certain phenomena and projecting others. The presence of parameterizations highlights that the epistemological status of climate models is closer to instrumentalism than realism, since they are not built exclusively on the basis of established physics or chemistry.

Furthermore, a simulation is not an experiment, but rather a substitute for the experiment, since in it we do not manipulate the things themselves but rather lines of code, through which we seek to reproduce a process through another process of a numerical nature. In simulations, real entities are not handled but rather mathematical entities (or, rather, in silicon), which prevents us from referring to simulations as true experiments, at the risk of confusing the simulation with reality. We are faced with a debated style of doing science, based on simulations, beyond the classic theorization-experimentation dyad (Petersen, 2012).

Conlusions

Climate models indicate that global warming cannot be explained by natural factors alone, with anthropogenic GHGs being the most important cause of climate change. However, in certain aspects, knowledge is still incomplete. There are various sources of uncertainty, related to classic problems in the philosophy of science that scientists face such as theoretical burden of observation, and empirical underdetermination of models. Throughout the paper three classes have been distinguished. Firstly, an uncertainty of values or observation, since the data extracted from instrumental series or proxy data of temperature, CO_2 concentration and other variables, may be scarce or inaccurate for certain regions. Secondly, a structural uncertainty, since the modeling of key processes such as couplings, forcings and parameterizations, as well as the numerical resolution, can be excessively simple and imperfect. And, thirdly, a temporal uncertainty, linked to the presence of deterministic chaos and the dependence on scenario projections. Finally, connecting the philosophy of science with ontology, pointing out how the various sciences of climate change have determined what today is called the global climate system or, simply, global climate, a notion was accepted by the World Meteorological Organization. On the Earth there is not a single climate but rather a plurality, a mosaic of very different climates. In the same way that there is no climate change that affects all regions of the planet equally. However, scientists, thanks to the construction of a global meteorological network of stations, buoys and satellites orbiting the Earth as well as the design of a hierarchy of climate models with increasing more couplings have put people before that new interconnected reality that is the global climate (Bueno, 1992; Morton, 2013).

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