Climate Press

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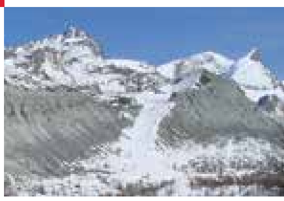

How accurate are climate models?

Climate models are important to understand the processes in the climate system, to determine the reasons for observed changes and to estimate future developments. It is therefore reasonable to ask how accurately such models can reflect reality.
Climate models are mathematical-physical depictions of the climate system. They describe the atmosphere, oceans, land surfaces and ice coverage. Like any scientific model or theory, they do not depict reality precisely but contribute to understanding and, to a limited extent, predicting processes. Climate models are able to depict quite well single aspects like the long-term development of global temperature and certain precipitation changes. On the other hand, it is difficult to correctly model the entire water cycle or changes in atmospheric circulation patterns. Correct interpretation of model results requires knowing the strengths and weaknesses of models. Verification of model results by means of measurements is difficult since measurements, too, often contain errors or are simply not readily available, in particular for the past. Whereas model results are rather reliable for future developments on the global and continental scales, there are large uncertainties on the regional scale. In recent years, enormous progress has been made with regard to identifying uncertainties. In contrast, climate models are still weak in the way they represent changes in atmospheric circulation patterns which are crucial with regard to regional climate changes. Thus, there is great potential for improvement in this area.

Climate models play an important role in the discussion of anthropogenic climate change and with regard to mitigation and adaptation measures. They are the only way to estimate what the global climate may be like in thirty, fifty or a hundred years from now. But how dependable are climate models? Is it possible to verify model results by means of measurements? Why is it possible for climate models to make predictions for a period of a hundred years whereas it is not possible to predict the weather for the next two weeks? Some important explanations for understanding climate models are compiled in the following sections.

Climate models: physics and mathematics in grids

There are a wide variety of climate models that basically differ in terms of their complexity, the number of processes considered and the accuracy of these processes. Simple models are predominantly used to analyse certain processes in a climate system. Below, the more complex models, the so-called Atmosphere-Ocean General

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Different types of climate models

Atmosphere-Ocean Global Circulation Models (AOGCMs)
The models on which climate projections are based are Atmosphere-Ocean Global Circulation Models (AOGCMs). They combine a meteorological model for the atmosphere, an ocean model, a snow and ice model and a vegetation model. In these models, many processes and influencing factors are considered directly or described approximately. The horizontal distances between grid points are between about a hundred and several hundred kilometres. Well-known models of this type are, for instance, ECHAM5 (Max-Planck-Institut, Hamburg), HadGEM1 (Hadley Centre, UK), GISS-E (NASA, US) or CESM (Community Earth System Model; NCAR, US).

Regional Climate Models (RCMs)
Regional Climate Models calculate the climate for a certain region (e.g. a continent) according to the same principle as AOGCMs, but with a much higher grid resolution (some ten kilometres). Thus, certain processes can be represented more accurately, and better account can be taken of the influence of the topography, in particular of mountains. The conditions at the borders of the region are taken from an AOGCM. Many aspects of regional climate models are rather strongly influenced by the global model.

Earth System Models of medium complexity (EMICs)
The so-called EMICs are climate models that generally describe the dynamical processes in the atmosphere and in the oceans in a slightly simpler way than AOGCMs. On the other hand, EMICs often consider more components and influencing factors, such as the carbon cycle. EMICs show great differences with regard to capturing processes and including influences and are often tailored to the study of certain problems, e.g. the simulation of ice age cycles.

Simple climate models
Simple climate models describe the processes in the atmosphere and in the oceans very roughly only and are used to simulate certain characteristics of the global climate system or specific processes. An example for this is the estimate of the global mean temperature as a result of the change in greenhouse gas concentration. Instead of a grid, the most important processes are represented by boxes only, e.g. two boxes for the Atlantic and the Pacific and one box for the atmosphere.

Circulation Models (AOGCMs), will be described in more detail because their results form the basis for estimating future climate development and for analysing the impacts of climate change.

A climate model – similar to a weather model – describes the atmosphere or the earth system by means of mathematical equations. The basic equations of physics reflect the fact that the respective totals of energy, mass and impulse are constant within a system. This is also true for water: water can only move, freeze or evaporate, it cannot disappear – the total amount of water is constant. In a climate model, a grid is superimposed over atmosphere and oceans, with horizontal distances of usually more than a hundred kilometres and vertical distances between a few hundred metres from the ground and several kilometres in the upper atmosphere (see Figure 1). The model calculates the values for all variables considered (wind speed, wind direction, temperature, humidity, radiation, evaporation, etc.) for all grid points. In a climate simulation, the model calculates the changes of the variables mentioned for all grid points for a given time step, based on the initial state. Accordingly, numerous processes are taken into consideration when calculating the change in temperature at a certain grid point, such as the temperature of the air at neighbouring grid points that is transported by the wind, or the radiation from the sun or from the ground. In addition, after every time step, all laws of physics need to be obeyed. Accordingly, after every time step, a set of numerous equations need to be solved simultaneously. The calculation is performed using complex mathematical methods. After that the variables are calculated in the same way for the next time step and so forth.

These calculations are challenging, firstly because of the impact of small-scale processes occurring between the grid points, such as cloud formation and dissipation, or eddies of turbulent air; secondly, because of the processes on the earth surface, such as the air current slowing down near the ground or evapotranspiration of plants and the soil. Since it is impossible to model these processes directly due to their complexity, they are taken into consideration in the form of statistical

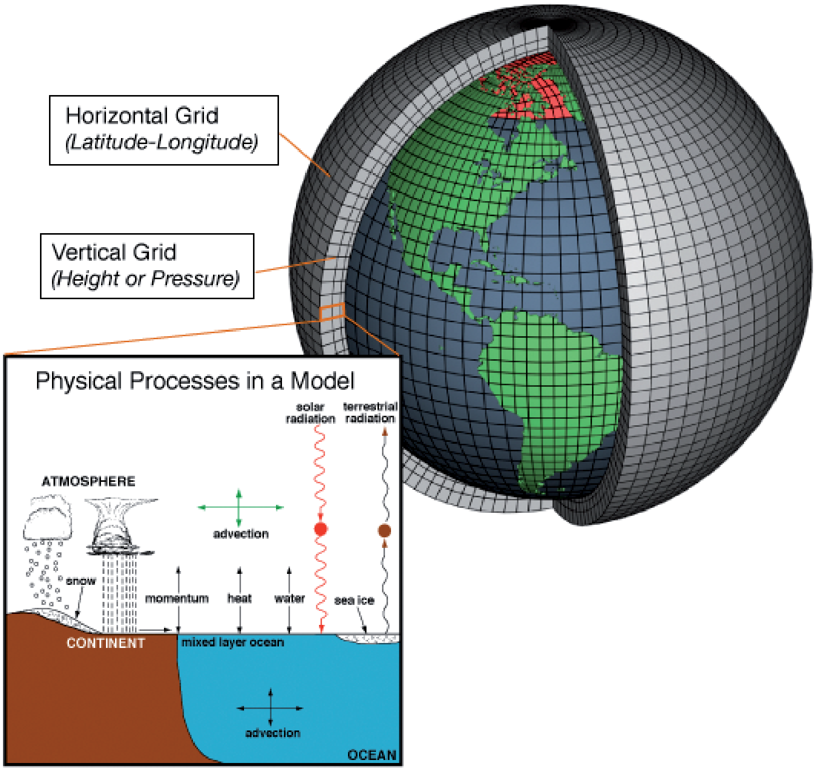

Figure 1: Principles of a climate model
Quelle: NOAA

relationships and simulated mean values. The relationships are often based on measurements. Thus, there is, for instance, a statistical relationship between evaporation on the ground on the one hand, and the mean values of radiation, temperature and wind speed at the grid points above on the other hand. Since the latter are calculated by the model, evaporation can be estimated and taken into consideration in the model.

Why are there climate predictions for 50 years, but weather forecasts for 5 days only?

Climate models are not fundamentally different from weather models; both of them are controlled by the laws of physics. Why, then, is it possible to "see" the future in 50 or 100 years with a climate model, whereas the weather can be forecast for a small number of days only? This is because climate models and weather forecasts answer completely different questions. The central question of a weather forecast is the exact situation on a particular day, e.g. on 2 December 2011. For a climate simulation, however, 2 December 2091 is not relevant; we would rather like to know how the long-term average of temperature and precipitation will have changed in the decade from 2090 to 2099 if the concentration of CO2 in the atmosphere has doubled by then in comparison to pre-industrial levels. In short, climate predictions are concerned with long-term mean values, weather forecasts deal with the current state of the local atmosphere. The influencing factors are very different: The mean long-term global climate mainly depends on the fluxes of energy into and out of the atmosphere. In contrast, the local current weather is the result of the distribution of energy within the atmosphere. Irradiation – the inflow of energy – primarily depends on solar radiation and reflection of radiation by clouds, airborne particles and the ground. Emission, that is the outflow of energy, is determined by the characteristics of the ground, the clouds and the composition of the atmosphere, in particular greenhouse gas concentration. If inflow and outflow are not the same, the energy content of the atmosphere changes until a new balance is established. Inflow and outflow change very slowly, often over decades. In addition, there are components in the earth system, such as the oceans, that react very slowly and delay the adjustment of climate variables. From these slow changes the long-term global mean temperatures can be calculated.

In contrast, the short-term regional distribution of warm and cold air masses, of clouds, precipitation and airflows are largely chaotic and can therefore be calculated for a few days only. The fluctuations at a certain location over a period of some days are much larger and much faster than the long-term trends.

By way of comparison: In a pot with boiling water the chaotic distribution of the rising bubbles corresponds to the weather. The temperature of the hot plate represents the energy supply. There is no way for us to predict the "weather", that is we cannot tell when and where the next bubble will rise and how big it is. However, if we reduce the temperature of the hot plate, that is if we change the external influence, we can predict with certainty that the "climate" will change inasmuch as, on average, fewer and smaller bubbles will rise. If we increase the temperature, the bubbles will become bigger and more numerous. By observing the mean bubble size when we change the temperature of the hot plate, we can describe the findings in a model which predicts the typical bubble size (the climate) as a result of the hot plate temperature without knowing the exact position of the individual bubbles (the weather).

Is climate change built into the models?

It is sometimes claimed that climate models are constructed in such a way that global warming will be the inevitable result. This does not hold true. As a basic principle, climate models obey the laws of physics and depict observed processes. In addition, external influences, such as solar irradiation and greenhouse gas concentration, are specified. In former climate models, certain processes had to be corrected (the so-called flux corrections) because they gradually resulted in unrealistic developments. In most of today's models, such corrections are not necessary any more. Model adjustments in order to obtain results that agree to the greatest possible extent with measurements are primarily made for single processes. However, it is hardly possible to selectively modify the model to arrive at a specific climate projection. The most important results that can be drawn from the model can also be observed in reality; they are based on known physical processes: They include the global warming of the atmosphere, constant relative humidity, the increase in water vapour in the atmosphere, the spatial and temporal concentration of precipitation, the uptake of warmth by the oceans, the retreat of the arctic ice caps or the rise of sea levels.

How can climate models be validated?

Climate models are a combination of various highly complex processes. Some of these processes – the radiation properties of gases, for instance – can be simulated and measured in the laboratory. However, any change of the greenhouse effect cannot be simulated in the laboratory. The atmospheric greenhouse effect is much more complex in reality than is suggested by the strongly simplified picture of the greenhouse. The greenhouse effect refers to a constant uptake and release of radiation by gas molecules in air layers, which become colder and thinner with increasing altitude. Such conditions can hardly be reproduced in the laboratory and cannot be measured in detail in the real atmosphere by means of radiation meters. Thus, calculating the greenhouse effect already requires complicated mathematical-physical modelling. This is, however, only one of many processes. At least it is possible to compare the results of climate models for instance, the global mean temperature with reality if we apply the models to the past. This can only be done, though, if we have sufficiently reliable measurements for the past. The problem is that measurements are increasingly unreliable and scarce, the further back we look into the past. At the same time, measurement methods and instruments have changed over time. This is why we often do not know whether changes in measured climatic values reflect real processes in the atmosphere, or are attributable to changes in measurement methods or data analysis problems (or both). If measured values do not agree with those of climate models, it is therefore not clear whether it is the model or the measurement that is wrong. Yet there are also natural fluctuations that allow the quality of climate models to be checked. The volcanic eruption of Mount Pinatubo in June 1991 caused a global cooling of about 0.4 °C. Climate models were able to predict this cooling correctly shortly after the eruption.

Is it possible for models to be more accurate than measurements?

Measured values of global earth surface temperatures appear to be reasonably reliable since the mid-19th century. While individual local measurements may be defective, these errors tend to cancel each other out with global averaging. In addition, for any measurement station, the deviation from the mean temperature is used rather than the measured absolute value so that systematic (constant) errors, for instance due to incorrect instrument setting or environmental conditions, are hardly relevant. Since temperatures are similar over relatively large distances, gross errors can be eliminated by making comparisons with neighbouring stations. It also appears that the urban heat island effect, for instance, is of minor importance because the values for global warming do not change substantially if only rural stations are used for the

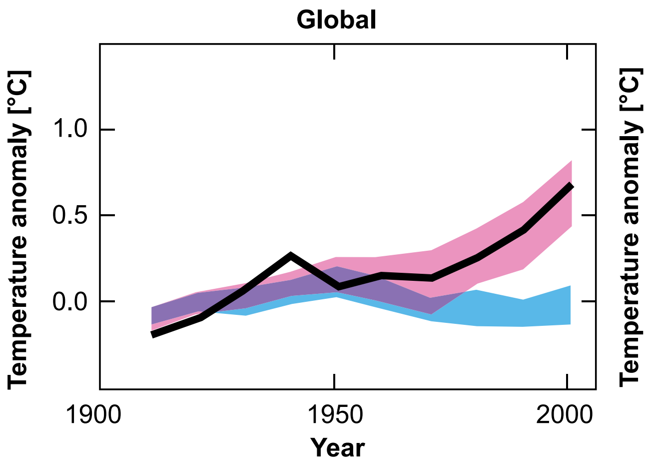

Figure 2:
Course of the global earth surface temperature in the 20th century, calculated by models (red bar) and measured (black line). The blue bar shows model calculations without considering the influence of greenhouse gas concentrations.
(Source: IPCC AR4 WGI)

calculation. The global mean temperature therefore seems to be useful to check the quality of climate models. Figure 2 shows a comparison of different model results (displayed as a red bar, which includes the range of the different model calculations) with the measured temperature (black line); the model results without human influence are shown in blue. The red bar (including human influence) and the black line agree quite well, with one exception in the 1940s. The reason for this discrepancy was not clear for a long time. It turned out that the measurement technique for ocean temperatures, often carried out from ships, changed considerably during and after the Second World War. Recently, a study[1] has been published that aims to eliminate these inconsistencies. The resulting correction of the global mean temperature reduces the differences between measurements and model results, but does not bring about a full agreement. However, this example demonstrates that discrepancies between model results and measurements are not necessarily due to deficiencies in the model. This applies even more to temperatures in the lower atmosphere that are calculated from satellite data. For years, large differences between the trends of satellite temperature data and climate model results were observed. The satellite data showed a much less marked warming. A few years ago, it turned out that the programme for calculating the satellite data contained a simple calculation error, namely a sign error. After this had been corrected, the difference between satellite data and model calculations virtually disappeared. In recent years, discrepancies between measurements and model results have often turned out to be due to errors in the measurements rather than in the models – even for temperature measurements, which are relatively easy to take. For many other measured variables, such as precipitation, which is spatially much more heterogeneous, or relative humidity, for which the measurements for the past are much less reliable, it is even more difficult to check the models using measurements.

Coincidence complicates comparisons

While the global climate depends on external influences, it exhibits many accidental fluctuations as well, not only over days, but also over years and, for some aspects, even over centuries. This fact further complicates climate modelling. If there were many identical worlds the atmosphere of which would show only very small differences at the outset, the resulting climate developments would be very different – within a range given by external influences. The climate development observed on our planet is therefore one specific variant of many possible ones. Therefore, the result of a climate model may correspond to one of the many possible variants, but not exactly to the variant of our planet. This is why many model runs are carried out with the same model, if possible, and then the results are averaged. For the same reason, it makes sense only to use long-term mean values of the models, namely for periods of 20 or 30 years, and not the values of single years or decades. It has also become clear that the mean value of different models is often closer to reality than the mean value of a single model.

Comparison between models

One possibility to identify the uncertainties of models is to compare models. The individual models are programmed differently and do not always comprise the same processes or integrate them in the same way. Differences and agreements between models therefore provide indications on uncertainties with regard to various aspects. However, all models are based on more or less the same knowledge and processes. It is therefore theoretically possible that there are important unknown processes that are neglected in all models. This is unlikely, though, because the existing models, in that they include the known processes, reflect the observed reality correctly – at least along general lines – as far as this is verifiable. If there was some hitherto unknown process with a major impact on model results, integrating it into the model would cause a considerable deviation from reality. Alternatively, there might be another unknown process which – by chance – would compensate for that deviation, which is highly unlikely.

Which information is provided by climate models, and which is not?

Today, climate models are far from being perfect. Many processes are described very rudimentarily only. Furthermore, today's models represent various processes incorrectly, such as the El Niño phenomenon or the distribution of sea surface temperatures in the tropics. The simulation of cloud formation and its change has been the biggest problem in climate modelling for years and is still largely unsolved. Nevertheless, the models are able to describe, at least roughly, past long-term and large-scale climate changes as far as they are known. Climate models also predicted rather well the global cooling that was caused by the volcanic eruption of Mount Pinatubo. Thus, models appear to be able to represent fairly well the effects of changes in the radiation budget under today's conditions. Whether or not this is also possible for the future is not clear because the fluctuations of the past, which can be determined reasonably precisely by means of measurements and reconstructions, are much smaller than what we expect in the future. The question is whether models are still reliable when greenhouse gas concentrations are much higher, when the arctic sea ice and the glaciers have disappeared, when the large ice sheets have retreated and vegetation has changed. These are processes and conditions for which we can find parallels in the distant past, but for these time periods we have too few data and little sound knowledge. Furthermore, changes happen much faster today than they did then, that is within a 100 years instead of tens of thousands or even millions of years.

"Climate models are wrong, but useful"

Climate models can provide important and useful insights and results for some aspects whereas for others they cannot. Climate researchers sometimes express it in this way: "Climate models are wrong, but useful." That is to say, climate models will never be able to reflect the entire reality just like any scientific model or theory. The results of a climate model run will therefore always be "wrong", but they can still provide important insights and help to understand and simulate certain aspects and processes. A weather forecast model is also "wrong" in this sense, because it neglects many processes, but it is sufficiently "correct" to forecast the weather for the next three days. For correct interpretation of model results it is very important to know the limits of climate models.

In spite of the many uncertainties, a lot of useful information can be obtained from the models. As pointed out above, the results for the long-term development of the global and presumably also of the continental mean temperatures are relatively good. About half of the continuing uncertainty range is due to knowledge gaps with regard to the development of cloud cover and with regard to changes in the carbon cycle (change in $CO2$ uptake or emission by plants and oceans), the other half is attributable to the unknown development of greenhouse gas emissions.

Although today's models still have difficulties in representing the water cycle correctly, they can provide some reliable results for processes that concern precipitation in general. Most models show that precipitation will increase in areas where it already rains a lot now, which is physically plausible. This means that there will be more and more intensive rain in today's high-precipitation areas. On the other hand, today's dry areas will become even drier. It also seems clear that the subtropics will extend to the north. Consequently, areas like the Mediterranean that are located at the pole-side border of the subtropics will increasingly have to expect a subtropical climate, and will dry up strongly in summer and autumn (see Figure 3).

Models are indeed deficient when it comes to simulating atmospheric flows and atmospheric circulation. Changes in atmospheric circulation due to seasonal phenomena, such as El Niño, or short-term patterns are represented by models inadequately and simulated very differently, depending on the model. However, it is especially these changes in circulation patterns that are crucial with regard to the regional consequences of global warming. Furthermore, these regional changes are most relevant for human beings and for taking adaptation measures. There is still much room for improvement here.

How can climate models be further improved?

Climate models are being improved with regard to various aspects. One of them is spatial resolution, that is the distance between grid points. The smaller the distance, the better small-scale processes can be understood. Resolution directly depends on the calculating capacity of the computer. It has to be chosen in such a way as to make possible calculations over several hundred years within a reasonable time (that is within weeks). At best, improvements of the calculation methods can reduce the computing time and thus enable a better resolution. A distinctly improved resolution, that is grid point distances of only a few kilometres, means that important processes can be integrated into the model and need not be estimated indirectly by means of relationship calculations.

Today, regional climate models can partly solve the problem of spatial resolution. Regional climate models simulate the atmosphere of a region only, for instance Europe, with much smaller grid point distances. At the borders of the region, they adopt the values of global climate models and calculate the values within the region on the basis of a more closely meshed grid. Thereby, they offer a higher resolution. However, this does not solve the problem of large-scale changes of the atmospheric currents or of El Niño since such changes would be adopted from the global models. It has turned out that the results of a regional model in many ways still largely depend on the characteristics of the global model, which provides the basic data. It remains to be seen whether the problem of circulation changes can be understood more clearly after achieving a higher resolution and/or other improvements of the global models.

The simulation of single processes offers another possibility for improvement, especially in the case of processes that can be described only indirectly by way of observed correlations with known variables. There is constant improvement here; in view of the overall picture, however, the steps forward are relatively small.

Conclusion

Climate models describe the real, large-scale processes in the atmosphere and in the oceans and provide quantitative estimates as to how the climate will change if the composition of the atmosphere changes, in particular regarding the amount of greenhouse gases and solid particles. Although major trends can be estimated for the regional level, there are considerable uncertainties, particularly concerning variables that are influenced by the water cycle. Nevertheless, some developments are obvious, such as the increase in precipitation in the higher latitudes and in the tropics or the drying of the Mediterranean. Even if there is still much room for improvement of the models, it will never be possible to precisely predict future conditions on the local level. This is due to the complexity of the climate system, the unknown development of greenhouse gas emissions and the little measure of coincidence that overlies all processes. Thus, decisions have to be taken in some uncertainty, as it is the case with all questions concerning the future. Thanks to knowledge of the laws of physics and of many processes in the climate system, models can objectively support decision-making. Eventually, society and politics have to decide on how to deal with the potential developments shown by model calculations.

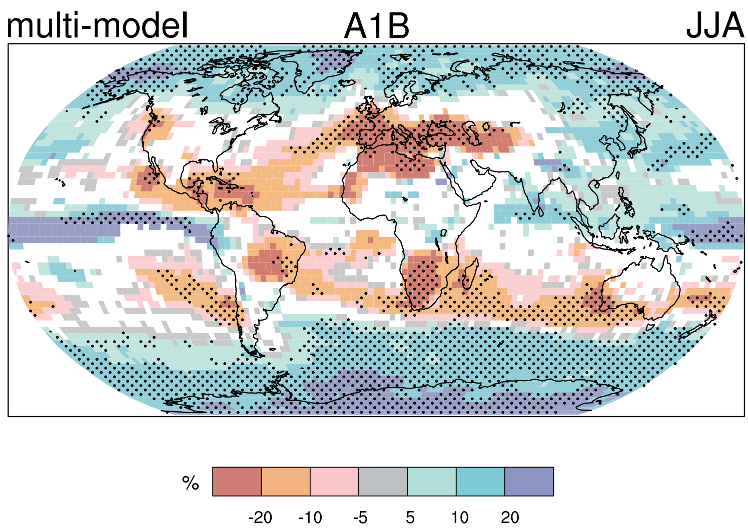

Figure 3:
Model projections for precipitation change by the end of the 21st century in comparison to the end of the 20th century.
(Source: IPCC AR4 WGI)

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Citation:
[1] Kennedy J.J. et al., 2011. Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2. Biases and homogenization. Journal of Geophysical Research, Vol. 116: D14104 (download: www.metoffice.gov.uk/hadobs/hadsst3/part_2_figinline.pdf).

Further reading:
Knutti R., 2008. Should we believe model predictions of future climate change? Triennial Issue Earth Science of Philosophical Transactions of the Royal Society A, 366, 4647–4664 (download: www.iac.ethz.ch/people/knuttir/papers/knutti08ptrs.pdf).