

Climate Change Modeling a Systematic Review

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Abstract

Climate change models permit the simulation of the special effects of the assemblage of greenhouse gases centuries into the future, based on contemporary thoughtful of atmospheric physics and chemistry. The global climate modeling characterizes the climate system implementing a 3D grid with horizontal coarse resolution of 250 km-600 km over the world and 10-20 vertical layers in the atmosphere as well as around 30 layers in the oceans. Although, regional climate models which zoom in on precise areas, have much finer resolutions, commonly a few tens of kilometers. This is ample quicker to the scale of real world observations about topography, land cover and soil types, all of which affect the climate system. Because of this reason, regional climate models can use more real life data than global models and their simulations are generally more accurate. Though, regional climate model is useful for investigating natural variations in the Earth's climate; studying how land use (such as agriculture and deforestation) can affect regional weather patterns; and making more detailed predictions about how climate change will affect the places where people live. Conjoining global and regional models allows finer scale investigation of regional details of change to horizontal resolutions of 10 km-50 km. Consequently, scientists use climate models to predict how the climate might change in the future, especially as human actions, like adding greenhouse gases to the atmosphere, change the basic conditions of our planet.

Keywords: Climate change • Climate change model • Projection • RCM • Scenarios

Introduction

According to IPCC, Bonan and Doney, and Palmer and Stevens climate models are computer programs that use mathematical equations based on the laws of physics and chemistry to simulate the Earth's climate change. Since climate cannot be studied in a laboratory, these models are run on computers to make projections of how the climate is changing. As Webster et al., IPCC and Carbon Brief, climate model was only with the advent of computers in the 1950's, that capable of simulating the response of the global circulation, were developed alongside numerical weather prediction systems. These models were based on simulating the weather, and thereby the climate, from first principles using fundamental physical laws that represented by mathematical equations, have to be solved using sophisticated numerical techniques. Mauritsen et al., and IPCC, stated also, by dividing Earth's atmosphere, oceans, land and ice into millions of grid cells and solving the equations forward in time, simulations of the evolution of the world's weather and climate in each cell over the coming hours to decades can be created [1-3].

Based on Dufresne et al., IPCC, Gettelman et al., Mauritsen et al. and Schmidt et al., there are three main types of climate models; Energy balance model, global climate models and regional climate models. Lohmann stated, Energy Balance Models (EBMs) are highly simplified

models of the climate system, providing admissible conceptual tools for understanding climate changes. The global temperature is calculated by the radiation budget through the incoming energy from the Sun and the outgoing energy from the Earth. Global Climate Models (GCMs) couple an atmospheric model or general circulation model (also abbreviated GCM), with an ocean model, so they are often referred to as coupled global models or Atmosphere-Ocean General Circulation Models (AOGCMs) that are numerical models describing natural mechanisms in the atmosphere, land surface and ocean. However, Regional Climate Models (RCMs) have a higher resolution, their grid cells are at most 50 kilometers wide so they are used to generate weather data for climate change impact studies. These high resolution data are produced by running an RCM within the boundary conditions set by a particular GCM or "nesting" the RCM within a GCM [4,5].

Nevertheless, as Feser et al., and Kharin et al., stated, the Global Climate Models (GCMs) produce trajectories of future climate change, including global and regional changes in temperature, precipitation and other physical characteristics of the climate system. The resolution of global models has increased significantly since IPCC FAR. However, even the latest experimental high-resolution simulations, at 15-30 miles (25 km-50 km) per grid box, are unable to simulate all of the important fine scale processes occurring at regional to local scales. Instead,

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downscaling methods are often used to correct systematic biases or offsets relative to observations, in global projections and translate them into the higher-resolution information typically required for impact assessments.

Accordingly, the essential objective of this review paper is to analyze the climate change modeling with the specific objectives.

- To describe the development of climate change modeling.
- To explain the importance of climate change modeling.
- To identify the challenges of climate change modeling prediction.

Methods and Materials

This review paper aimed to address the climate change modeling. To review this paper, the methods that adopted was a literature search and analysis of relevant peer reviewed articles and published articles were systematized from web of science, with extra records from Scopus and Google Scholar were used to assess resources. Subsequently, articles pertinent to the purpose of the paper were collected and reviewed; at that juncture, the analyzed result was inscribed and offered in this paper.

Some keywords were employed in searching english language automatic documents accessible up to date of March 2023. Those were containing climate change model, future climate change scenarios, climate change prediction, global climate models and regional climate models. Although, I search to identify papers published aforementioned to 2007-2023 that include climate change model outputs containing both a time series of projected future Global Mean Surface Temperature (GMST) and future forcing's (including both a publication date and future projected atmospheric CO₂ concentrations, at a minimum). The climate change modeling efforts were primarily undertaken in conjunction with the IPCC process and model projections were taken from models featured in the Fourth Assessment Report (AR4-IPCC, 2007). As a final point, by evading repetitions, solitary 10 papers that comprise original research articles 6 and reviews 4 were reviewed and combined [6].

The development of climate change modeling

As Randall et al. and IPCC, early weather models focused on fluid dynamics rather than on radiative transfer and the atmosphere's energy budget, which are centrally important for climate simulations. Dufresne et al., additions to the original AGCMs used for weather analysis and prediction were needed to make climate simulations possible. Furthermore, because climate simulation focuses on time scales longer than a season, oceans and sea ice must be included in the modeling system in addition to the more rapidly evolving atmosphere. Thus, ocean and ice models have been coupled with atmospheric models. The first ocean GCMs were developed at GFDL by Bryan and Cox in the 1960's and then coupled with the atmosphere by Minable and Bryan in the 1970's.

According to the IPCC, Nikulin et al. and Samuelsson et al., earliest and most basic numerical climate models are Energy Balance Models (EBMs). EBMs do not simulate the climate, but instead consider the

balance between the energy entering the Earth's atmosphere from the sun and the heat released back out to space. The only climate variable they calculate is surface temperature. The simplest EBMs only require a few lines of code and can be run in a spreadsheet. Many of these models are "zero-dimensional", meaning they treat the Earth as a whole; essentially, as a single point. Others are 1D, such as those that also factor in the transfer of energy across different latitudes of the Earth's surface (which is predominantly from the equator to the poles). Although, Dufresne et al. stated a step along from EBMs is Radiative Convective Models, which simulate the transfer of energy through the height of the atmosphere for example, by convection as warm air rises. Radiative Convective Models can calculate the temperature and humidity of different layers of the atmosphere. These models are typically 1D only considering energy transport up through the atmosphere but they can also be 2D.

Based on Palmer and Stevens, the next levels up are General Circulation Models (GCMs), also called global climate models, which simulate the physics of the climate itself. This means they capture the flows of air and water in the atmosphere and/or the oceans, as well as the transfer of heat. Early GCMs only simulated one aspect of the Earth system such as in "atmosphere only" or "ocean only" models but they did this in three dimensions, incorporating many kilometers' of height in the atmosphere or depth of the oceans in dozens of model layers. More sophisticated "coupled" models have brought these different aspects together, linking together multiple models to provide a comprehensive representation of the climate system. Coupled Atmosphere-Ocean General Circulation Models (or "AOGCMs") can simulate, for example, the exchange of heat and freshwater between the land and ocean surface and the air above (Figure 1).

Earth Models of Intermediate Complexity (EMICs) simulate the all Earth system with more simplifications than GCMs. This simplification allows simulations over larger time periods, which is useful to study past climates. Simple Climate Models (SCMs) use only a few key processes to answers specific questions. Yet, as Lucarini et al. and Hourdin et al., both complex and simple models have different strengths and weaknesses, and applications. GCMs are largely used to make climate projections for the next centuries. Since the numerical resolution of dynamical equations from the micro-scale (of order 10 m–3 m for dissipation) to the scale of interest (104 m) is still impossible, GCMs however need to represent sub-grid processes such as turbulent flows, convection or cloud's formation [7,8].

Even though, UNFCCC and Kirtland and IPCC stated, there are also Regional Climate Models (RCMs) which do a similar job as GCMs, but for a limited area of the Earth. Because they cover a smaller area, RCMs can generally be run more quickly and at a higher resolution than GCMs. A model with a high resolution has smaller grid cells and therefore can produce climate information in greater detail for a specific area RCMs are one way of "downscaling" global climate information to a local scale. This means taking information provided by a GCM or

coarse scale observations and applying it to a specific area or region. The Figure 1 below illustrates the development of climate change modeling and how the spatial resolution of models improved between the first and fourth IPCC assessment reports which have shown how the detail in the topography of the land surface emerges as the resolution is improved [9].

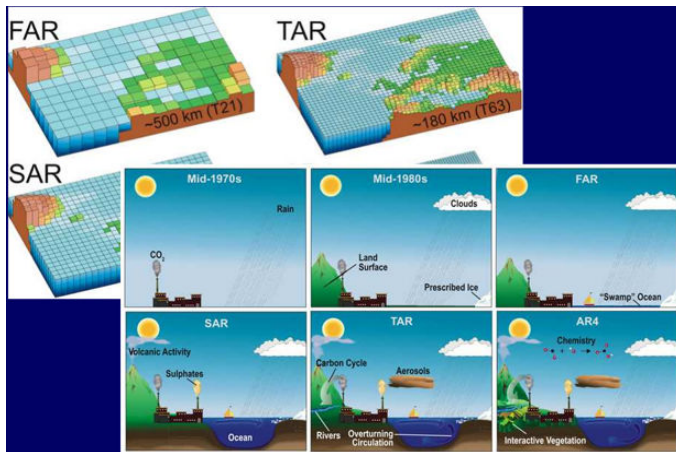


Figure 1. Increasing spatial resolution of climate models used through the first four IPCC assessment reports: First (FAR) published in 1990, second (SAR) in 1995, third (TAR) in 2001 and fourth ("AR4") in 2007. (Note, there is also a fifth report, which was completed in 2014).

To end with, a subset of climate modeling involves Integrated Assessment Models (IAMs) which add aspects of society to a simple climate model, simulating how population, economic growth and energy use affect and interact with the physical climate. IAMs produce scenarios of how greenhouse gas emissions may vary in future. Scientists can then run these scenarios through ESMS to generate climate change projections providing information that can be used to inform climate and energy policies around the world [10].

The importance of the climate change modeling

According to IPCC (AR5), IPCC and Lenssen et al., GCMs are used to establish the role of human emissions in climate change. For these assessments, GCM simulations are run for the recent past using only natural drivers of climate change and compared to observed warming trends. In general, GCMs are able to reproduce the full range of warming that has been observed in the past several decades only when human drivers of change (human forcing's) are included in the models. This is generally taken as strong evidence that human pollution is the cause of recently observed climate change. Jain et al. and IPCC (AR5) was stated Global Climate Models (GCMs), are the main tools used to project the extent of this future climate change and the Coupled Model Inter-comparison Project 3 (CMIP3) was the international collaborative effort of GCM groups to produce projections that directly informed the IPCC fourth assessment report. This database of global climate projections has been widely used to investigate global climate system processes as well as large scale climate change projections. This construction of a many GCM ensemble is vital for dealing with the uncertainty associated with future projections [11-13].

According to IPCC climate change models allow the simulation of the effects of the buildup of greenhouse gases centuries into the future, based on current understanding of atmospheric physics and chemistry. The typical horizontal resolution of a global climate model is 100 km-200 km and combining global and regional models allows finer scale examination of regional details of change to horizontal resolutions of 10 km-50 km. Most global models are run on supercomputers, whereas some regional models may be run on desktop computers (often taking 6-8 months for a single realization).

Freudenberger and Green Climate Fund was stated also, the viability of national and international emission mitigation policies must be tested using assessments based on climate change model simulations and predictions. These will serve to inform society of the consequences of failure to achieve the necessary emission reductions, on regional impacts and risks from extreme events which only with the best possible climate models can we show what is at stake, what might be lost and what the future climate damage and costs of inaction will be.

Raju and Nagesh Kumar and Hargreaves and Annan was detailed was detailed, GCMs represent the climate system adopting a 3D grid with horizontal coarse resolution of 250–600 km over the world and 10–20 vertical layers in the atmosphere as well as around 30 layers in the oceans (Figure 2). They are developed to indicate atmospheric physics, dynamics and to simulate past climate for analyzing future climate changes. GCMs follow conservation laws (momentum, mass, energy, moisture), fluid dynamics, equation of state and more. Some of the parameters and boundary conditions considered in GCMs are rotation speed of the Earth, thermo-dynamic and radiation constants of atmospheric gases and clouds, surface elevation, total mass of the atmosphere and its composition, soil type and surface albedo and (Figure 2) [14,15].

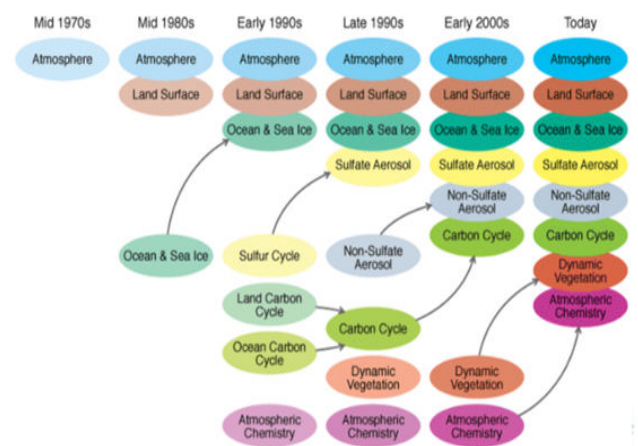


Figure 2. Illustration of the processes added to global climate models over the decades.

Generally, as above empirical suggestions on the global climate models data over decades have clear a significance similar to; can be provided for locations and periods without observations, climate models are the only source that can be used for the future, climate model ensembles can provide more information for the past/current climate and for the future with which uncertainties and natural variability can be estimated. However, to use the climate model in a

correct way, one should be aware of the limitations and assumptions behind the data too.

Climate change modeling scenarios and projections

Based on Mauritsen et al., UNFCCC, Knutti and Sedlacek, and IPCC indicated using transient scenarios such as SRES and RCP as input, Global Climate Models (GCMs) produce trajectories of future climate change, including global and regional changes in temperature, precipitation, and other physical characteristics of the climate system. According to IPCC future greenhouse gas emissions scenarios are one of the key forcing factors that determine future climate change and over 40 emissions scenarios have been produced by the IPCC Special Report on emissions scenarios. The emissions scenarios are based on a range of assumptions about future technological change and energy use as well as future trajectories for the global economy and population.

As IPCC, NRC, and Table 1 shows the most commonly used emissions scenarios for GCMs runs and even under the lowest emissions scenario, B1, the projected global concentration of Carbon dioxide (CO₂) by 2100 is higher by a factor of 1.6 (at 600 ppm) than baseline conditions in 2005 (about 380 ppm) (Table 1). Under the “business as usual” scenario, A2, the global CO₂ concentration is projected to increase to 1200 ppm by 2100. For purposes of comparison, B1 and A2 can be selected as a low emissions scenario and higher emissions scenario, respectively [16].

Scenario	2100 CO ₂ conc. (ppm)	Economy and population	Energy sources
B1	600	Sustainable economy with emphasis on equity, reduced consumption, environment. Global economic convergence. 2100 population 7 billion	Largely non fossil
A1B	850	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 billion	Balanced fossil/ non fossil
A2	1200	Moderate, uneven economic growth, regionally varied, function of culture. No global economic convergence. 2100 population 15 Billion.	Regionally mixed depending on availability
A1FI	1550	Rapid growth, materialistic, market-oriented, high consumption economy. Global economic convergence. 2100 population 7 Billion.	Fossil intensive

Table 1. Summary of the main features of selected IPCC emissions scenarios.

The challenges of climate change modeling predicting

According to According to Bonan and Doney, IPCC, and Deser et al., existing models have significant shortcomings in simulating local weather and climate because of available computer power. They cannot resolve the detailed structure and lifecycles of systems such as tropical cyclones, depressions and persistent high-pressure systems, which drive many of the more. Costly impacts of climate change, such as coastal inundation, flooding, droughts and wildfires; nor are they able to resolve ocean currents that are fundamental to climate variability and regional climate change.

Results and Discussion

However Mote and Salathé, stated, the A1B emissions scenario, which projects higher emissions at the beginning of the century than A2 and lower emissions at the end of the century (a plausible response to increasing impacts over time), is often selected as an alternate emissions scenario. If analysis is focused on the mid-21st century climate change, the A1B greenhouse gas emissions scenario represents potentially greater warming than the A2 scenario. Also, a larger number of GCMs were run with the A1B greenhouse gas emissions scenario than with the A2 scenario; they provide more information regarding the range of plausible effects. To analyze the impacts of rapid and essentially uncontrolled greenhouse gas accumulations by 2100, the A1FI emissions scenario might be the most appropriate choice, although the number of GCM simulations of this emissions scenario is limited. It is worth noting that actual greenhouse emissions have in recent years exceeded the average of the A1FI scenario family, although they have not exceeded the single representative scenario used in the IPCC GCM simulations [17].

Gettelman et al., Mauritsen et al., and Schmidt et al. was detailed that, models are commonly evaluated by comparing “hindcasts” of prior climate variables to historical observations, the development of hindcast simulations is not always independent from the tuning of parameters that govern unresolved physics. There has been relatively little work evaluating the performance of climate model projections over their future projection period (referred to hereafter as model projections), as much of the research tends to focus on the latest generation of modeling results. Although, specified, General Circulation Models or Global Climate Models (GCMs) are among the best available tools to represent reasonably well the main features of

the global distribution of basic climate parameters. But these models, so far, are unable to reproduce well the details of regional climate conditions at temporal and spatial scales of relevance to hydrological studies in other words, outputs from GCMs are usually at resolution that is too coarse for many climate change impact studies. Hence, there is a great need to develop tools for downscaling GCM predictions of climate change to regional and local or station scales. Hence the use of a many model ensemble is required to provide some measure of likelihood of the projected future climate [18-20].

Based on IPCC, lack of complete information about atmospheric processes, approximations during numerical modeling, spatiotemporal scales, coarser or finer resolution, different feedback mechanisms (cloud and solar radiation, greenhouse gases, aerosols, natural and anthropogenic sources, ocean circulation, water vapour and warming, ice and snow albedo) and different perspectives (physical parameterizations, initializations and model structures) are the causes of uncertainties that lead to either overestimation or underestimation of values of the considered climate variable, as compared to the observed variables (Figures 1 and 2). This inadvertently results in different outcomes for different GCMs for the same forcing also indicated, regional climate models do not yet provide all the solutions for generating climate change scenarios. There will be errors in their representation of the climate system and their resolution will not be sufficient for some applications and Predictions from an RCM are dependent on the realism of the global model driving it; any errors in the GCM predictions will be carried through to the RCM predictions. On the other hand, this limitation is shared by all techniques for generating realistic climate scenarios.

Climate change models countenance the simulation of the impacts of the stockpile of greenhouse gases centuries into the future, based on current understanding of atmospheric physics and chemistry. The model showing the physical and biological progressions included in current generation climate models and underscores the importance of atmospheric and ocean flows in driving fundamental cycles of the earth water, carbon, atmospheric chemistry and ocean biogeochemistry. Thus, global climate models combine the latest scientific understanding of the physical processes at work in the atmosphere, oceans and earth's surface and how they are all interconnected. In beside global climate model can produce projections of precipitation, temperature, pressure, cloud cover, humidity and a host of other climate variables for a day, a month or a year. Even though regional climate model with a high resolution has smaller grid cells and consequently can produce climate information in greater detail for a specific area.

Conclusion

Climate models were selected for use in the investigation based on a demanding set of criteria, including the model's efficiency in duplicating past and current climate change within specific region. Statistical downscaling studies using atmospheric predictors have addressed numerous predictions, with the paramount emphasis particular to different variables. Climate models are fundamental to understanding climate change and anticipating its risks. They provide the basis for predicting impacts, guiding adaptation decisions and setting mitigation targets. Human being now needs more detailed and accurate evidence to enable forceful decision making in the aspect of rapidly intensifying climate change.

Authors Contribution

For this article collecting, conceptualization, analysis, writing the original draft, writing review and editing all reviewed documents were done by the author. Although, all elements of the reviewed paper were analyzed and justified by author.

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Data Availability

All data used in this review paper were obtained from online sources. The outputs of this review paper, which are shown as Figures and Tables, are available upon reasonable request. No extra code was made to create the results presented here.

Declaration of Competing Interest

Ethical approval; The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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