Anticipating Nature

Predictability in Question: On Climate Modelling in Physics

Peter D. Ditlevsen, Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen

> 'The Climate is what we expect, weather is what we get'
>
> *Mark Twain*

'Climate' has the same etymological root as 'inclination', referring to the inclination of the Sun as the primary determining factor of temperature. This dependence of climate on latitude was already well known by the Greek. Climate variations beyond the season have probably been noted even before then, when agriculture made humans strongly dependent on weather conditions. In more modern times the understanding of climate variations was part of the great achievements in natural history in the middle of the nineteenth century. Three discoveries changed the general view of a steady World. One was the discovery by Richard Owen (1841) of the fossilized remains of the no longer existing giant dinosaurs; the second and most important was Charles Darwin's expedition on the Beagle (1839) leading to the discovery of evolution of the species. The third was Louis Agassiz' discovery of the ice ages (1837).

Often the great discoveries lie right below our noses if we are capable of asking the right questions. Agassiz attributed the occurrence of huge boulders far away from their possible bedrock source to the action of past glaciers, by analogy to the action of present Alpine glaciers, rather than the work of the Biblical flood. As was the case for Darwin's theories it took more than quarter of a century for the scientific establishment to accept the existence of ice ages. Understanding the cause for ice ages was for more than a century considered the major challenge in climate theory. Today, we still do not fully understand the mechanisms governing the ice ages, but focus in climate research has changed.

The year 1957 was appointed International Geophysical Year, where a broad range of fundamental research on the physical properties in the Earth was initiated. Among these was the monitoring of atmospheric CO_2 concentration at the Mauna Loa observatory in Hawaii (Keeling, 1976), a location remote from any major emission source. The measurements have shown a steady increase in atmospheric CO2 originating from biomass - and fossil fuel burning. The urge for deeper understanding and modeling of the climate and the increased scientific resources has come with the public awareness that anthropogenic greenhouse emissions cause climate changes and possibly inflict natural hazards with societal implications. There is thus a moral dimension in the assessments of climate change and mitigation measures. Climate science has in the last few decades therefore received large attention. The Intergovernmental Panel on Climate Change (IPCC), which is a UN body, has not only had a strong impact on policy making, it received the Nobel Peace Prize in 2007, it has also been influential in the way scientists conduct climate research (Hulme, ibid.). In fact other natural hazards, like earthquakes, tsunamis and volcanoes have at present caused much higher immediate casualties than climate changes, but they are free of the moral burden, and are highly unpredictable. On the other hand, with the global economy relying heavily on fossil fuel burning, strong economic and political interests have given a few scientists, 'climate deniers', refuting the existence of anthropogenic greenhouse warming, disproportionate attention.

In this essay, I shall refrain from the heated semi-scientific debate on anthropogenic climate change, which seems to be slowly settling. For some time the debate was quite polarized; the term 'climate denier' has negative connotations alluding to religious deniers of natural selection, which are not to be taken serious in the scientific community. On the other hand, using the term 'climate skeptics' in stead would imply that those scientists, who are concerned about global warming, do not conduct the sound practice of skepticism towards own and others scientific results.

The potential impacts of climate change on societies call for not only action but also predictions and future projections. In this sense the climate sciences anticipates nature as a calculable entity, where decision-making can be based on rationality and reliable model predictions. This is partly due to the successes of weather prediction models. When these numerical models became practical with the development of the computer after the Second World War, it was not known how far into the future a prediction was possible. Today we know that weather predictions are fundamentally limited, but we anticipate that climate predictions can be made much further into the future than the range of a weather forecast.

The greenhouse effect

The greenhouse effect is very well understood based on basic laws of physics. French mathematician and physicist Joseph Fourier asked the simple question; when the Sun constantly heats the Earth by short wave radiation, why does its temperature not increase steadily? Fourier realized, in a paper published in 1824, that the Earth itself radiates heat back into space. By experiments he could estimate this long wave radiation and found that the Earth's surface was warmer than it should be in order to balance the incoming solar radiation. He then argued that the atmosphere acts as a greenhouse keeping the surface warm. He was right about the warming, but not that the air acts as the glass in a greenhouse, however, the term has stuck ever since. It was not until 1896 that the physical explanation for the greenhouse effect was given by the Swedish physicist and chemist Svante Arrhenius. He measured the absorption of the long wave radiation by the CO_2 in the atmosphere, observing the long wave radiation from the Moon. Even though his measurements were not accurate by today's standards, his calculations showed that a doubling of the atmospheric CO_2 concentration would lead to an increase in surface temperature of 4 degrees. This result stands more or less unchanged after more than a century.

The atmosphere is transparent for visible light (short wave radiation), which is the dominant radiation from the Sun. The transparency is apparent, since we can see very faint stars through the atmosphere at night. The part of the solar radiation not reflected back to space is heating the land and ocean surfaces. This heat is re-emitted partly by evaporating water and partly as long wave radiation into the atmosphere. Water vapor and greenhouse gasses absorb the long wave radiation, thus the atmosphere is not transparent for the long wave radiation emitted by the Earth. The infrared radiation is invisible to us. This is, of course, not a coincidence. Our eyes are developed to sense radiation at exactly the wavelengths where the transparency is highest. Could we see the long wave radiation, we would be looking into a fog when looking into the atmosphere. According to the laws of thermal physics any body will radiate a heat depending in a specific way on its temperature. This goes for any part of the atmosphere, so the unhindered radiation into space will be depending on the temperature of the layers of the atmosphere close to the top, which can be seen from space in the long wave band. This is about three kilometers up in the atmosphere. The temperature at this height is then the temperature at which radiation will be emitted balancing the incoming radiation. This means that the balance between the incoming and outgoing heat determines the temperature three kilometers up in the atmosphere and not the temperature at ground. The difference between the two is the greenhouse effect, which on Earth is about 32 degrees. If more absorbing molecules are emitted into the atmosphere, the level from where the radiation is emitted to space raise, since, seen from space, the atmosphere becomes even less transparent in the long waves. The temperature, at this new higher level, then rise to balance the incoming radiation, and with an unchanged decrease of temperature with height the ground also heats more.

Understanding the mechanism for the greenhouse warming, and knowing the amount of CO_2 emitted into the atmosphere, it should be very easy to calculate the resulting greenhouse warming. However, the climate system will react to the changes. If the surface warms, more water will be evaporated into the atmosphere. Water vapor is also a greenhouse gas, which will in turn lead to even more heating. This is called a positive feedback, where the original heating is further enhanced. On the other hand, more water vapor in the air might lead to more clouds, which in turn cool the surface, by reflecting the sunlight. This is called a negative feedback, which will dampen the original heating. In order to make quantitative predictions on the greenhouse warming, all the important feedbacks must be calculated, so that not only the direct effects, but all the responses in the system, are taken into account. This is an extremely complex task, since even though we may have a qualitative understanding of the immediate response in one variable to changes in another, the interconnectedness and feedbacks makes it necessary to model everything simultaneously.

Chaos and predictability

Climate predictions are of a different kind than weather predictions (Lorenz, 1975). In order to understand this difference we shall for a moment digress and consider the weather prediction. A weather prediction is the prediction done for the future based on the conditions observed today and in the past. This is called an initial value problem. The initial value being the state of the system observed at the initial time, now. The prediction could then be based on solving the equations for the fluid-mechanical evolution of the system. Had the system been the Moon and we observe a full moon today, we can predict a new moon in 14 days from now. For that we do not even have to solve the equations of motion, since we know that their general solution is a periodic cycle of 28 days. In case of the weather the situation is much more complicated. The equations of motion for the atmosphere cannot be solved in the same way as the equation of motion for the moon. The equations are such that the atmosphere is chaotic. There are several features in such a dynamical system that signifies that it is chaotic. The most general feature is what is called "critical dependence on initial conditions". This means that an infinitesimally small difference in initial conditions in two situations will in time lead to completely different final states. This effect is coined the "butterfly effect" in meteorology, quoted as the fact that "the flap of the wing of a butterfly over Brazil could cause a tornado over Texas". This was the title of a talk given by Edward Lorenz in 1972 on the subject. The term originates from the 1952 short story "A Sound of Thunder" on time travel by Ray Bradbury.

The critical dependence on initial condition (Lorenz, 1963) implies that we need to know the initial condition with certainty, which we cannot do, in order to make a future prediction. In a non-chaotic system uncertainty in the initial condition also lead to uncertainty in the predicted final state, but the uncertainty is limited in some proportion to the uncertainty in the initial condition. In the example above, if I did not observe a perfect full moon, my prediction would not be too wrong, since the new moon would be 13 or 15 days away and not my predicted 14 days. In the case of a chaotic system the error will grow exponentially in time until eventually the predicted state and the actual state differs as much as any two randomly chosen states of the system. At this time all information of the initial condition is lost.

To further appreciate the difference between a non-chaotic and a chaotic system let us consider two games. The first game is Pool, in which a ball is hit to make a precise orbit across the table with the goal of hitting some other ball into a pocket. The second game is rolling a dice with the goal of having a specific face pointing upward when the dice comes to a rest. These two games are fundamentally different in the sense that the first game is won by the most skillful player, while the last game is won by the luckiest player (any random player). In the first case the rolling of the ball after the initial hit is predictable for a long time. It depends in a calculable way on the hit and position of the ball (the initial condition). In the second case the outcome of rolling the dice also depends on exactly how the dice left the throwing hand, how it hit the table, how it rolled etc. Now, since a minute change in how the dice hit the table would make it turn right over a corner rather than left, the rolling is highly unpredictable. Both games (dynamical systems) are deterministic and governed by well known dynamical equations. The first is non-chaotic (or very weakly chaotic) while the second game is so strongly chaotic, that we consider it random. Considering the outcome of the dice rolling as random is a very good model of the process. One can argue that at the fundamental level there is no randomness, but the chaotic nature of the deterministic equations will be indistinguishable from pure mathematical randomness.

The fact that a system is chaotic does, however, not mean that predictions cannot be made within some limited time horizon. In the case of rolling the dice, the turning of the faces could be calculated as a function of how fast the dice rotates in the air all the way until it hits the table for the first time. The time scale of predictability is thus the time it takes the dice from leaving the hand until it hits the table. Likewise, even though the weather is chaotic, skillful predictions can be made within some time scale of predictability. Numerical weather predictions, presented on any TV channel, are based on solving the dynamical equations of the atmosphere in a computer fed with the previously calculated state and new observations. These weather predictions are skillful for several days, but not several weeks. This is a prediction of the first kind.

Let us now return to the example of rolling dice. Even though each throw is completely unpredictable there is still a strong regularity in the statistics of dice throwing. So if our goal was not to predict the next outcome, but the average outcome of a series of throws we obtain a new type of predictability: The average will be close to 3.5, with certainty growing as the number of throws averaged over grows. The climate can be considered as the average state of the weather, so even though we cannot predict the weather beyond weeks, we might be able to predict the climate. This has of course been done at all times in the sense that, based on previous experience (observations), we expect the climate at a given location or a given time of year to be close to the average over the period of experience for that location or time of year.

If we had no previous observations, the climate state could in principle be obtained from running the weather prediction model long enough or many times with different (randomly chosen) initial conditions. This would be pretty similar to throwing the dice many times in order to observe the statistics. (Though for the dice we would not even have to do the experiment, since the symmetry of the dice alone provides all the needed information). A numerical climate model is intended to do exactly this kind of calculation. Predicting the statistics of a system is called prediction of the second kind. So even though a chaotic system (the weather) is fundamentally unpredictable in the sense of predictability of the first kind it can be predictable in sense of predictability of the second kind (the climate).

The forecast models and the climate models

The numerical weather predictions have had a long birth. The physical equations governing the flow of the atmosphere were formulated already by Euler (1757), Navier (1822) and Stokes (1842). The main equation is the Navier-Stokes equation. The general solution of the equation remains today one of the big challenges in physics. The first attempt for a numerical solution was done -by hand- by physicist and pacifist L. F. Richardson while working as an ambulance driver during World War I. The calculation, which was a 6-hour forecast for May 20, 1910, was of course not a real forecast but a hind cast. It failed for technical reasons in how the observed atmospheric pressure was included, though his method and calculations were essentially correct. The amount of numerical calculations necessary for determining the evolution of the atmosphere from the equations is so huge that the computer is essential for doing the task, especially if it has to be done in time for the forecast to be useful. Parallel to the efforts of calculating the weather, a fundamentally different approach for anticipating the weather changes, especially in terms of the passing cyclones over Europe and North America, was taken by the Norwegian physicist and meteorologist Vilhelm Bjerknes (Friedman, 1989). The weather should be understood in terms of physical laws, so even though Bjerknes could not solve the equations for the atmospheric flow, he developed a general theory, 'physical hydrodynamics', by identifying the physical cause for generation of winds in the atmosphere. The engine for that is the meeting between the warm tropical air and the cold polar air. The warm air is lighter that the cold air and will thus rise above the cold air. In that process the rising air will cool and the moisture will condensate to rain. The places where cold and warm air masses meet were named fronts. Fronts passing indicate changes in the weather. The Bergen school, headed by Bjerknes, developed a whole new paradigm of meteorology, sometimes named 'frontology', by which the coming weather was anticipated through weather maps, with wavy patterns of cold and warm fronts, dissimilated to the public in newspapers and TV.

During World War II computer technology advanced, mainly from the demand of code cracking. In the 1950's, mathematician John von Neumann, co-constructer of the ENIAC computer and meteorologist Jule Charney engaged in numerical weather predictions. It took another 25 years before the numerical weather predictions in the mid-1970's outperformed the more empirical front-system predictions based on hand drawing of weather maps.

The validation of the forecast models, performing predictions of the first kind, in order to verify that relevant physical processes and so on are adequately represented, can be done by observing the skill by simply comparing the predictions with observations. For the climate models, performing predictions of the second kind, the situation is different: In this situation we can only compare with observations going back in time. This means that we examine if the mean state (the climate) predicted by the model compares well with the observed climate. For predictions of a future changing climate we have to make the crucial assumption that the reason that the climate model performs well in simulating the past and present climate is that the model adequately represents the physical laws and equations governing the climate, and thus it will also be adequate in simulating the future climate where conditions have changed.

Physical parameterization and model resolution

In order to appreciate the working of the climate models, we shall briefly consider the rational behind solving the equations of motion for the atmosphere. The physical nature surrounding us is described by sensible or measureable quantities; the atmosphere is characterized by its temperature, wind, pressure, density and humidity. These variables can be ascribed measurable values at each point in space and time. Variables with values depending continuously on space and time are named fields. The value of a field, say temperature, at a specific location, say in Copenhagen, changes in time, say from noon to 1 pm. The temperature may rise, because the temperature is higher west of Copenhagen and the wind is blowing from the west bringing in warmer air. The temperature could also be rising because the sun is heating the air or because the moisture condensates out and fall as rain. Thus the rate-of-change with time in temperature depends on the wind, the rate-of-change with space in the direction where the wind comes from, the rate-of-heating and the condensation of water. The changes are accounted for in the equations of motion for the flow (Holton, 2004) . As mentioned before, these equations are complicated and cannot be solved exactly. The way we can solve them approximately is by substituting the rate-of-change of, say temperature, by finite differences between the temperature at one point in time and at some time before that, say at 12.15 and 12. This difference in temperature will, among many other things, depend on the rate-of-change of temperature with distance. This rate-of-change is substituted by finite differences as well, say the difference between temperature in Copenhagen and Hamburg. We thus advance the evolution of temperature by expressing the temperature in Copenhagen at 12.15 as a complicated function of temperatures, winds and so on in Copenhagen, Hamburg and a few other locations at 12. The locations where we define the variables are spread over the globe in a regular grid.

The general circulation models solve the equations of motion for this set of variables in the mesh of grid points distributed over the globe. Locations between the grid points are not represented, so the values of the variables, or fields, are taken as some interpolation between the values in the grid points. The grid points are in present days climate models typically hundreds or thousands of kilometers apart. Inside the model whatever goes on inside a grid box (cornered by the grid points) must be represented by the few values of the parameters in the grid points. When the results of a model, a huge amount of numbers, is to be interpreted and presented it is done graphically typically in terms of maps of the fields, interpolated smoothly from the grid points to cover the globe overlaid a map of land contours. Now since most countries are smaller than the square grid boxes, the land contours are plotted in a much finer resolution, than actually represented in the model. The graphical impression might then lead to anticipation of much more realism in the model output, than what is actually substantiated.

One very important physical process in the climate is the formation and evolution of clouds. They strongly alter the radiation; as we all know, it is immediately felt when a cloud blocks the sun, and, on the contrary, a cloudy winter night is warmer than a clear sky. The clouds also have a greenhouse effect. Cumulus clouds are typically of sizes less than square kilometers and thus much smaller than the grid boxes (which are perhaps 10^5 km^2). A cumulus cloud is formed by condensation of moisture in an ascending air mass. An air mass rise if it is lighter than the surrounding air, and the moisture begins to condensate into cloud droplets in a complicated way depending on microphysical conditions of temperature and aerosols, acting as nucleation seeds. All of these processes within a grid box, in the model, can only depend on the few variables at the grid points contained within the model. The unresolved processes are then represented by some empirically, statistically or reasoning based functional relationship with the resolved variables of the model. This is called physical parameterization. The purpose of the physical parameterization is to determine, the other way around, the influence of the unresolved physical processes on the variables of the model. The physical parameterization is one of the Achilles heels of the climate models. The validity of the functional relationship of a given physical parameterization can only be established by examining how well the climate predicted by the model compares with the observed climate. This is part of the tuning of the models. When then running the models with changed conditions for future projections, we thus have to assume that the parameterizations are still valid under the changed conditions.

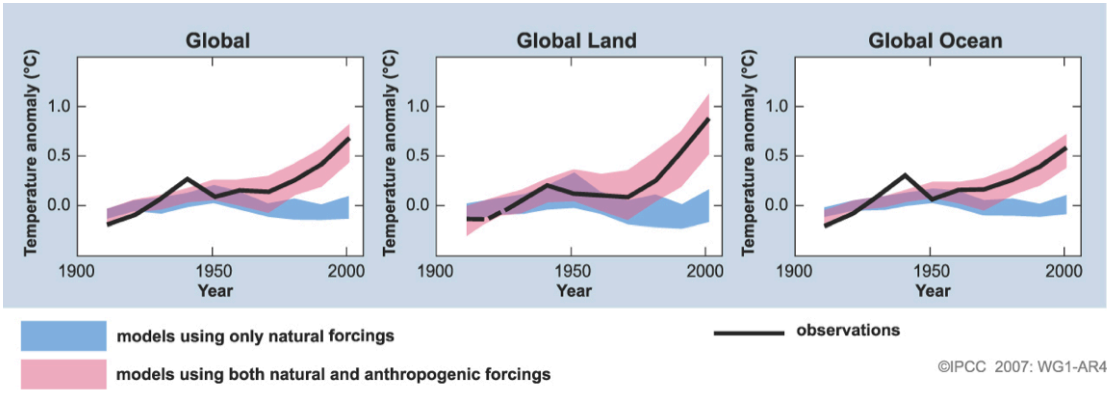
As the grid of model resolution is refined, the more variables are included in the computation and the smaller are the computational time steps required (more steps to obtain the same progression). This implies that the higher the resolution of the model is, the more computer power is demanded. This is the case in any numerical solution of a physical problem. One will then ask; what is the sufficient resolution required to solve the problem? In order to answer this question in a meaningful way, we have to specify to what accuracy we want the answer. We thus have to be able to identify an error margin, such that when the model resolution is larger than some limit, the model results stays within the error margin from the correct result. Unfortunately, this cannot be done for the climate models. Each time the resolution is increased, the unresolved physical processes get better resolved, and the parameterizations need retuning. Until the physical processes are truly calculated there is no guarantee of convergence. Another, even more fundamental problem in the limited resolution is the problem of turbulence, which we shall return to later.

Coupled climate models

The climate models are not merely forecast models run for a long time. Beside the state of the atmosphere at the beginning of the forecast (the initial conditions) the forecast model is fed with boundary conditions such as the surface temperatures of the ocean. These variables have strong influence on the evolution of the atmosphere, but they only vary little during the week or so of the forecast and can therefore safely be considered constant. However, for the much longer time span of the climate model the slow variables, which change with seasons, or even on longer time scales, must now be considered as variables of the system. The sea surface temperature is such an important variable in the climate, that it is mostly just denoted by its acronym, 'SST'. The SST for the past century has been measured, mainly along shipping routes, by bucket sampling. With these measurements fed into climate models the climate of the last century has been simulated. The models nicely reproduced the warming of the first part of the century, the slight cooling in the 1940's-1960's and the subsequent warming. These model studies were a central part of the third assessment report from IPCC (2001) lending credibility to the validity of the climate models. However, all that the models showed was that the atmospheric temperature is so strongly influenced by the heating from the oceans that the prescribed SST completely dominated the signal. The reproduction of the past climate was thus not in itself a validation of the climate modeling, it testified that the models probably responded correctly to the prescribed SST. In order to predict future climate changes the SST also needs to be foreseen. This means that not only the development of the atmosphere but also the development of the ocean temperatures and currents must be calculated.

In contrast to the atmospheric climate models, which were developed along with or from the forecast models, the ocean models cannot be guided by forecasting. For forecasting, the initial state, that is currents, temperatures and salinities, more or less everywhere, should be known. This would be extremely costly to do, because only the ocean surface can be remotely observed, say from satellites, thus an enormous mesh of ships or buoys should be implemented. Thus the limited economic interests in this in comparison to the vestments in weather forecasting makes ocean forecasting prohibited. The expense of measuring deep in the oceans means that we only have a rough picture even of the climatology (mean state) of the oceans. Ocean general circulation models reproduce this roughly known mean state. These models are fed by the influence from the atmosphere, through heat exchange, surface winds generating waves and water exchange through evaporation and precipitation. The coupled climate models contain a model for the circulation of the atmosphere and a model for the circulation of the oceans. The parameters in the atmosphere influencing the ocean are calculated in atmospheric model and vise versa. This sounds more straightforward than it is. Now that the two components are free to evolve together, and one part is not kept to the observed climate by the boundary conditions from the other part held fixed, the coupled models in general resulted in unrealistic model climates. This implies that the different parameterizations of physical processes need retuning.

The coupled models are the basis for the future climate projections in IPCC's fourth assessment report (2007). Judgments of the quality of the computer models are based on simulation of the twentieths century variation, where the models are fed with the observed increase in CO_2 and natural variations in volcanism and solar radiation. The global temperature shows larger natural variation, the 1940’s rapid warming and subsequent cooling, than any of the models predict. This is seen in the figure taken from the IPCC report (2007), where the black curve is the observed twentieth century temperature. The red band is the 5% - 95% range of 58 simulations from 14 different climate models. Especially the temperature variation over the oceans is not captured (the black curve falls outside the red band in the 1940's).



©IPCC 2007: WG1-AR4

Scales of predictability

The climate is the average of the weather, a practical definition of the climatic temperature is a running thirty years average of the temperature. The distinction between predictability of the first kind, the weather prediction, and prediction of the second kind, the climate projection, is well defined in mathematical sense. But when it comes to Nature the situation is much more complex. As mentioned above, the climatic global temperature has changed through the twentieth century. Are (were) these variations predictable? Or is a period of thirty years to short to reliably determine the "true" climatic mean?

In order to answer these kinds of questions, we shortly return to our simple example of throwing a dice. Imagine that we do not know the number of eyes on any of the sides, we thus have to throw the dice a number of times in order to observe the mean, 'the climate', taken as the total sum of eyes divided by the number of times we throw the dice. How many times do we have to throw the dice to get a reliable measure of the mean? This question can be answered very precisely in this simple case, everything can be calculated: If we want to know the mean to an accuracy of 0.5 we must throw the dice 10 times. If we want to know the mean to an accuracy of 0.1 we must throw the dice 250 times. (The accuracy increase inversely proportional to the square root of the number of throws). Now, imagine a climate change where the eyes on the sides of the dice change slightly, say the 1-eye side gets another eye, so there are now two sides with 2-eyes. For this new dice the true mean is 3.67 and not the 3.5 as it was for the original dice. In order to detect the change in mean, the 'climate change', we now have to measure with accuracy large enough to detect the difference between 3.5 and 3.67, thus we will have to throw the dice of the order 250 times. If we push this simple analogy to the limit, we imagine that the dice is thrown once every month, thus we need to observe for 250 months or about 20 years in order to detect the climate change. That sets a time scale of detection. Another time scale is the time scale of change of the parameters causing the change in the statistics, say, changes in atmospheric greenhouse gas concentration. This time scale of change has to be long in comparison to the time scale of detection if the knowledge of the climate state should be relevant in the times of change. If this is not the case, the specific development of the system in transition is more important. Are we then back in the situation of a prediction of the first kind, where the future must be calculated from the present initial state?

To know if this is possible, we have to know what the time scale of predictability of the first kind is. Here our analogy with the dice breaks down, since the dice is un-predictable as soon as it hits the table. So we must ask what the time scale for predictability is in the weather-climate system: The lows and highs passing in the west wind belt have typical length scales of 1000 kilometers and time scales of days for passage, thus if it is possible to calculate forward in time the motion of a few passages of highs and lows, they are predictable in order of a week. This is also the time scale obtained in practice in weather forecast models. But something has been sneaked in here: We have decided for a length scale of variations, namely the hundreds to thousands of kilometers of variation between highs and lows. If we were interested in, say, the specific direction of the wind in the courtyard, the time scale is completely different. As can be seen when the fallen leaves are carried erratically around in the autumn, the time scale for predictability is of the order minutes. If we are interested in the development of a specific cumulus cloud, to determine if it will rain on a specific field or the neighboring field, the predictability is perhaps of the order of one hour. There is thus a close connection between the spatial scales of variation that we want to predict and the time scale of predictability.

If we thus make a weather prediction of a day or more, which is an initial value problem, we already passed the time limit of predictability for some smaller scales, where we can thus only make predictions of the second kind. When the forecast says showers, it is not predicting rain at a specific location at a specific time; it is predicting some probability of rain in a statistical sense. We thus have a mixture of predictions of the first kind and the second kind. This would also be the case had the models had such a high resolution, that they actually resolved single clouds.

It is not only the spatial scales that determine time scale of predictability. The speed in which things vary is also important. Some parts of the climate system vary very slowly. The overturning of the ocean, which is very important for the exchange of heat and CO_2 between the atmosphere and the ocean, takes hundreds to thousands of years. There is enormous inertia in the oceans, so if we knew the present state of the deep oceanic currents to some high degree of accuracy, the large scale flow could in principle be predictable (of the first kind) for very long times, even on the climatic time scales. These slow variations in the climate system might be responsible for the natural twentieth century variations, which the state-of-the-art climate models cannot reproduce as a function of the known solar, volcanic and anthropogenic influences. In order to predict climate changes in the near future the climate models thus might have to accurately resolve and calculate the slow development of ocean flow, ice sheets, vegetation in the sense of an initial value problem.

The turbulence problem

In the climate system variables and conditions vary on a huge range of scales (Ditlevsen, 2004). So when we want to make predictions we have to focus on a specific range of spatial and temporal scales, such that whatever changes very slowly on the scale of focus can be considered constant. As an example, the continents and mountain ranges can safely be considered constant, even though they move and erode on geological time scales. On the other hand, variables, which change much faster than the time scales in focus, can be considered in an average sense. The extreme is the motion of the molecules constituting the atmosphere, the mean motion in a small portion of the atmosphere is the wind, while the erratic variations of the molecular velocities on top of the wind is only felt in an average sense. This average motion is the temperature of the air. These two extremes, the geologic variations on millions of years and the molecular motion at the scale of about a millionth of a centimeter are separated from the climate dynamics of days, years, meters and thousands of kilometers. These gabs in scales are called scale separations.

In the range of weather and climate scales we face the fundamental problem that there are no clear scale separations between scales that are resolved in the climate and weather prediction models and the scales, which must be treated in a statistical sense. In its most fundamental form this is the “turbulence problem”. The turbulence problem can be formulated in many ways. Consider a fluid (the air is a fluid in this connection) set in coherent motion at the large scales, which in this connection could be the size of the globe, or the size of some basin. What causes this motion could be the equator to pole difference in solar radiation. This motion at large scales will break up into motion at smaller scales, which in turn break up into motions at even smaller scales until eventually the variations in motion is at such a small scale that it is dissipated as heat. In technical terms, the kinetic energy of the flow is cascaded into smaller and smaller scales. The range of scales in the atmosphere, from the size of the planet to the sub-millimeter scale of dissipation is enormous and completely outside reach for resolving in any climate - or weather prediction model. We thus have to make some cutoff in spatial scales, where variations above that scale are resolved and variations below that scale are ignored. The choice of cutoff could be made naturally if there was a clear scale separation, such as the one between the fluid motion and the molecular motion, but that is not the case. The cutoff is rather set by the computational affordability.

Another way of choosing the relevant cutoff would be by improving the resolution until the obtained results do not change appreciable, as we discussed in connection with the physical parameterizations. We are thus expecting a convergence of the predictions as resolution is increased. However, as the resolution is increased, more and more of the flow is resolved and the calculated flow becomes more and more varying, and the convergence is extremely slow. A consequence of this is that the coarse resolution of the climate models implies that that calculated flow is much less variable than the real atmospheric flow, which in turn can also imply that the rare extreme events are under-represented in the model simulations. This could be another complementary possible cause for the deficiency in the climate models to reproduce the observed variations in the mid-twentieth century climate.

Past climate and climate proxies

The question whether the twentieth century climate variations can be attributed to the variation in the solar radiation, aerosols from volcanoes and increased greenhouse gas concentration, or if there is a component of unpredictable natural variation is still open. If we are to be sure that the observed global warming can be attributed to the anthropogenic CO_2 increase and not just a coincidental natural variation, we have to evaluate the range of natural variability. In order to do so, we need to know the variability back in time. This can only be done by indirect measures, called proxies, since the instrumental record almost only covers the industrial era, where the atmospheric CO_2 has been increasing. One proxy is the annual growth rings in trees. Their width and density depend on the weather conditions in the specific year of growth, so in this way a proxy for these weather conditions back in time can be constructed from ancient tree trunks. Other proxies can be obtained from biological sediments in lakes and oceans, corrals or records of crops yield. Each record contains different indirect measures.

A very prominent proxy can be obtained from ice cores in the ice sheets in Greenland and Antarctica. The ice sheet is build through hundreds of thousands of years from deposited snow compacted into ice. The ice sheet is thus a huge sedimentation out of the atmosphere. The main proxy, discovered by the Danish geophysicist Willi Dansgaard, is the depletion of heavy water in the ice in comparison to the ocean waters. Heavy water contains heavy stable isotopes of either oxygen (^{18}O) or hydrogen (^{2}H, deuterium). Heavy water is chemically identical to normal water, but the higher mass makes it a little less volatile. A water molecule found in the ice has undergone the process of evaporating out of the ocean, being transported as gas, being recondensated as ice crystals or water droplets in clouds, re-evaporated and recondensated several times, before eventually falling on top of the ice sheet in a snow flake. All these phase transitions on the way from the ocean to the ice sheet will differentiate between the normal and the heavy water molecules. All the processes from the evaporation somewhere in the ocean, the transport, the cloud formations and the snowfall depend on the specific weather and climate conditions. When measuring the concentration of heavy water in the ice, some very indirect measure of the climate conditions at the time of deposition is obtained. By empirical correlation in present days conditions, where the temperature is known, it turned out that there is a linear relationship between the depletion of heavy water and the temperature (Dansgaard, 1964). The more depleted, the lower the temperature. By drilling an ice core at the summit of the ice sheet, a very long proxy record of the past temperature has been achieved. The ice is so old that the very cold climate of the last ice age has been obtained. The ice ages were of course known before then, but the ice cores record revealed an unexpectedly variable glacial climate (Dansgaard, 1993). The climate had apparently flipped very quickly between two very different climate states during the ice age, something that no climate theories had foreseen, and something that the present state-of-the-art climate models cannot reproduce. These events are called Dansgaard-Oeschger events after their discoverers (Hans Oeschger was a Swiss glaciologist working together with Dansgaard). Even though the conditions in the ice age were very different from the conditions today, the findings opens the possibility of fast irreversible climate changes either if some threshold, say in greenhouse gas concentration, is exceeded, or if some extreme weather event perturb the climate enough to change into another state. Such behavior is described as "tipping points".

Tipping points and extreme events

In most of daily life we are used to some extend of proportionality between cause and effect. Say, the cause, or 'forcing', is some heating and the effect is some melting of ice. If the doubled amount of heating is applied, the amount of melted ice, also doubles. However, this simple linear response does not always describe the situation. In some cases, crossing a critical threshold in the forcing will lead to a dramatic and irreversible response. This means that, if the previous sub-threshold value of the forcing is reestablished, the system does not return to its original state. One such system is the ice sheet: An ice sheet will build up if the temperature is below zero at the ground for some time. In this case more snow will accumulate than will melt off at the margin. The ice sheet will eventually build up into a 2-3 kilometer mountain of ice. The temperature on top of the ice sheet will be very low, since the atmospheric temperature decrease with altitude, and the top of the ice-sheet will be 1.5-2 kilometers above sea level (one third will be below sea level, due to depression of the solid crust). In 2 kilometers height the temperature is almost 20 degrees lower than at sea level. Thus if the temperature change, so that the temperature at sea level is now 10 degrees, the top is still -10 degrees and the snow accumulated on top of the ice sheet can balance the melt off at the margin. This is the situation in summer for the ice sheet in Greenland. If it was not there, it could not build up, but since it is there it can be sustained. There are thus two possible stable states for the ice sheet. It can be there in its present extent or it can be completely gone. Now, if temperature is slowly increasing the ice sheet will shrink in proportion to the additional heating. However, at some point the ice sheet shrinks such that the temperature on top is above the freezing point, and it will melt completely back. The response is no longer proportional to the forcing and the system will reside in its other possible state, the one without an ice sheet. In order to reestablish the ice sheet it is not enough to return the temperature to the level, where the ice sheet was previously stable. It is necessary to lower the temperature to freezing at sea level, which is a much lower temperature. This scenario is a strongly non-linear dynamics, where the system undergoes a tipping point or bifurcation. Tipping points in the climate may lead to dramatic changes, as seen in the paleoclimatic record. If the Greenland ice sheet collapses the global sea level will rise 7 meters. If this unfortunate situation should occur, it will not happen over night, but the actual time scale for this to happen is poorly understood. The recently observed speed of shrinking of the ice sheet has been surprisingly fast in comparison to the present understanding of the ice sheet dynamics.

The climate system probably possesses more tipping points, where sudden changes to new stable configurations happen. The system has multiple stable states, which means that with the given external factors unchanged, the climate can be one of two or more possible different climates. One of the most dramatic examples is related to the state of the Atlantic Ocean circulation, the thermohaline circulation (Broecker, 1997), being either in a state where warm waters is transported to the north, giving a warm Northern European climate or a state where this circulation is absent with a much colder Northern Europe.

If we were to predict a future crossing of a tipping point, the dynamical climate system should be modeled with some quantitative accuracy. Although these switches are understood in terms of simple mathematical models, when it comes to the numerical general climate models, from which the IPCC assessments for future warming are derived, then it seems that the models do not show a dynamical behavior which include tipping points. On the contrary, the general circulation models react very linearly to (the logarithm of) the CO_2 concentration or any other perturbation applied to the model. The reasons for this are not well understood. Two quite complementary effects may cause the discrepancy between the models and our anticipation of climate change based on the paleoclimatic records.

The first effect is fundamentally related to the way in which we conduct numerical solutions of the governing equations. The governing equations are in the technical mathematical sense 'field equations'. This means that the variables we want to predict, temperature or wind, change continuously in space, thus we can ascribe a value for the temperature field or wind field in each and every spatial point for a given time. When we want to describe how these continuous fields develop in time, we can only contain the values of the fields in a finite limited set of points, we thus reduce the one field equation to a set of equations for the values in the limited set of points. This is the computational grid, which was described above. In reality the fields are split into a discrete set of waves rather than point values, but that is not important here. The procedure is mathematically well controlled and well defined. In the limit of infinitely many points covering the space, the field equation and the set of equations for each point are equivalent and yield exactly the same results. Now, as we can only handle a limited set of variables, we make a truncation, exactly as discussed earlier when we introduced the physical parametrizations. Instead of increasing the number of points in the calculation, let us imagine that we decrease the number of points in a coarser and coarser grid. In the end, we only obtain a few coupled equations, which in technical terms are called a low order system. It turns out, when simulating such low order systems on a computer, that they exhibit multi state solutions and the kind of dynamics we expect for tipping points.

To understand this behavior, consider the flow in a basin, say a bathtub. We only described the flow by monitoring or calculating in two points in each side of the bathtub near the walls. Close to the wall, the flow is parallel to the wall, say, either to the north or to the south. We know that the bathtub does not move, so the average flow is zero. This also goes for our calculation containing only the two points, so the sum of the flow in the two points will be zero. If the flow in the point to the left is towards the north, it will be towards to south in the point to the right and vise versa. Thus the flow is either clockwise or counter-clockwise in the basin. If furthermore some applied force sets the strength of the flow, we have a system, which can be in one of only two possible states and tipping, by bifurcation, between the two can happen as the force is varied. Increasing the number of points in the calculation, more and more possible flow patterns can be represented, and in the end, with very high resolution, there is a continuous set of possible flows. Thus in this example, the two distinct states and the bifurcation between them are artifacts from the coarse numerical resolution, not representing reality. In this scenario, we would not expect the bifurcations observed in Nature to be caused by the physics described in the climate models, even though low order models do exhibit a bifurcation structure.

The second effect is also related to the numerical resolution in the model. When the resolution is low, no variation on scales smaller than the distance between grid points is represented. This is the same as smoothing out all details, with the consequence that large deviations from the mean are underrepresented. These unresolved extreme events could be important for triggering large excursions in the climate, so large that tipping points may be reached. This could then explain why tipping points are not seen in the climate models. The apparently unrealistically linear response of the models to perturbations is then because of the systematic underrepresentation of the natural variability especially the extreme events.

The extremes are not primarily important for the possibility of triggering climate changes. For construction safety, insurance and mitigation measures, risks over long time spans must be estimated. The instrumental records of meteorological observables are for the most only a little more than a century long, there are historic recordings of extreme events, flooding, devastating storms, severe winters, draughts and other extremes influencing living conditions going further back in time. From the recordings we may estimate the risks associated with extreme events. So even though we imagine that we can get a reliable picture of the natural climate by observing the mean over thirty years, such a period is way to short to estimate, say, the storm of the century. This is another reason, why reconstructing the past climate prior to the time of the instrumental records is important.

Perspective

All through human history we have anticipated the natural weather and climate based on past experiences. Giving up migration and hunting, settling for farming, with the expectation of a life sustaining crops yield next year relies on a strong anticipation of unchanged climatic conditions. Actually, as seen from the paleoclimatic record, climate has never before in human existence been as stable as during the last 8000 years, coinciding with the period of agriculture. This is a striking observation, where drawing a connection between agriculture and climate stability is tempting. That can also very well be, but in order to verify, it seems to me that previous farming attempts, ruined by climatic changes to big to adapt to, must be found. Nothing indicates that the human intellectual capacity has changed appreciably for the last 100,000 years, so it is a puzzle why agriculture did not arise before. The later enormous population growth relies on the success we have had in taming Nature. Human activity has changed local environments by deforestation and farming, but only since the industrial era, has the anthropogenic change had global consequences. Climate is and will be changing due to human activity.

The challenge of predicting how and how much climate will change, and which mitigation measures will be practical and feasible, puts climate science in the eye of the storm. The numerical climate models do a fair job in reproducing the present observed climate so that we rely on their ability to forecast possible future climates as they are fed with different CO_2 emission scenarios. However, if we try to reproduce the distant past rapid and large climate changes, as documented in the paleoclimatic records, the models fail. Likewise, the fundamental question of how ice ages arise is still open; the numerical models do not have the capacity or dynamical range to reproduce those either. Whether the deficiency is in dominating physical processes not included or resolved in the models or if it is merely a problem in computational capacity is not clear. The solutions to these questions will probably be fundamentally different from other breakthroughs in science, like Einstein's theory of relativity, which in a single paper completely resolved the issue of the constant speed of light and revolutionized our perception of space and time. The recent consensus about a discernible anthropogenic greenhouse warming did not arise with one or a few deciding findings. It rather grew out of a slow process of mounting and circumstantial evidences. This will probably continue for a while still until we have a practical experience on where the limit, if there is a limit, is to our detailed predictions for the future.

The climate models of today are so complex and computationally heavy that their behavior cannot easily be understood. They are considered as laboratories, in what by some physicists are considered as the new third way, beside experiments/observations and theory, namely computational physics. In this third way the model development is seen as more and more precise representation of Nature. The model computer simulations are thus believed to be maps of real or possible manipulations of Nature. However, we are left in the fundamental problem: How detailed a map of Nature should the models be? The enigma is captures in the tale by Jorge Luis Borges (1960) in which a group of cartographers is assigned to draw a prefect map of the Empire. The question is to what scale it should be drawn in order to capture all the details of the Empire, after several attempts a 1:1 map is constructed where each and every detail is copied to the map. However, the map turns out to be useless, since unfolded it covers the whole Empire, blocking the sun light out. It thus ends up in ruins.

The development of climate models over the past three decades has been toward including more and more processes and components of Nature. This has been the standard solution to correcting for insufficiencies or inaccuracies in the model simulations when comparing with observations. The question is if this process ever stops, or if, at any point, the models are accurate or detailed enough. Even being able to understand what "accurate enough" means for anticipating an unpredictable and changing natural world is a challenge.

Litterature

Broecker, W. S., Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO2 Upset the Current Balance?, Sience, 28, 1582-1588, 1997.

Dansgaard, W.,Stable isotopes in precipitation, Tellus, 4, 436-468, 1964.

Dansgaard, W et al, Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218-220, 1993.

Ditlevsen, P., Turbulence and Climate Dynamics, Frydendal, 2004.

Friedman, R. M., *Appropriating the weather : Vilhelm Bjerknes and the construction of a modern meteorology,* New York 1989.

Holton, J. R., An introduction to dynamical metorology, Academic Press, 2004.

IPCC Third Assessment Report: Climate Change 2001 (TAR), Working Group I Report, The Physical Science Basis, 2001.

IPCC Fourth Assessment Report: Climate Change 2007 (AR4), Working Group I Report, The Physical Science Basis, 2007.

Keeling, C. D. et al, Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii, Tellus, 28, 538-551, 1976.

Lorenz, E. N., 1963: Deterministic Nonperiodic Flow. *J. Atmos. Sci.*, **20**, 130–141.

Lorenz, E.N. Climate Predictability. In: The Physical Bases of Climate and Climate Modeling, number 16 in GARP Publ. Ser., pages 132-136. World Meteorol. Org., 1975.