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More than a half century of Computational Fluid Dynamics / *Plus d'un demi-siècle de mécanique des fluides numérique*

Climate models

Modèles de climat

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Abstract. The first climate models have emerged in the 60s and have been continuously developed since then. They have progressively included the representation of all the climate system components: the atmosphere, the ocean, the cryosphere and the biosphere. Inside each component, they have also been enriched by the representation of more processes with the aim of improving their realism. These models are used to make climate projections over the coming century but they are above all a laboratory tool to improve our understanding of the climate system.

Résumé. Les premiers modèles climatiques sont apparus dans les années 60 et n'ont cessé d'être développés depuis. Ils ont progressivement inclus la représentation de toutes les composantes du système climatique : l'atmosphère, l'océan, la cryosphère et la biosphère. Au sein de chaque composante, ils ont également été enrichis par la représentation d'un plus grand nombre de processus dans le but d'améliorer leur réalisme. Ces modèles sont utilisés pour faire des projections climatiques sur le siècle à venir mais ils sont surtout un outil de laboratoire pour améliorer notre compréhension du système climatique.

Keywords. Climate, Ocean, Atmosphere, Biosphere, Projection.

Mots-clés. Climat, Océan, Atmosphère, Biosphère, Projections.

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1. Introduction

Atmospheric and ocean models are based on computational fluid dynamics. In the following, we will explain what are climate models and how they are built. This article attempts to highlight the hypotheses and inherent limitations of these models. The first climate models have been developed based on weather forecasting models. The original question raised in pioneering studies [1] was "what happens if we integrate atmospheric models over periods longer than a few days?" Does the numerical atmosphere reach an equilibrium? And if yes does this equilibrium look like reality? These atmospheric models called General Circulation Models (GCM) were based on the Navier–Stokes equations and were developed in the early 1950s [2] thanks to the development of computers. These models were able to simulate the large-scale circulation and the basic features of the atmospheric climate and have then been used as a digital laboratory by Manabe and Wetherald [3] to assess the effect of doubling the carbon dioxide atmospheric concentration on the climate. It is remarkable that theirs results have not been denied since

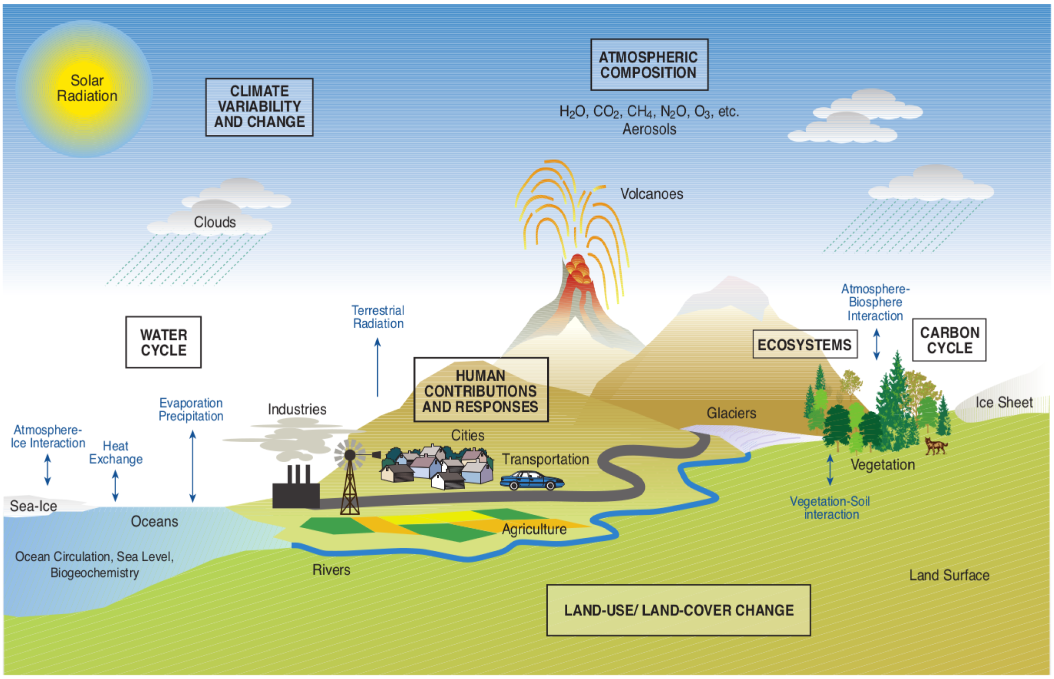

Figure 1. Main components of the climate system (atmosphere, oceans, cryosphere, biosphere and lithosphere). [Source: Report by the Climate Change Science Program, 2003, © US Climate Change Program.]

then, the award of the 2021 Nobel Prize to S. Manabe is a recognition of these innovative studies.

The introduction of the ocean system in climate models has quickly become a necessity since energy transport in the climate system is half done by the ocean, which has a much larger heat capacity [4]. Since then, models have evolved to include all the relevant components to simulate the climate over a few centuries: atmosphere, ocean, cryosphere and biosphere (Figure 1) and each component representation has been continuously improved. This increased of model complexity has been possible thanks to the continuous increase in computing capabilities. These models are now routinely used to make climate projections for the next century, but also as a digital laboratory to explore the complex processes that make up the climate system. The original version of this article has been published in the encyclopedia of environment [5].

2. Climate model components

2.1. *Ocean and atmosphere*

Both ocean and atmosphere are fluids, therefore their dynamics follow the Navier–Stokes equations. In climate models, several simplifications are made to this set of equations, in particular the hydrostatic approximation (allows for neglecting the vertical acceleration). Actually, both components are modelled using the so-called primitive equations system which consists of the equation of momentum, the continuity equation for mass conservation, the thermodynamic equation for energy conservation and the equation of state [6, 7]. Translated in numerical form, these equations are solved on a mesh (Figure 2) [8] and the temporal evolution is done in successive

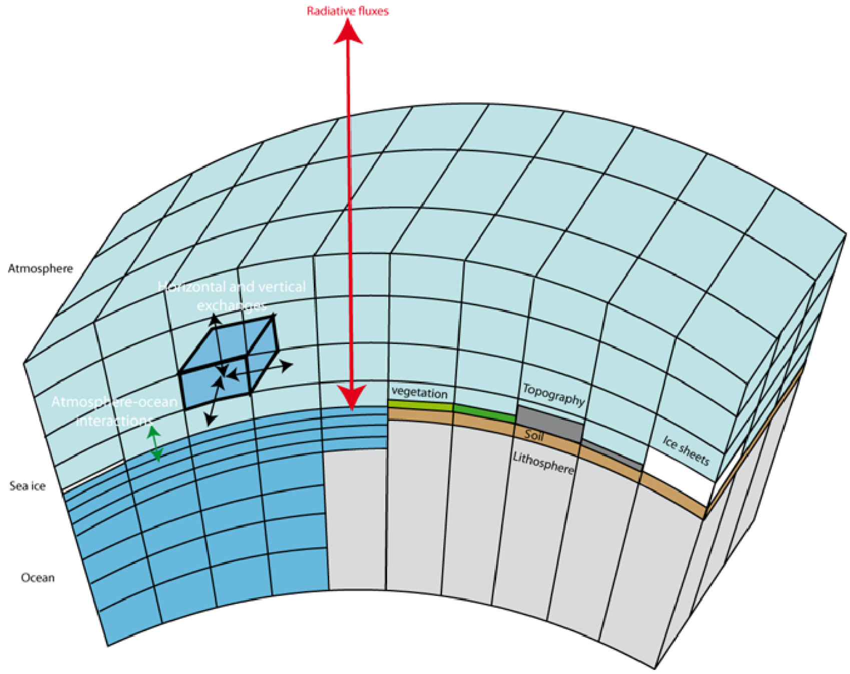

Figure 2. Mesh structure of a climate model. [Source: © Goose et al. [8], licence CC-BY-NC.]

time steps. There are several numerical methods for representing the fluid mechanics differential equations. Among these, the most commonly used are the finite difference and the spectral method, the latter being more efficient computationally but also more dissipative. These equations are used to determine the averaged state parameters (temperature, winds, humidity of the atmosphere, temperature, currents and salinity of the ocean) on each mesh cell at each time step. The type of mesh used in climate models also differs in between models. The obvious way to discretize the equations in spherical coordinates is to use a regular latitude-longitude grid. However, such grids suffer from complications associated with the convergence of meridians near the pole. To alleviate this singularity, other types of grid have been used: triangular grid for spectral models and more recently finite difference models turn to icosahedric grids which have the advantage of anisotropy [9], some groups even turn to using unstructured grids [10] which allow to adapt the local resolution to the local processes.

In climate simulations, the size of a mesh cell is of the order of a hundred kilometres, and the time step is a few tens of minutes. Subgrid processes, such as cloud or precipitation formation, cannot therefore be represented directly by fluid dynamics equations. As these processes must be taken into account: they are thus represented using empirical parameterizations that picture their effect on the state variables at the scale resolved by the dynamics equations.

Atmospheric models include parameterizations for radiative transfer, turbulence, convection, cloud and precipitation formation, cloud interactions with radiation, etc. Ocean models also contain parameterizations to represent the solar radiation penetration into the water, mixing related to smaller scale eddies, tide-induced mixing and turbulence. Parameterizations are also used to represent transfers of water, energy and momentum between the ocean and the atmosphere. Such parameterizations are equations written empirically from observations, but they intend to be universal in a given model, in the sense that they are the same at any point on the globe[1].

The atmospheric models used for climate simulations are thus constructed in the same way as weather forecasting models. The difference stems from the period over which these models are integrated and the way in which their results are interpreted (see Part 3). Additionally, global weather prediction models are operated using cells of a few kilometres horizontally and a few hundred metres vertically. To reduce their calculation cost, climate models use larger cells (see Figure 2), especially on the horizontal, which allows integrations over several decades or even centuries. Note that even if the cells are larger, the time-step of climate models remains of a few tens of minutes, therefore, they can represent the succession of meteorological phenomena such as rain, drought, storms, etc.

2.2. *Other components*

In addition to the atmosphere and the ocean, the climate system has to include a land surface component and a representation of the cryosphere. Continental surface models aim to represent the exchange of water and energy between the soil, the biosphere and the atmosphere. They are based on energy and water conservation principles. For example, an area of forest will capture more solar energy because it is darker (its albedo is lower) than an area covered with pastures. On the other hand, if the surface soil is dry, a tree will be able, thanks to its deeper roots, to use water in the deep soil and produce a flow of water to the atmosphere by evapotranspiration, while grass will not be able to do so. These models also represent seasonal snow on the ground as well as frost in the soil. As in atmospheric models, many processes take place at scales smaller than the mesh size and need to be parameterized.

Aside from snow cover on land, the cryosphere is mainly composed of two elements: sea ice and glaciers. Sea ice is the ice forming over the ocean, whereas glaciers are formed over continents and include ice sheets which are polar cap glaciers. Sea ice models represent the exchanges of water, salt and energy between the sea ice and the ocean, but also between the ice pack and the atmosphere. In these models, the ice pack moves as a function of near-surface winds and ocean currents. These movements lead to sea ice piling up in some areas and divergence[2] in other. Climate models also include ice sheet models but these are generally very simplified and are primarily intended to represent the effect of ice cover on land, without any change in their extent. More complex ice sheet models already exist, particularly for the Arctic and Antarctic, but they require the atmospheric parameters to be represented with finer grids than in current global climate models. Their coupling within climate models is one of the current challenges of climate modelling and becomes crucial for very long-term climate simulations (several centuries).

In climate models, the different components are coupled: they evolve jointly, interacting with each other. In general, continental surface models and atmospheric models interact at each time step of the atmospheric model (a few minutes). Exchanges between ocean models and atmospheric models take place at least once a day or even hourly depending on the model.

3. Complexity and computational cost

To make realistic climate projections, climate models have to describe the four components of the climate system: atmosphere, ocean, biosphere and cryosphere. The complexity of a model is defined as the number of climate processes taken into account. The first climate

[1] Some parameterizations can however include latitude as an input parameter [11].

[2] Divergence: indicates that dynamic tends to export ice to other regions. For example, if sea ice is transported offshore along a coast by local winds, the ice will tend to disappear or become thinner at the coast.

models developed in the 1970s represented only the atmospheric component. By the late 1990s, models evolved rapidly and managed to include all four components. Since then, models have constantly improved by refining existing parameterizations and adding the representation of new processes. For instance, most current models represent the life cycle of particles in suspension in the atmosphere, called aerosols. The models thus represent their transport by winds, their interaction with cloud formation processes and their leaching by rain. The most complex models also represent the entire carbon cycle, and allow to estimate carbon fluxes between the different components. The fluxes themselves depend on climate, properties of seawater and the ability of vegetation and marine biosphere to convert carbon into organic matter. In these models, the carbon dioxide atmospheric and oceanic concentration becomes a modelled variable and is no longer an external input.

There are also very simplified, one-dimensional models based on the terrestrial radiation balance, which simulate only the global mean surface temperature without any information on the regional disparities. However, in order to represent the effect of an increase in carbon dioxide concentration in these simple models, information from the full models described above is needed. In between these highly simplified energy balance models and the full models, there is a range of models of increasing complexity (Figure 3), developed for specific applications.

The most complex models are also the most expensive ones in terms of computing time. However, depending on the study performed, it is not always necessary to take all processes into account. In particular, the inclusion of the full representation of the carbon cycle relies on parameterizations that are still uncertain and which feedbacks may be important. In order to study the impact of a given increase in atmospheric carbon dioxide concentration on features such as El Niño phenomena, it could be preferable to use a model without representation of the carbon cycle, which results will be easier to interpret. The results will then help to understand the projections of the carbon cycle model. It is therefore sometimes necessary to decouple the questions to improve our understanding of processes.

Thus, the most complex model is not necessarily the most suitable for all uses. With an increased level of complexity, more degrees of freedom are also introduced into the system. This complicates its calibration and validation, sometimes at the expense of model robustness. The interpretation of the results is also more delicate. Additionally, the more complex the model, the more powerful the computers required and the longer the computation time. Note also that it is often necessary to carry out several tests before reaching reliable conclusions on a given study. It is therefore important that the calculation cost is reasonable in order to be able to perform several tests.

The cost of running a climate model increases with its complexity and with its resolution, i.e. the number of grid cells. The calculation cost also depends on the numerical methods used to represent the model equations. Thus, to simulate one year, current climate model needs from a few dozen days to a thousand if only one processor was used. This is why these models are implemented on supercomputers: by using a large number of processors simultaneously, the simulation of a year of climate can then be done within a few hours. Therefore, it takes several weeks to make a 100-year climate projection simulation. The volume of data produced is also very large, of the order of a few hundred Gigabytes (GB) per simulation year, or a few dozen Terabytes (TB) for a 100-year simulation.

A climate model is a numerical laboratory for testing hypotheses, as done in biology with test tubes. In biology, the same treatment is often repeated may times to verify its effectiveness. Similarly in climate, it is often appropriate to carry out the simulations in the form of ensembles. As the climate system is chaotic, it is sometimes difficult to separate the climate changes that are due to imposed forcing, for example an increase in greenhouse gases, from the internal variability of the climate system. Simulation sets subject to the same forcings but with slightly dif-

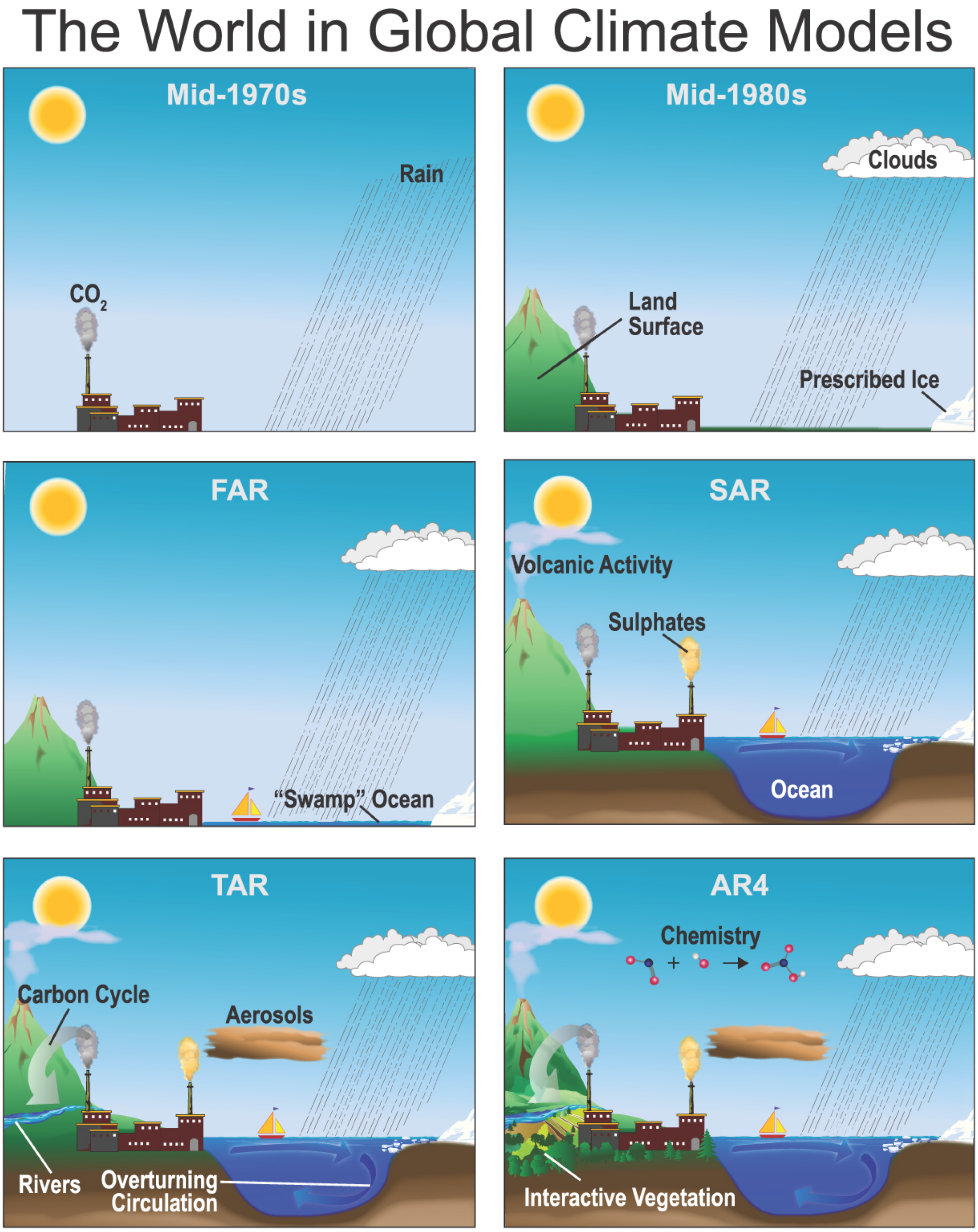

Figure 3. Level of model complexity as a function of the components represented. [Source: © Figure 1.2 in Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.]

ferent starting states are then performed to determine the robust impacts of the applied forcings.

The less numerically expensive the model, the larger the size of the ensembles that can be performed and the more confidently the results can be interpreted.

The calculation cost also determines the mesh size of the climate models. Currently, these meshes are generally close to 100 km × 100 km, although some models manage to reach a few tens of km^2. This spatial resolution makes it possible to represent many phenomena such as the succession of perturbations in the mid-latitudes, or tropical monsoons. On the other hand, these global models do not allow the representation of more local phenomena, such as cyclones and regional circulations directly linked to the topography. Thus, in a climate model with a resolution of 100 km, the topography is too smooth for the Rhône valley to be represented distinctly, and this prevents Mistral episodes from being represented in the model.

To carry out studies on finer resolution phenomena, a regional climate model can be used, as is done in weather forecasting. The finer-grid regional model will need to be constrained at the boundaries of its domain by a global climate model (Figure 4). Regional models are built on the same principles as global models (similar algorithms, same processes) and can themselves be more or less complex. Some represent only the atmospheric component, but there are also coupled regional ocean-atmosphere models. Such models make it possible to study smaller-scale phenomena, but the results depend on both the regional model and global model used to constrain at the boundary. It is therefore important to take account of this double uncertainty, for example by carrying out a set of regional simulations forced by several global models.

4. Validation of a climate model

4.1. *Input data*

When simulating with a climate model, there are two types of input data: initial state and forcings. While in weather forecasting, the initial state is a key input, in climate modelling, forcings are the most important input. The main forcings are: greenhouse gas concentrations (except water vapour, simulated by the atmospheric component), aerosol load, but also land cover, volcanic eruptions and solar energy received at the top of the atmosphere. Because the climate system is chaotic, information from the initial state is quickly lost. The initial conditions are therefore of little importance for climate simulations over several decades.

However, the memory of the climate system is longer than that of a weather prediction model, because in particular of the thermal inertia of the oceans. This property is the ground base to make forecasts on a seasonal scale. Indeed, seasonal forecast models are climate models in which the atmosphere and ocean components are initialized based on observations. They take advantage of the fact that the climate system has significant inertia in the ocean but also on land to forecast trends over the coming months. These systems are much less reliable than weather forecasting models but provide relevant information on the evolution of phenomena such as El Niño and on tropical variability in general. Such forecasting models are run over past periods as in forecast mode (ignoring the observation available after the initialisation is done), this is called hindcasting. Hindcasting over a large number of past years allows a seasonal forecasting system to be tested and is a form of model validation. However, this type of validation is limited to simulations of a few months, which is still short compared to the climatic time-scales.

The use of climate models to make forecasts at longer time horizons of a few years is a current research topic [12]. Some studies consider predictability[3] to be possible for up to one or two

[3]Predictability: Predictability measures the ability to predict with respect to the target time frames under the assumption that the initial state is well known.

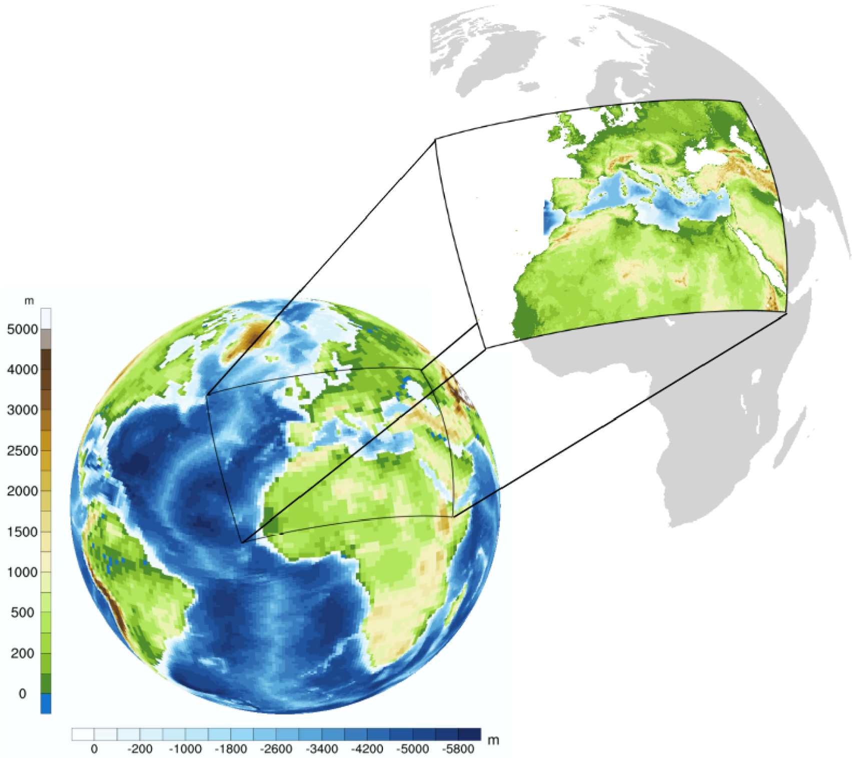

Figure 4. Orography and bathymetry of a global climate model at 100 km resolution and of a regional model over Europe at 12 km resolution. [Source: © CNRM/Realisation Pierre Nabat and Aurore Voldoire.]

years. Beyond a few years, initial conditions are of little importance and applied forcings become dominant.

4.2. *Validation*

Aside from being used in seasonal hindcasts, a climate model is validated in successive stages. Each component of the model is developed independently of the others by applying observations as input variables. Within this constrained framework, it is verified that the model produces realistic results. Thus, a land surface model will be used alone by providing meteorological observations as input variables and it will be assessed that the temperature, soil moisture and vegetation evolve in accordance with the observations.

Each component is thus adjusted and validated separately from the others. Each component is also used for studies specific to its domain. In this step, a few model parameters can be considered to be unconstrained by available observations and the range of acceptable values for these parameters will be assessed. These parameters can eventually be adjusted within this range once the complete model is assembled. During the steps constrained by observations, the simulation results can be directly compared with observations in terms of time evolution.

For the full climate system, the chaotic nature of the climate system implies that they do not follow closely the evolution of the real system. A simulation over several decades, even when forced by observed forcings, will not follow the chronology of observations due to this chaotic

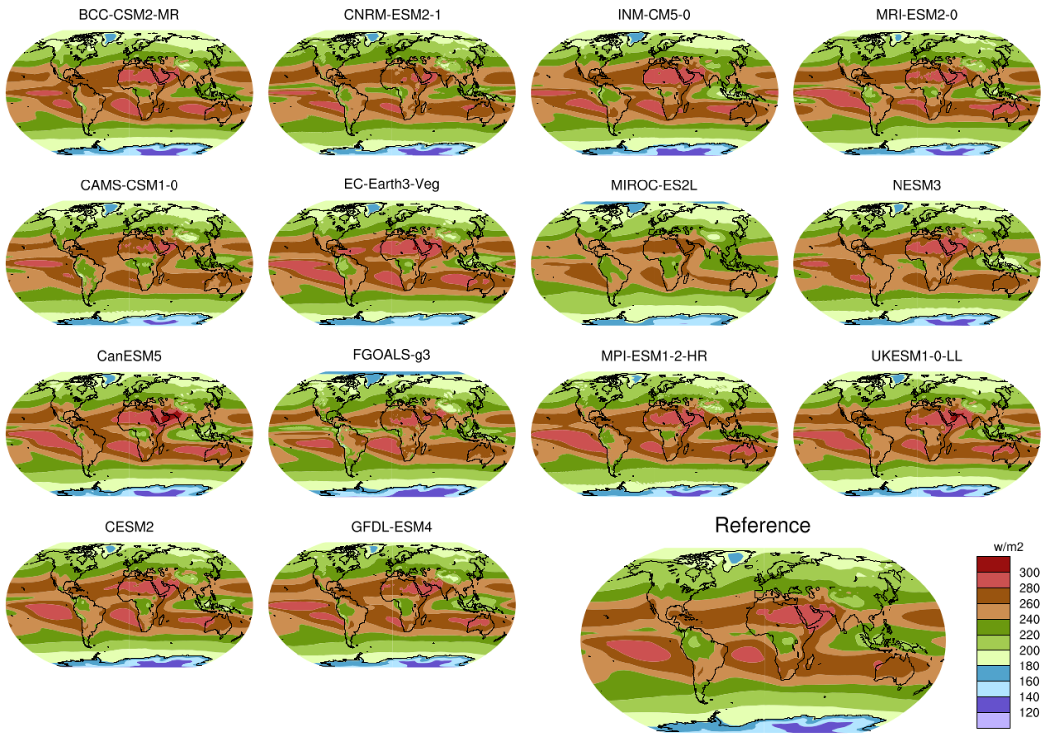

Figure 5. Map of the 30-year (1985–2014) averaged top of the atmosphere outgoing long-wave radiation simulated by a set of models in the CMIP6 database for the "historical" simulation. The map in the lower right-hand corner represents the reference estimate over the same period obtained from satellite measurements (CDR monthly product "Outgoing Longwave Radiation"). [Source: © CNRM/Aurore Voldoire production.]

nature (and model imperfections). Even if the model were perfect, it would not be able to follow the sequence of weather events as they occur. It will therefore not be possible to compare the evolution of the temperature over a country directly with observations. On the other hand, the model will be able to represent the climatological characteristics of the climate (Figure 5) [13]: the seasonal cycles of temperature and precipitation averaged over 30 years can be compared with the (average) climatology of the observations. Similarly, long-term trends can be compared with those of the observations. For example, the models show the reduction in spring snow cover at mid-latitudes during the 20th century [14].

Validation is not only possible on the long-term climate characteristics. It will also assess the model's ability to adequately represent the daily variability of precipitation, i.e. its ability to represent the number of dry days and very wet days in a given season at a given location around the globe. The model's ability to represent extreme events, such as storms, can also be assessed.

The validation step determines the limits of these models. For example, they are often able to represent the distribution of different types of clouds around the globe, but for the most part, they currently fail to adequately represent the thin stratocumulus-type clouds on the eastern edges of the tropical oceans, such as off Chile, California or Angola [15]. When simulations of future climate are analysed, these shortcomings will have to be taken into account as a limitation of model reliability in these regions. The validation step also indicates the processes that need to be improved in models to make them more reliable.

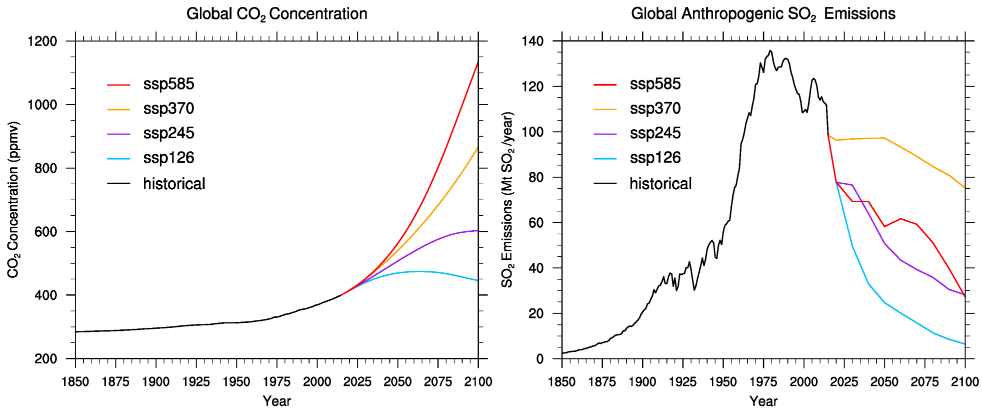

Figure 6. Evolution of (a) CO_2 concentration and (b) sulphate aerosol emissions, observed (black line) and according to the 4 main scenarios (colored lines) for the 21st century considered in AR5. [Source: © CNRM / Réalisation Pierre Nabat.]

Climate models produce information on all time scales (Figure 1), from the diurnal cycle to trends at the century scale. They are therefore evaluated on their ability to represent many processes at all these temporal and spatial scales. Our confidence in these models emerges from the physical consistency of all the processes represented. Downstream of the modelling activity, the work of climate researchers also consists of processing large masses of data produced by models using appropriate statistical methods.

5. Climate projections

To make climate projections, modellers must prescribe the evolution of forcings over the coming century, as input data for climate models.

For solar radiation and volcanoes, it is difficult to predict their level of future activity. So simple assumptions are made: for solar radiation, the last observed 11-year cycle is reproduced periodically over the next century[4], for volcanoes, only their average effect is considered in general for the future without variations (but more specific studies are carried out to address this issue).

For the other forcings, namely greenhouse gases, aerosols and land use, their evolution is highly dependent on the evolution of human activities, and are referred to as anthropogenic forcings. Economists provide different scenarios (Figure 6) of how these forcings will change based on demographic and economic assumptions. For this purpose, they use specific models known as "integrated impact models [16]".

Several types of evolution are envisaged, depending on whether or not the population becomes aware of the risk and adapts its practices, depending on demographic changes and whether or not regions are turning in on themselves. As the economic projections remain uncertain, economists produce several types of scenarios for changes in greenhouse gas concentrations. Climate models are then integrated over the 21st century by varying forcings under these economic scenarios. The initial conditions are derived from simulations of the 20th century and intrinsically incorporate the effect of the forcings over past periods.

[4]Cyclicity simulated from reconstructions over 9400 years for CMIP6 (Matthes *et al.*, 2017), available at https://solarisheppa.geomar.de/cmip6.

Depending on the level of complexity of the model, the type of forcing is adapted. For example, for models that do not represent the carbon cycle, carbone dioxide concentrations will be prescribed to the model. Conversely, if the model represents the carbon cycle, the model will apply anthropogenic carbon emission forcings, with natural emissions being dynamically represented in the model. Similarly, for models that do not include a life-cycle representation of aerosols, concentrations of these particles, which are themselves derived from specific models forced by the chosen economic scenario, will be prescribed.

6. IPCC and model intercomparison exercises

The Intergovernmental Panel on Climate Change (IPCC) regularly produces reports that aim to summarize the state of scientific knowledge on climate, its evolution, impacts and ways to adapt to projected changes. In order to coordinate the work of the various teams implementing climate models around the world, a model intercomparison exercise (Coupled Model Intercomparison Project—CMIP) is carried out upstream of the IPCC reports. The aim of these exercises is to propose common experimental protocols to the modelling centres that will make it possible to study climate change and characterise the uncertainty associated with climate modelling in a rigorous manner.

The CMIP project also provides modelling centres with storage space and tools to share the data produced by the models. These databases are public[5] and can be used by researchers around the world to conduct climate change studies. For the last IPCC report published in 2021, 31 teams have published data from 64 different models[6]. Many centres operate several versions of their models by modifying the complexity of the model and/or its spatial resolution.

For the last CMIP exercise (6th phase), 4 scenarios of changes in greenhouse gases and main aerosols were used to force the models (Figure 6). The lowest scenario, called ssp126, plans very limited concentrations which requires a reduction in emissions from the middle of the century and negative emissions from 2080 onwards. On the opposite, the highest scenario, called ssp585, projects an increase in emissions at the current rate which forecasts carbone dioxide concentrations of 1135 ppm in 2100. In between these two extremes, the ssp245 scenario represents an intermediate future where societies partially adapt, and the ssp370 scenario, also plans an intermediate future but with a higher concentration in carbone dioxide and a lower reduction in aerosol emissions.

By comparing the projections of all models under a given scenario, modelling uncertainty (distinct from scenario uncertainty) can be assessed. This is about 2 °C for ssp370 scenario, which projects a global mean temperature change of 4 °C as a multi-model average compared to preindustrial levels (Figure 7a). It is well understood that the total uncertainty in climate projections results both from uncertainty in the future of demographics and the economy (scenario) and from uncertainty in the climate models themselves. The level and source of uncertainty depends on the climate variable considered. For instance, for September sea ice extent (Figure 7b), the uncertainty is dominated by the model uncertainty whereas for the ocean acidity (Figure 7c), the scenario is the main source of uncertainty.

In order to better compare the models with each other, climate modellers have defined a more theoretical metric, called climate sensitivity, which corresponds to the increase in surface temperature after a doubling of carbone dioxide concentration compared to the pre-industrial era. This is the change in temperature at equilibrium, which implies that the model must be integrated long enough for the global surface temperature to stabilize. This theoretical quantity

[5] Earth System Grid Federation.
[6] As of 22/01/2024.

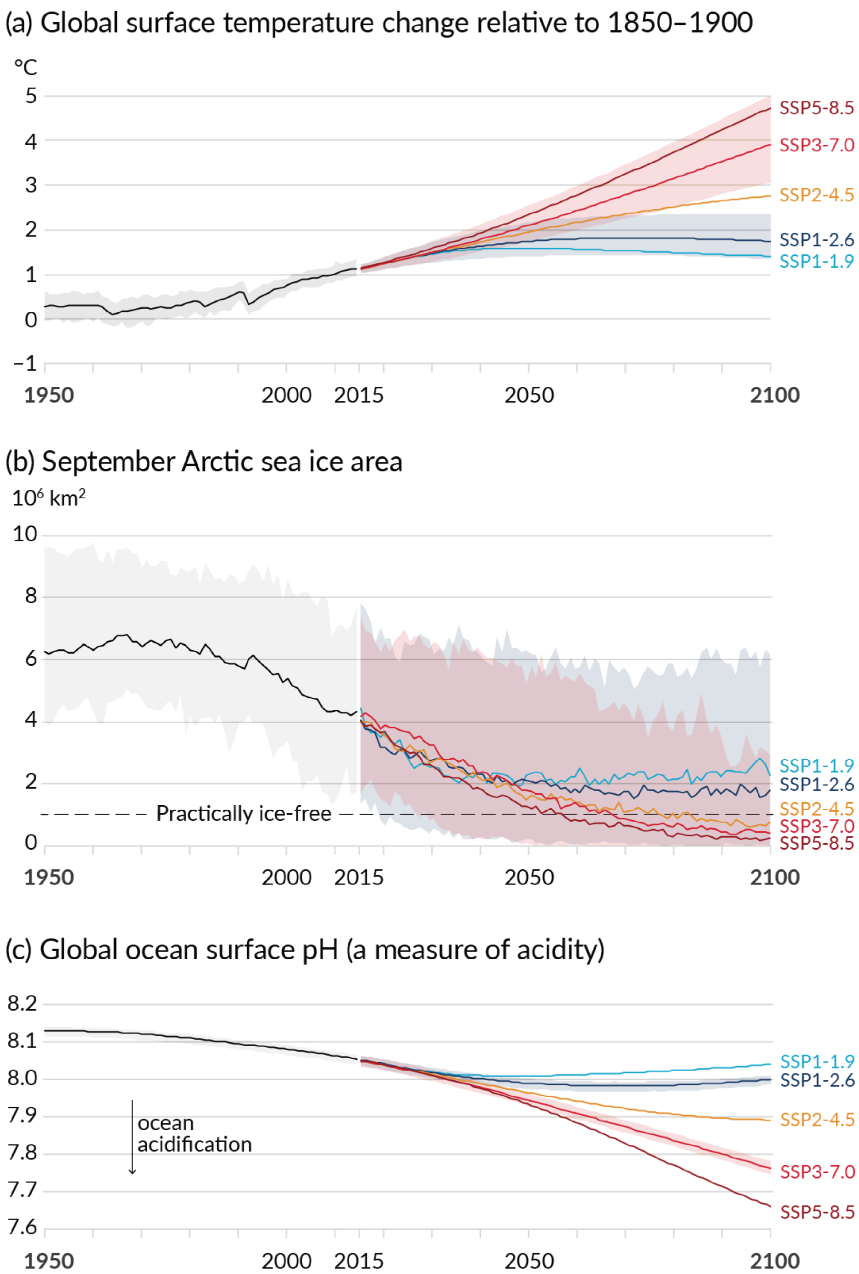

Figure 7. Scenarios of (a) global average temperature change (in °C), (b) September sea ice extent and (c) global ocean surface pH based on the 5 greenhouse gas concentration trajectories. The zero reference is the average over the end of the 19th century (1850–1900). The color shading indicates the likely range for ssp370 and ssp126 scenarios. [Source: Figure SPM.8 in IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–32, https://doi.org./10.1017/9781009157896.001.]

allows us to compare the magnitude of the feedbacks that appear in the climate system following an increase in carbone dioxide concentration. Indeed, the first impact of carbone dioxide is to warm the air locally, but this warming has multiple consequences, called feedbacks. For example, if the air warms up, the Clausius–Clapeyron relationship indicates that it will be able to hold more water vapour. This can have impacts on cloud formation, cloud positioning, etc. It is the relative importance of these different feedbacks that is uncertain and the study of several models allows to better understand them.

For the last intercomparison (CMIP6), the uncertainty between models has rather increased [17]; and the CMIP6 models ensemble has a wider range of climate sensitivity than the CMIP5 models ensemble. The higher CMIP6 climate sensitivity values compared to CMIP5 can be traced to an amplifying cloud feedback that is larger in CMIP6 by about 20%. The reasons for this increase in sensitivity in several models are the subject of intense research. Several studies also attempt to use recent observations to constrain sensitivity estimates. It is indeed crucial to determine whether such strong values are plausible.

Climate models are thus laboratory tools to better understand processes within the climate system and to advance knowledge. However, it should not be forgotten that these models are imperfect. It is necessary to compare them with observations in order to understand their limitations and continuously improve them.

7. Conclusion

As recently highlighted by the Nobel Prize Academy, climate models are physically based on the well-known system of equations of Navier–Stokes. They are a numerical representation of the climate system and have grown in complexity over the last 50 years. Now, varying complexity climate models exist and the level of complexity for each specific study is chosen according to its scientific objective. Indeed, climate models are used to make projections of the future climate under a scenario of economic and demographic evolution. But they are also a very valuable laboratory tool for advancing our understanding of the climate system.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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