World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

Check for updates

General circulation models cannot predict climate

Michael Jonas *

Independent Researcher, Exeter NSW 2579, Australia.

World Journal of Advanced Research and Reviews, 2024, 22(01), 1313–1318

Publication history: Received on 09 March 2024; revised on 19 April 2024; accepted on 22 April 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.22.1.1235

Abstract

This study draws on Chaos Theory to investigate the ability of a General Circulation Model to predict climate. The conclusion is that a General Circulation Model's grid-level physical processes and parameterisations cannot predict climate beyond maybe a few weeks. If a General Circulation Model is to be used at all, longer term climate features can be analysed externally and fed into the model but they cannot be represented by the model any better than by the external analysis. The external analysis, which is likely to be simpler, has the added advantage that the assumptions that are used, and the uncertainties in the results, are much more likely to be explicitly identified, quantified, and understood. Consequently it would be clear which aspects of the climate are being predicted, and how reliable those predictions are. The longer the timescale is, the less relevant the grid-level physical processes and parameterisations in a General Circulation Model become. Although a General Circulation Model can be made to represent climate over a longer time scale, its grid-level physical processes and parameterisations cannot predict the climate. A General Circulation Model calculates weather at each time step and this is then amalgamated into a final prediction of climate. This process is back to front. A realistic long term climate model would calculate climate and then weather would be deduced from the climate.

Keywords: Climate Model; General Circulation Model; GCM; Chaos Theory; Prediction horizon; Projection; Stadium-wave network; Weather

1. Introduction

This paper is concerned only with General Circulation Models (GCMs), including coupled GCMs, and any other climate models with a similar structure and methods. They will all be referred to here as GCMs. Any models with a different structure or methods are excluded from the analysis in this paper.

The GCMs, as currently referred to by organisations such as the Intergovernmental Panel on Climate Change (IPCC), apply the physical processes of Earth's atmosphere, surface and oceans, using a three-dimensional grid ("the grid") [1].

* Corresponding author: Michael Jonas

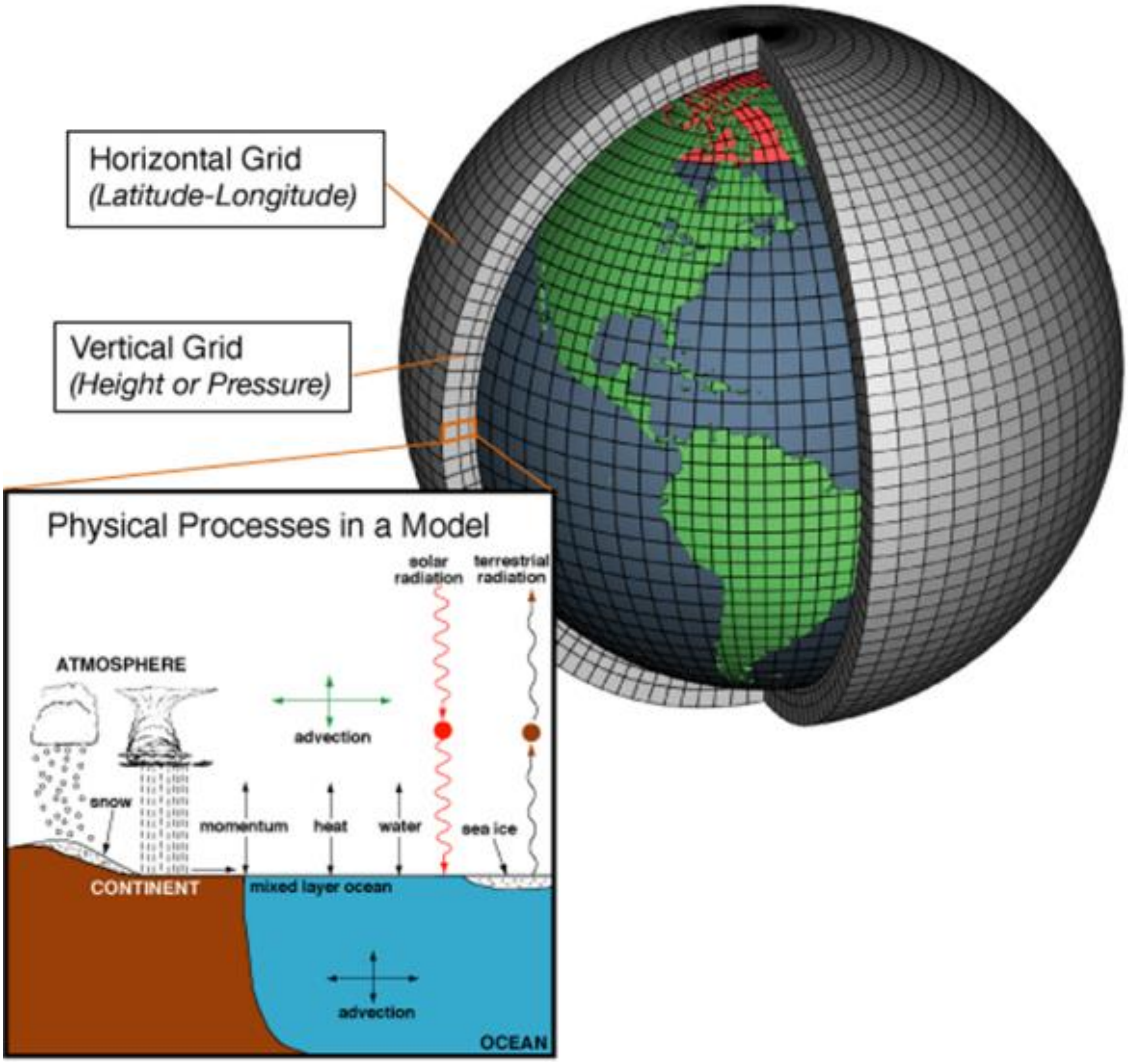

Figure 1 Climate Model Schematic from Climate.gov Media (ref. [1]), illustrating the subdivision of the planet into grid cells, together with some of the physical processes that are represented

Properties such as temperature, pressure, and wind or ocean current velocity, are evaluated at each grid point over a set of time intervals. A typical distance between atmospheric grid points could be 200km, and a typical time interval could be 20 minutes, but the distances between grid points, and the time intervals, can vary within a GCM and between GCMs.

In 2001, the IPCC stated: "*The climate system is a coupled non-linear chaotic system, and therefore the long-term prediction of future climate states is not possible.*" [2]. This paper shows why GCMs cannot predict the climate and outlines a better approach.

The analysis draws on Edward Lorenz' Chaos Theory [3], [4]. A useful decription is given in The Conversation, which explains in simple terms why, in a chaotic system such as climate, a tiny error will relentlessly increase in size until it has completely swamped the predictions, and why even in a deterministic chaotic system there is a prediction horizon - the length of time beyond which we can no longer accurately forecast its behaviour. [5].

Chaos Theory ("the Butterfly Effect") is represented as being a sensitive dependence on initial conditions. This was demonstrated by Kay et al who imposed tiny (less than a trillionth of a degree C) adjustments to initial conditions for multiple runs of the same GCM, and the results varied by several degrees C [6]. The results were represented as being the Butterfly Effect operating on the planet ("Because each member is run using the same model, the differences between runs can be attributed to differences in natural variability alone.") [7]. It was actually the Butterfly Effect operating on the model, not on the planet. The range of differences is dictated purely by the model, and different models would have different ranges.

In fact, there is a sensitivity to everything in a model as well as to initial conditions, because a model's results at the end of each time interval are the initial conditions for the next time interval. In other words, results are just as sensitive to even a tiny error or variation in the model itself.

2. Analysis

The climate models use a large number of processes to progress from one time interval to the next. Many of these are direct implementations of physical processes, but some processes such as the initial formation of clouds or the behaviour of the boundary layer are parameterised because they occur on too small a scale or are too difficult to represent in the grid [8] [9]. Some assumptions may also be applied in the models, for example, assumptions about future man-made CO2 emissions or future behaviour of the sun.

Because GCMs are also used for weather forecasting, it would be reasonable to suppose that this would be a reasonable guide to a GCM's prediction horizon. Weather models have a prediction horizon of about a week (it is hypothesised that there is an absolute limit of about two weeks - see ref [5]), so a climate GCM is unlikely to have a prediction horizon of more than a few weeks. ie, after at most a few weeks, the errors in a climate GCM will have swamped the calculation. Estimates of a GCM's prediction horizon vary, for example Koutsoyiannis et al suggest that for hydroclimatic processes it is some hours to a few days, while Collins suggests that for mid-latitude surface air temperature over land it appears not to be more than a season or so but for tropical regions over the ocean it is decadal [10],[11]. Prediction horizon can be different for different features of climate, but since surface air temperature over land is a frequently referenced projection of GCMs, and a season is similar to a few weeks, for simplicity this paper will use 'a few weeks'.

Just as it is thought that there is an absolute time limit for a weather model, so there would be an absolute time limit for a GCM, in other words, going into finer and finer detail in a GCM cannot extend its prediction horizon indefinitely. The fact that errors swamp the calculations doesn't mean that the results will be absurd or impossible, because the model will typically contain constraints so that the results are always within a reasonable range. What it does mean, though, is that after the prediction horizon has been reached - probably after a few weeks - the values at the grid points will be meaningless. Effectively, the results will be pseudo-random numbers within the model's assumptions and constraints. Since a constraint is itself a kind of assumption, assumptions and constraints will be referred to from here on just as assumptions.

In a bit more detail: Starting from a set of initial conditions, the model applies known physical processes to the data in order to arrive at the set of data for the end of the first time interval. In some cases, a parameterisation will be used instead of a known physical process. Necessarily, there will be some small errors. The model then iterates, applying the same calulations to each subsequent time period. Because climate is a chaotic system, by definition these errors grow with iterations of the model's calculations (that's what 'chaotic' means). After the prediction horizon has been reached, by definition the physical processes and parameterisations become meaningless (that's what 'prediction horizon' means). From then onwards, the only factors that are at all meaningful are the model's assumptions.

This implies that from the prediction horizon onwards, a reasonable result can be achieved simply by a higher-level application of the assumptions, although these results will almost certainly not be to as high a precision as the original grid. And a corollary of this is that, if a reasonable result cannot be obtained using a higher-level application of the assumptions, then running detailed iterations in the model cannot provide one either. An illustration of this is given later, in "Discussion". Note that such a higher-level approach is necessarily a kind of model (even a single formula is a kind of model), but it might not have the structure or methods of a GCM.

2.1. Predicting further ahead

For a climate model to be able to predict anything past the first few weeks, ie. past the prediction horizon as described above, it cannot use detailed physical processes or parameterisations that 'expire' at a short prediction horizon. The model must use assumptions and parameterisations that are relevant to the required timescale. Because prediction horizon can be different for different features of climate, the longer the timescale over which a GCM is applied, the less relevant ~~are~~ the grid-level physical processes and parameterisations in the GCM become. So, to be able to predict say a few years ahead, the model must abandon some uses of its grid-level physical processes and parameterisations of things like initial cloud formation and the boundary layer, and instead use assumptions for factors like relatively short term (seasonal or annual scale, say) atmospheric and ocean movements. The three-dimensional grid will likely be of no use now, and would probably need to be replaced with something more relevant, maybe a more region-based arrangement. If the model uses time steps then a much larger time step, maybe a year, would also need to be used.

Clearly, the model will not be able to give a detailed prediction with the precision of the original three-dimensional grid, but that's reasonable. It is what the IPCC meant when they said that prediction of future climate states is not possible. This approach is also in line with calls for climate prediction to be addressed in a probabilistic or stochastic way instead of a deterministic way, for example Giorgi 2010 [12]. The model's predictions would need to be recognised as being dependent on the accuracy of the new assumptions.

But now the model runs into a new prediction horizon. Just as a current GCM has a prediction horizon of maybe a few weeks, this new model would have a prediction horizon of maybe a few years.

There is in fact already some progress in this direction. Instead of relying on just the physical processes and parameterisations used in a typical GCM, it has been found that using seasonal patterns instead of a single annual average can improve a GCM's accuracy by an order of magnitude [13]. It should be noted that in this study the GCM that was not given seasonal patterns was poor at replicating them, even though it supposedly contained all of the physical processes that control seasons. It is reasonable to suppose that this is because a season (or a few seasons) is beyond the prediction horizon of the GCM - which is consistent with the expectation that a GCM's prediction horizon is just a few weeks. For the same reason, it should be recognised that probably many other longer term patterns, such as an ocean oscillation or an ITCZ (Intertropical Convergence Zone) shift, cannot be replicated, and that all of the physical processes and parameterisations that 'expire' at the prediction horizon should be replaced by longer term assumptions.

This is the crux of the matter. Even a relatively straightforward feature like seasons cannot be replicated well enough by a GCM. Seasons need to be analysed separately and fed into the GCM. So now when the GCM is run, its grid-level physical processes and parameterisations (ie, based on the grid and time intervals) are not predicting seasons. The same failure to replicate almost certainly applies to many other features with a time-frame of more than a few weeks. Ocean oscillations would have to be fed in. ITCZ shifts would have to be fed in. And so on. The GCM may now represent these features very well, or rather, it may now represent these features as well as the modeller understands them and is able to parameterise them, but the GCM's grid-level physical processes and parameterisations are now not predicting these features - those processes and parameterisations, if used at all, are just 'obeying orders'. The longer term features that have been analysed externally and fed into the GCM cannot be represented by the GCM any better than the external analysis. That is because, as explained above, the results at the GCM's grid points are pseudo-random numbers within the model's assumptions, so any results that do not represent features that have been fed in may be very interesting and may even lead to discovery of a new climate pattern, but they have no predictive value until they too have been analysed externally.

2.2. Multi-decadal Model

To be able to predict climate for, say, a few decades, the model must change again. For the same reason as before, it cannot use the assumptions and parameterisations of short term atmospheric and ocean movements that it used in 'Predicting further ahead', above. It must now use assumptions and parameterisations that are relevant over a decadal timescale, such as solar variation, cloud cover, longer term atmospheric and ocean movements, and man-made CO_2 emissions. The model's predictions will be even more approximate than before, and its performance is necessarily governed by the quality of the assumptions and parameterisations that it uses. And of course, this new model has a prediction horizon of only a few decades.

2.3. Centuries Ahead

For a climate prediction centuries or more ahead, yet another model will be needed. Again, it must use assumptions and parameterisations appropriate for this timescale. This is now the sort of timescale over which there are major periods in Earth's recent climate history that do not have a fully-understood mechanism - the Medieval Warming Period and the Little Ice Age, for example. For this timescale, therefore, it would be appropriate to use parameterisations to represent the multi-century warming and cooling cycles and variations of the past where we have no good reason to suppose that they will stop operating. Obviously, the predictions from such a model will be approximate at best, but the reality is that until the climate mechanisms of the past are understood, this is indeed the best that can be achieved.

This centuries-ahead model will have its own prediction horizon. To predict millenia ahead, yet another new model will be needed, with assumptions including factors like Milankovitch cycles. And so on, until the Sun dies.

Note that although a model must use a set of assumptions suitable for its timescale, these sets of assumptions are not necessarily mutually exclusive. A fairly long term assumption, like an ocean oscillation for example, can still be useful in a shorter term prediction. But a short term assumption or parameterisation, like the initial formation of a cloud for example, is unlikely to be useful in a longer term prediction.

3. Discussion

This doesn't mean that a GCM is completely useless. Far from it. A GCM does have many very valuable uses, it's just that those uses don't extend to predicting climate beyond a few weeks.

The IPCC uses the word 'projection' rather than 'prediction', but the model projection ensembles that they use are treated by the IPCC and others as predictions. As explained above, any one projection beyond a few weeks from a GCM is of little value, and any prediction needs to be made using a higher-level method. Such a prediction should be presented together with uncertainties of course, and with the understanding that it is based on certain assumptions, but it does have value as a prediction. Model ensembles are addressed later.

A very simple example of such a higher-level analysis is given by Eschenbach, where the results from several GCMs in the Climate Model Intercomparison Project 5 (CMIP5) are shown to be replicable using one simple formula [14]. Unlike the GCMs that it replicates, its underlying assumption is clearly stated and easily understood. Obviously, not all higher-level analyses will be this simple.

If such a higher-level analysis can be made, then the GCM is of no use for predicting future climate because the GCM's relevant results are already available. Those 'relevant results' are not the values at grid points, which are of little or no predictive value anyway, but amalgamations such as global average surface temperature. If an amalgamation is not one that can be predicted from the model's assumptions, then it has little or no value, as explained in 'Predicting further ahead' above using seasons. Further, if a higher-level analysis is not made, there can be no assurance that the assumptions are correct and do not 'expire' at a prediction horizon, so the GCM still has no predictive value. An example that illustrates this is given in Swanson 2013 where GCMs improved their fit to Arctic warming but worsened it everywhere else [15], [16]. The implication is that the models' physical processes had 'expired' and/or that the models were working with incorrect assumptions. In either case, the features need to be analysed in their own right and then fed back (parameterised) into the GCMs.

Averaging the results from multiple GCMs will not help, because there is no reason to suppose that these GCMs will vary randomly from the correct result. Because they tend to use many of the same assumptions they almost certainly will not vary randomly [17]. But what is in the models is not all that matters, what is not in the models matters too. Any error that occurs because a feature is missing from the models will be included in every ensemble. ie, no matter how many models are averaged in an ensemble, the end result is of little or no value.

In simple terms, if the behaviour of the assumptions in a GCM can be predicted externally, then the GCM is not needed for climate prediction. If not, then the GCM has no value for climate prediction.

The title of this paper is "General Circulation Models cannot predict climate". This is not intended to mean that a GCM can never give a correct prediction. Rather, it means that the grid-level physical processes and parameterisations in the GCM cannot reliably predict climate. In particular, a GCM cannot give a better prediction than a higher-level method. The higher-level method is likely to be simpler, and has the added advantage that the assumptions that are used, and the uncertainties in the results, are much more likely to be explicitly identified, quantified, and understood. Consequently it would be clear which aspects of the climate are being predicted, and how reliable those predictions are. A model that implemented the stadium-wave network, for example, although not global, could be such a model [18]. It is notable that the features of the stadium-wave network appear not to be reproduced in the GCMs, even though the GCMs attempt to apply all relevant physical processes. This is a similar situation to a GCM being poor at replicating seasonal patterns ('Predicting further ahead', above).

Future weather

In the GCMs, the process involves calculating the weather all around the globe at every time step - that's because conditions at a grid point at a point in time are weather - and then amalgamating them into a final prediction of climate. This process is back to front. With higher-level models as described in this paper, a model would predict climate at a future point in time. From that, it can be estimated what kind of weather each place or region can expect. The estimate could be carefully based on knowledge of what kind of weather each region experienced in the past when conditions were similar, or it could use any other meaningful technique. In other words, a realistic climate model does not calculate weather and then deduce climate from the weather, a realistic climate model calculates climate and then weather (ie, local and/or regional weather patterns) can be deduced from the climate.

4. Conclusion

A GCM has a prediction horizon of maybe a few weeks. The longer the timescale over which a GCM is applied, the less relevant the grid-level physical processes and parameterisations in the GCM become. If a GCM is to be used at all, longer term climate features need to be analysed externally and fed into the GCM. A GCM can thus be made to represent climate over a longer time scale, but its grid-level physical processes and parameterisations cannot predict the climate.

References

[1] Climate.gov Media. Atmospheric model schematic. https://www.climate.gov/media/10042

[2] IPCC Third Assessment Report, Climate Change 2001. Working Group I: The Scientific Basis, chapter 14, Advancing our understanding.

[3] Wikipedia, Chaos Theory. https://en.wikipedia.org/wiki/Chaos_theory

[4] Edward Lorenz, The Essence of Chaos, University of Washington Press, 1996.

[5] The Conversation. Explainer: what is Chaos Theory? https://theconversation.com/explainer-what-is-chaos-theory-10620

[6] J E Kay et al. The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. Bulletin of the American Meteorological Society, Volume 96, Issue 8.

[7] L Snider. 40 Earths: NCAR's Large Ensemble reveals staggering climate variability. NSF National Center for Atmospheric Research. https://news.ucar.edu/123108/40-earths-ncars-large-ensemble-reveals-staggering-climate-variability (not peer-reviewed).

[8] IPCC Fourth Assessment Report: Climate Change 2007. Working Group I: The Physical Science Basis, section 8.2.1.3 Parametrizations.

[9] Wikipedia. Representations of the atmospheric boundary layer in global climate models. https://en.wikipedia.org/wiki/Representations_of_the_atmospheric_boundary_layer_in_global_climate_models

[10] D Koutsoyiannis et al. On the credibility of climate predictions. Hydrological Sciences Journal, Volume 53, 2008 - Issue 4.

[11] M Collins. Climate predictability on interannual to decadal time scales: the initial value problem. Springer Link, October 2002, Volume 19, pages 671–692, (2002).

[12] F Giorgi. Uncertainties in climate change projections, from the global to the regional scale. EPJ Web of Conferences, Volume 9, 2010.

[13] M F Howland, O R A Dunbar, T Schneider. Parameter Uncertainty Quantification in an Idealized GCM With a Seasonal Cycle. Journal of Advances in Modeling Earth Systems, Volume 14, Issue 3, March 2022, e2021MS002735

[14] W Eshenbach. Into The Black Box. https://wattsupwiththat.com/2022/02/03/into-the-black-box/ (not peer-reviewed).

[15] K L Swanson. Emerging selection bias in large-scale climate change simulations. Geophysical Research Letters, Volume 40, Issue 12, 28 June 2013, Pages 3184-3188.

[16] R McKitrick and J Christy. A Test of the Tropical 200- to 300-hPa Warming Rate in Climate Models. AGU Earth and Space Science, 5, 529–536.

[17] R Knutti, D Masson, A Gettelman. Climate model genealogy: Generation CMIP5 and how we got there. Geophysical Research Letters, Volume 40, Issue 6, 28 March 2013, Pages 1194-1199.

[18] M G Wyatt and J A Curry. Role for Eurasian Arctic shelf sea ice in a secularly varying hemispheric climate signal during the 20th century. Climate Dynamics, 2013. Full text as submitted is at http://judithcurry.com/wp-content/uploads/2013/10/stadium-wave1.pdf