The climate scientists' crystal ball

Credible predictions of future climate depend on climate models that simulate past and present climate convincingly.

Photo: EUMETSAT, Meteosat-8.

By Bo Christiansen

■ Weather and climate are two sides of the same coin, since climate can be defined as the average weather over a long time scale. To describe the weather at a given point in the atmosphere is quite simple – it only requires knowledge of temperature, pressure, humidity and wind direction. However, it is considerably harder to *predict* the weather. Despite the fact that great efforts have been made, throughout history, to make accurate weather forecasts and that today we have numerous data from monitoring stations, and enormous processing power at our disposal, it is still not possible to make reliable weather forecasts that reach more than a week into the future.

To predict the development of the climate does not differ fundamentally from the daily work with weather forecasts. When you talk about predicting future climate it is obviously not the weather at any particular time in the future, we are interested in predicting, but rather the statistical parameters of average weather conditions and variations around this average. Regardless of whether you want to predict the weather in the coming days or the climate 100 years from now the central requirement is knowledge of the circulation in the atmosphere and ocean. This knowledge is converted into models that simulate this circulation. Thus, climate models become very important to the interpretation of future climate development and thereby also constitute the technical basis for the political climate debate. In short, it is vital that these climate models are as good as possible and work to improve the models is an ongoing process.

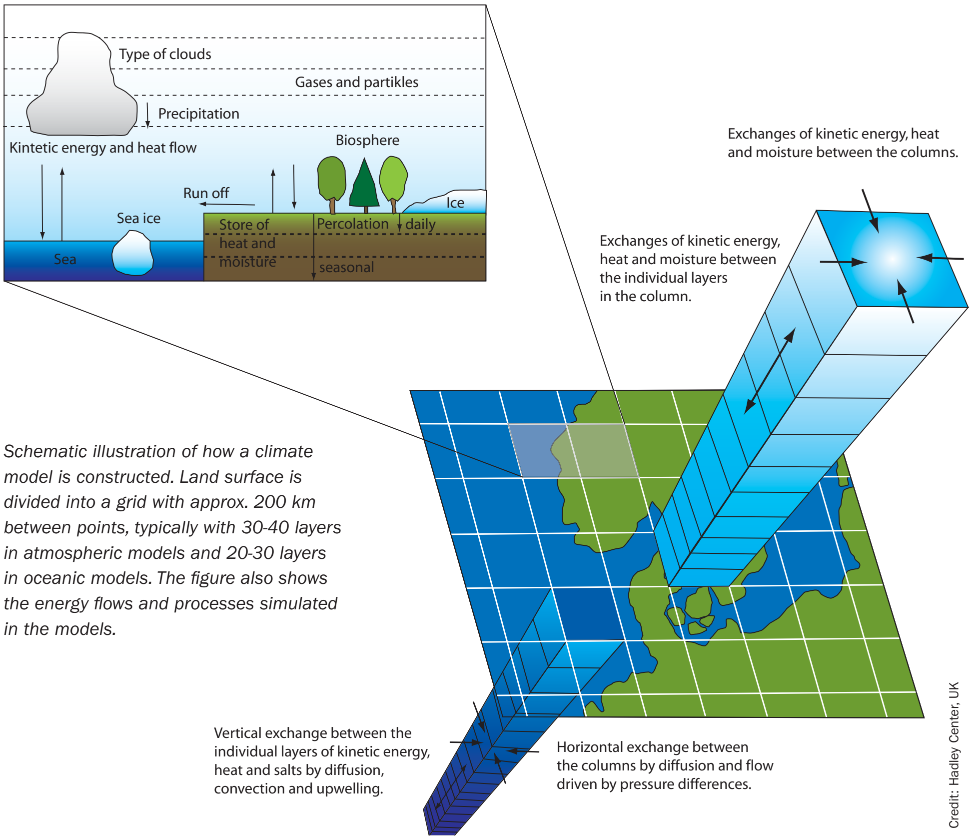
Climate models

The laws of physics are the foundation of any climate model and give a mathematical description of the climate system's individual components (that is, atmosphere, oceans, biosphere, ice and snow, and the earth).

Models serve two purposes. On the one hand, researchers try to reduce the complex behavior of the climate to a set of mathematical equations in the hope of getting an insight into how climatic processes work. In this sense, working with climate models has a purely cognitive dimension - in particular in the case of the relatively simple models. On the other hand, when dealing with more complex climate models (also called general circulation models), the purpose is instead to simulate the entire climate system (that is incoming and outgoing radiation, air movement, cloud formation and precipitation, growth of ice sheets and melting etc.) even if things become so complicated that it is not always fully understood what is going on. The equations are adjusted (within reasonable limitations) so that the model reproduces as well as possible past and present climate as we know it from actual observation. Then the model can be used to predict how climate will evolve in the future.

A fundamental problem when researchers try to assess the quality of a climate model is that they cannot, as is the case with weather forecasting models, systematically compare the predictions they produce with real life observations. Climate models are instead tested by examining how well they can describe the current climate and climate variability throughout the 20th century. Today, the best models are able to reproduce the development of global temperature over the last 100 years. In addition, they are able to simulate

Climate Models and the laws of physics



Schematic illustration of how a climate model is constructed. Land surface is divided into a grid with approx. 200 km between points, typically with 30-40 layers in atmospheric models and 20-30 layers in oceanic models. The figure also shows the energy flows and processes simulated in the models.

Credit: Hadley Center, UK

For a climate scientist, the atmosphere is essentially a system determined by the laws of physics and these laws can be expressed quantitatively by mathematical equations.

If we know today's atmospheric conditions, we can use these equations to calculate its state in the future. Because of the inherently chaotic nature of the climate system and the equations that describe it, the calculations will become increasingly inaccurate the farther we try to look into the future. While this is a significant problem for weather forecasts, the problem is less important to climate researchers who are more interested in the average weather over a longer period than in the weather on a particular day. This average, which we call the *climate*, is essentially determined by boundary conditions such as the CO_2 content in the atmosphere and solar radiation.

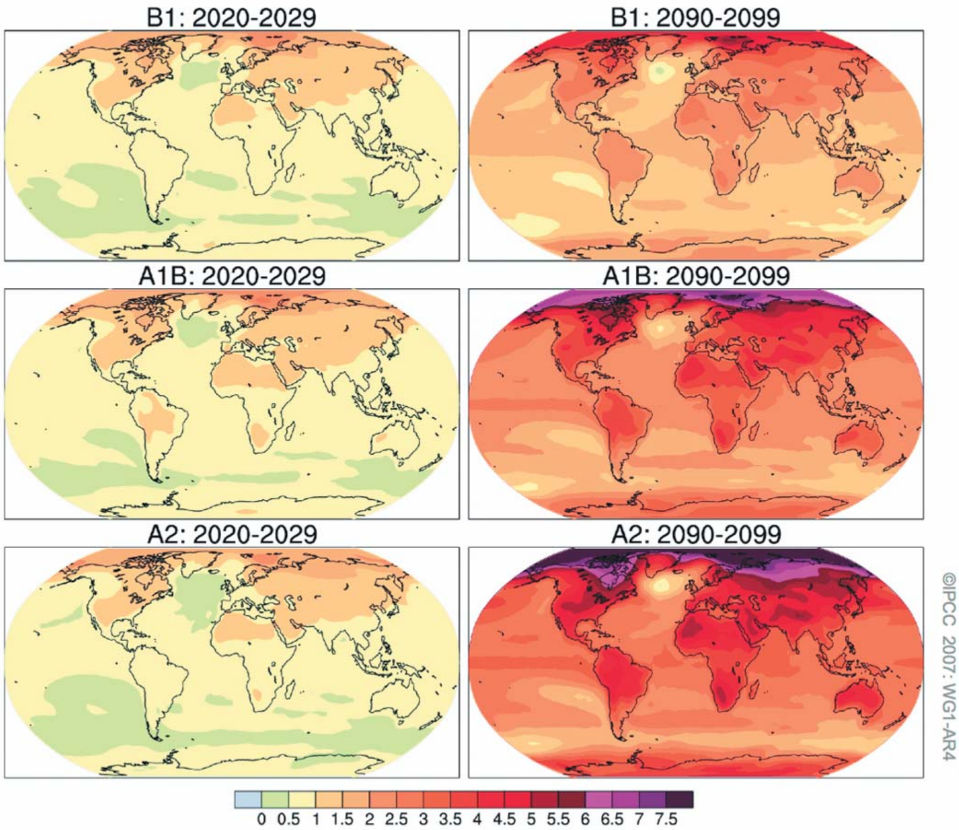
The most important laws of physics which are incorporated in climate models are:

- Equations of motion (Navier-Stokes equations) based on Newton's laws.
- Mass and energy conservation.
- Equations for the state of ideal gases.
- Radiation equations describing how solar and thermal radiation is propagated and converted in the atmosphere.

Aside from these laws, which are based on well established principles of physics, the models also contain empirical laws, that is relationships based mainly on observations and which do not necessarily have a solid theoretical basis. These empirical laws often describe processes that take place on time and space scales beyond the resolution of the models. The empirical laws often contain parameters that are set by "tuning" (that is they are tweaked, until the model behaves in a reasonable way). The formation of clouds being one example; the lifecycles of clouds can hardly be modeled by climate models. Clouds often form and disappear in models depending on the relative humidity.

Another example are gravity waves which occur in the atmosphere. When an air mass that is in equilibrium with its surroundings moves vertically into an area of different density, the earth's gravitational field pulls the air mass back toward the point of origin. This results in an oscillation around the point of equilibrium. These gravitational waves are essential for the development of the middle atmosphere, but have a wave length that is much smaller than the model resolution. Therefore, the formation and spreading of such waves are described by simple equations based on a combination of observations and theoretical considerations.

How much ice is going to melt? That is one of the many questions that climate models try to answer.



Credit: IPCC

IPCC scenarios

The colored maps show the temperature development on the Earth's surface in a series of future scenarios of greenhouse gas emissions. The maps represent an average of the estimates from different atmosphere-ocean-climate models. The most optimistic scenario (the B1 scenario) is based on a future characterized by high economic growth, low population growth and rapid introduction of energy efficient technologies, resulting in low greenhouse gas emissions.

essential characteristics of the current climate, including the geographical variation on a large scale. The models can also reproduce the cooling effect of major volcanic eruptions.

With regard to future climate developments, climate researchers use models to assess the climatic impact of external effects. The effects can have both natural causes, such as changes in solar radiation, or they can be anthropogenic in nature, like an increase in greenhouse gas emissions or a change in the earth's surface properties due to logging, etc.

Such impact assessments are very difficult make, since climate models are not sufficiently detailed to be able to describe all elements of the real world's climate. The greatest weaknesses of today's climate models are in predicting clouds and the hydrological cycle; most models also have shortcomings in their simulations of the middle atmosphere as well.

The structure of climate models

A climate model is essentially constructed like the atmospheric models used for weather forecasting. A climate model simulation starts off with a given set of initial conditions and calculations are made for small time progressions of 2 to 30 minutes, depending on the model. In a weather forecast model, weather is normally simulated up to 10 days ahead in time, while climate models run simulations for many years into the future. As climate researchers are interested in average values, climate modeling is not dependent on the initial conditions of the simulation, but only the so-called *boundary conditions* such as atmospheric CO_2 content, volcanoes and the earth's surface.

A climate model can be either purely atmospheric or a coupled atmospheric-oceanic model. Climate models, like weather forecast models, contain descriptions of conditions on the earth's surface as well as the upper layers of the soil,

Dry river in Africa.

Photo: Colourbox

where the fundamental variables are temperature, humidity and snow cover. There are also a large number of parameters in climate models that describe surface properties, such as vegetation types and soil conditions.

As for weather forecasting models, climate model variables are organized into a grid which determines the spatial resolution by which the variables in the model can be described. For both the global atmosphere models and the ocean models, the horizontal distance between the grid points is typically a couple of hundred kilometers, while vertically there are typically 30 to 40 layers in atmosphere models and 20-30 layers in ocean models.

The significance of processes taking place at spatial scales that are smaller than the model grid must be calculated based on the fundamental variables. It is important to include these so-called parameterized processes as accurately as possible, so that their overall impact on the fundamental variables in the grid is described as well as possible. Examples of important parameterized processes in the atmosphere one should mention are radiation, cloud formation and precipitation, and processes on and in the soil. It is essential that these processes are described by physical laws whenever possible and not by empirical relationships, otherwise one cannot be certain that the description will still be valid when the climate changes. The difference between the various climate models that are used today lies primarily in the description of the parameterized processes.

What do the models predict?

The report from the International Panel on Climate Change (IPCC), published in 2007, assessed future climate development based on a number of scenarios for greenhouse gas emissions. For the next two decades, climate models show a temperature increase of 0.2°C per decade for all the IPCC scenarios, in which no political intervention against greenhouse gas emissions are accounted for.

If, however, we imagine that the concentrations of greenhouse gases and particles (aerosols) were maintained at the year 2000 level (which it already is too late for), the increase would be reduced to 0.1°C per decade.

Climate developments in the late 21st century will increasingly depend on the global emissions of greenhouse gases. The current rate of greenhouse gas emissions, not to mention emissions at a higher rate, will cause even more warming. The probable temperature rise described in the different emission scenarios lies somewhere between 1.1°C and 6.4°C by the end of the 21st century. Such an increase in temperature can lead to a number of changes in the global climate system; changes which will probably be greater than those we have experienced in the 20th century.

Even if we manage to stabilize the level of greenhouse gas emissions, anthropogenic warming and sea level rise will continue for centuries due to the time scales of the climate processes and their various feedback effects. Even with a scenario projecting low emissions, climate models indicate further warming of about 0.5°C after the year 2100 and a global sea level rise due to the thermal expansion of water of 0.3 to 0.8 meters in the year 2100 and further, though slower, increases thereafter. ■

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