Some Reflections on the Predictability of Climate Change

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2022 Balzan Prize for Glaciation and Ice Sheet Dynamics

IinteR-La⁺B, International Interdisciplinary Research Laboratory, Milan, Società Svizzera, Tuesday 9 September 2025

The predictability of climate has always been a fascinating subject. The work of two persons had a large impact on me when I studied geophysics in Utrecht, in the first place, meteorologist and mathematician Edward Lorenz, who was one of the first to carry out numerical experiments on the predictability of climate change and weather prediction. He obtained very interesting results that in the end led to the development of the chaos theory. Secondly, there is Klaus Hasselmann, 2021 Nobel Prize for Physics (Edward Lorenz should also have received it), who designed a framework "Stochastic climate modelling" to quantify uncertainty in the climate system.

Professor Hasselmann demonstrated that in a complex system like the climate system, short-term weather fluctuations tend to make quantities with a larger time scale (a lake level, an ocean current, a glacier) drift away from a mean state. This is somewhat comparable to Brownian motion, where a small particle in a fluid gets pushes from moving molecules all the time and starts to wander around in a direction which is not predictable. When we have 100 particles, we know how the cloud of particles will disperse in a statistical sense. Einstein had already formulated this problem and solved it. However, it is impossible to predict the trajectory of an individual particle.

What Lorenz did was to integrate the fluid dynamics equations, starting with a certain initial state. He looked at how this evolved in his computer, and he repeated the experiment with a very small change in the initial state. To his great surprise, it led to a totally different solution after a while.

At this point I want to recall that randomness is not the same as chaos – in a chaotic system there is structure in the phase space (for instance, the famous "butterfly graphic" obtained by Lorenz for a simple dynamical system with only three variables). In this system a variable may follow a specific orbit in the phase space, and then suddenly switch to another orbit to stay there for a while. The involved large dependence of the evolution of a system on its initial state has led to the development of the so-called ensemble prediction methods. Here The European Center for Medium-Range Weather Forecast was really the pioneering institution. To illustrate schematically the idea, Fig. 1 shows a set of temperature predictions from a numerical weather forecasting model. The different curves refer to different starting temperatures, and the solutions tend to diverge. The important point to note is that the temperature prediction is not given as a number, but as an evolving probability distribution.

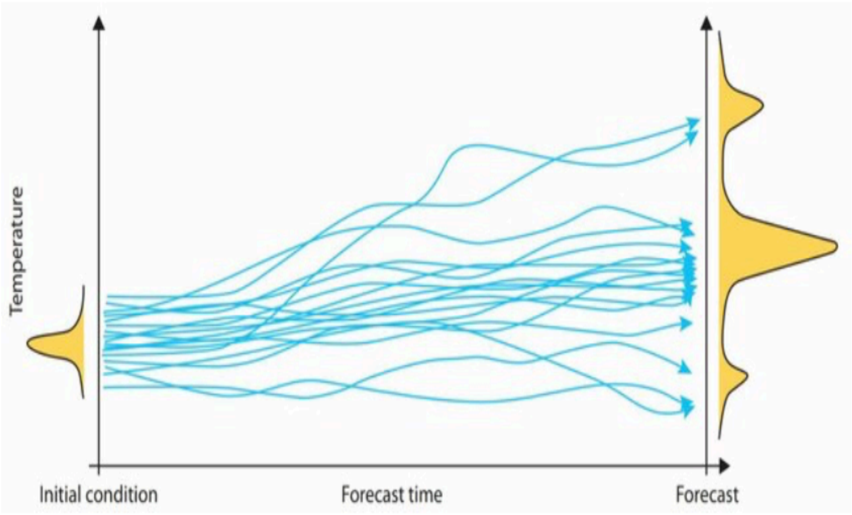

Fig. 1: A schematic illustration of ensemble prediction methods (drawing by Peter Grönquist). The forecast evolves as a probability distribution changing in time.

Ensemble prediction methods are used in many fields now. For any chaotic system, in which the evolution depends so much on the initial state (or on sometimes poorly known parameter values), it is the only meaningful way to quantify the inherent uncertainty.

At a time where project funding plays a larger and larger role in science, hypes naturally develop. In the world of dynamical systems theory, words like chaos, strange attractors, bifurcations, feedback loops, tipping points, catastrophe theory, transilience, etc., are used in a fairly loose matter. It is a bit of a fancy world where people try to reinvent old ideas and give things new names (and of course have much better means to do graphical presentations of complex systems). But at the basis of most of this is that non-linearity in a mathematical system may lead to multiple solutions (bifurcations / Hopf bifurcations), which tend to wipe out the memory of a system.

To further illustrate the issue of nonlinearity, we consider glaciation of a continent or an island [Fig. 2]. We may think of Antarctica or Greenland, or an island in the Arctic Ocean. The simplest way to represent climatic forcing is by means of the so-called equilibrium line. The equilibrium line separates the region where snowfall exceeds melt from a region where melt exceeds snowfall. There is more snowfall when going up in the atmosphere, because it is becoming colder. So above the equilibrium line, the mass "budget", is positive, and a glacier can grow. Therefore, when the equilibrium line is lowering for some reason – because the climate gets colder – it may hit the top of the mountain of the continent, and a glacier will start to form.

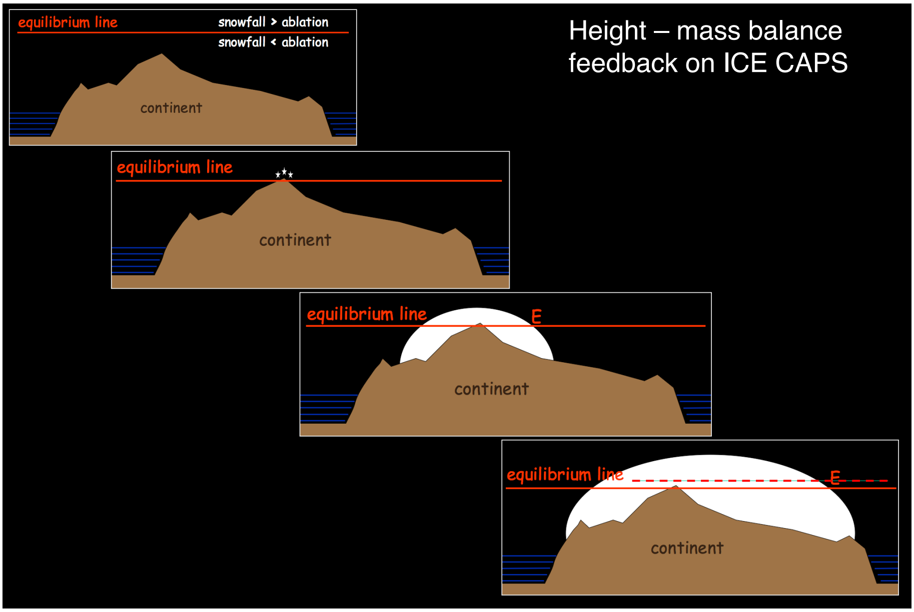

Fig. 2: Glaciation of a continent when the equilibrium line (red dashed line) is lowering due to colder and/or wetter conditions.

When the glacier / ice cap grows, the intersection of the equilibrium line with the ice sheet surface changes, and that determines how large the accumulation area actually is. So by growing upward, an ice sheet also extends its accumulation zone, which is called the height – mass balance feedback. In this way, a small lowering of the equilibrium line can generate a big ice sheet. If the equilibrium line is lifted because it gets warmer, the ice cap can still stay even when the equilibrium line is above the highest point of the bed. So here we have a system which has two stable states (an ice sheet or no ice sheet) for a given range of the height of the equilibrium line. It is obvious that for the evolution of the system, it is crucial whether during a colder period the equilibrium line dips just below the highest mountain or just not. This is a clear example of bifurcation in the system: for given external parameters (the forcing), there is more than one possible state, and the one we are in depends on the history. But when an ice sheet goes, the history is lost.

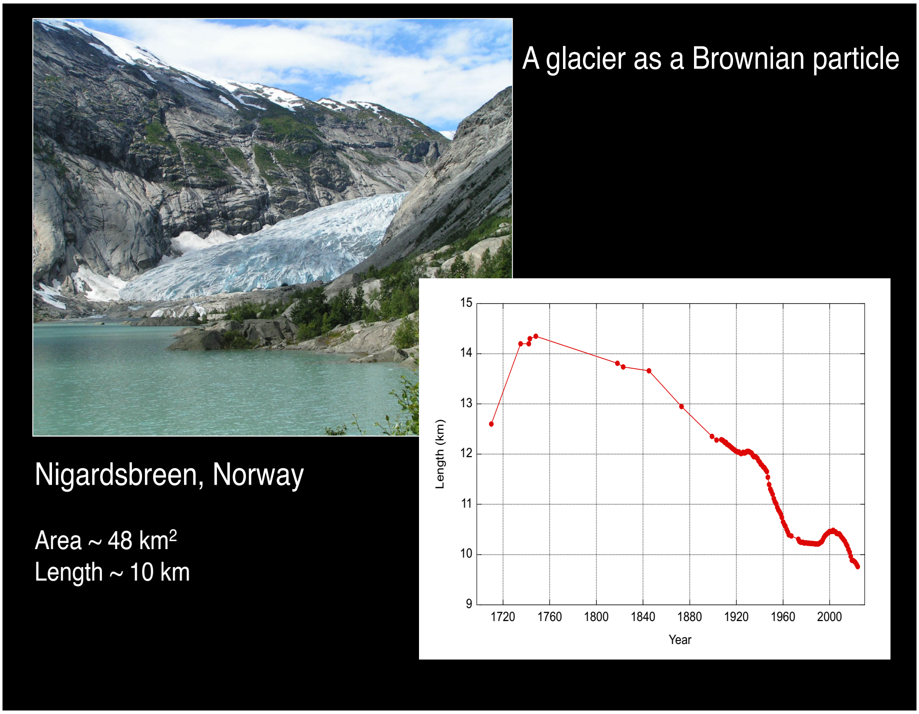

Fig. 3: The snout of Nigardsbreen in southern Norway. The graph shows the observed glacier length over the past few centuries.

Next, we turn to a different scale and consider a mountain glacier, Nigardsbreeen in Norway [Fig. 3]. A spectacular glacier, which has retreated by over four kilometers in a few hundred years. The observed glacier length is plotted in the graph on the lower right. With respect to the year 1720, one can see a huge retreat of the glacier (more than 4 km).

This must somehow be related to more melting, less snow, or any other change in meteorological conditions, but this can again be formulated in terms of an equilibrium line. Fig. 4 illustrates how a glacier actually works.

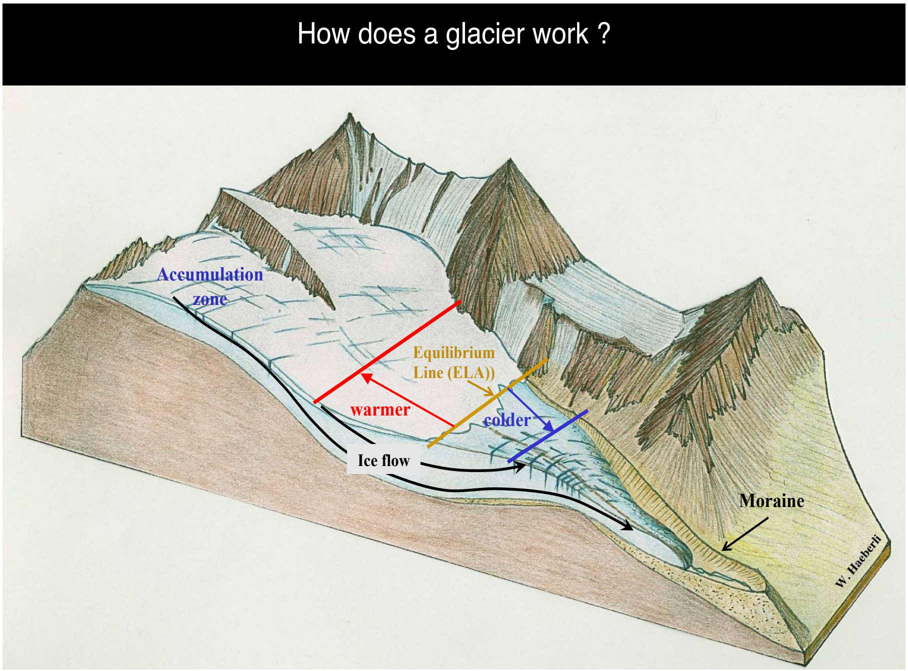

Fig. 4: Illustration of the most important processes that determine the evolution of a glacier. Credit Wilfried Haeberli, Zürich University.

Above the equilibrium line the mass budget is positive; below its negative. An increase in temperature would bring the equilibrium line upward, and in colder conditions the equilibrium line would go down, with the glacier becoming larger. So it makes sense to measure the height of the equilibrium line if you want to find out in which state a glacier actually is. The measurements are fairly simple. It starts with drilling stakes into the glacier by means of a steam drill. After one year, one can measure how much of the stake emerges from the glacier, which gives the loss of mass. Norwegian researchers in particular have done lots of measurements on their glaciers, mainly because they are essential for hydropower (meltwater filling the reservoirs in summer).

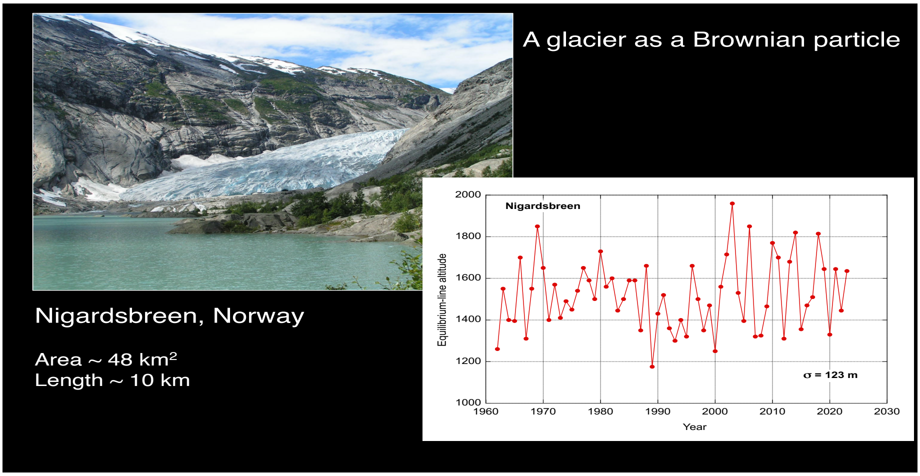

Fig. 5: The snout of Nigardsbreen in southern Norway. The graph shows the annually observed equilibrium line altitude.

Figure 5 shows a long series of equilibrium line measurements. One can see the shifts from year to year are typically about 100 to 200 meters. In the spirit of the stochastic climate models of Klaus Hasselmann, I used this graph to generate an equilibrium line deviation as the measurements. There is not much structure – basically just white noise – but I wanted to see how this works out on the glacier and therefore carried out a long integration.

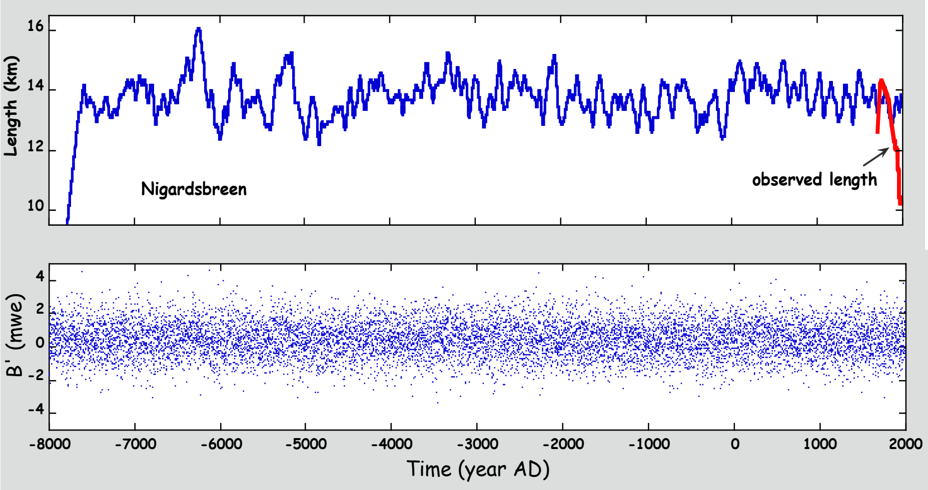

Fig. 6: Lower panel: synthetic annual mass balance pertubation series. Upper panel: modelled response of the glacier to the mass balance series

The bottom panel of Fig. 6 shows my 10,000-year synthetic mass balance perturbation (equivalent to changes in equilibrium line altitude) for every year. I forced a computer model of this particular glacier that had been tuned as well as possible to see what would happen. Again, it is a slow system – the glacier gets pushes all the time from year to year. In the upper panel of Fig. 6 the result is shown. Basically, in mathematical terms it is a red noise response to white noise forcing. So the glacier exhibits fluctuations of the order of a few kilometers as a result of random forcing. This is important when one tries to interpret paleoclimatic records. It works for the glacier, but if one looks at lake levels one would see the same type of response.

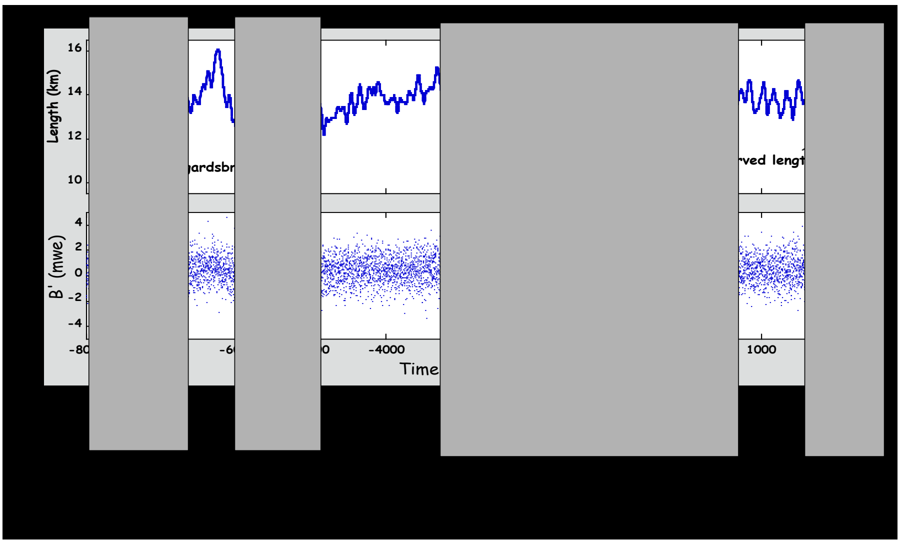

Fig. 7: Window looks at the synthetically generated glacier length fluctuations. Rapid climatic change, long-term trends, and periodic behaviour can all be seen.

In the synthetic glacier length record, at certain given points, One can see rapid climatic change. At others places one can see a steady trend over 2,000 years, or even periodic variations. Thus, if you were a paleoclimatologist and took proxy-observations, you would think that the climate always behaves in a cyclic way. However, it can all be due to white noise, to random forcing. This indicates that we should be extremely careful in interpreting climatic parameters that belong to a slow system. Of course, a retreating glacier is not without significance. But the real significance, of course, lies in the fact that virtually ALL glaciers behave in the same way. I have collected 500 glacier-length records that started before 1950 [Fig. 8].

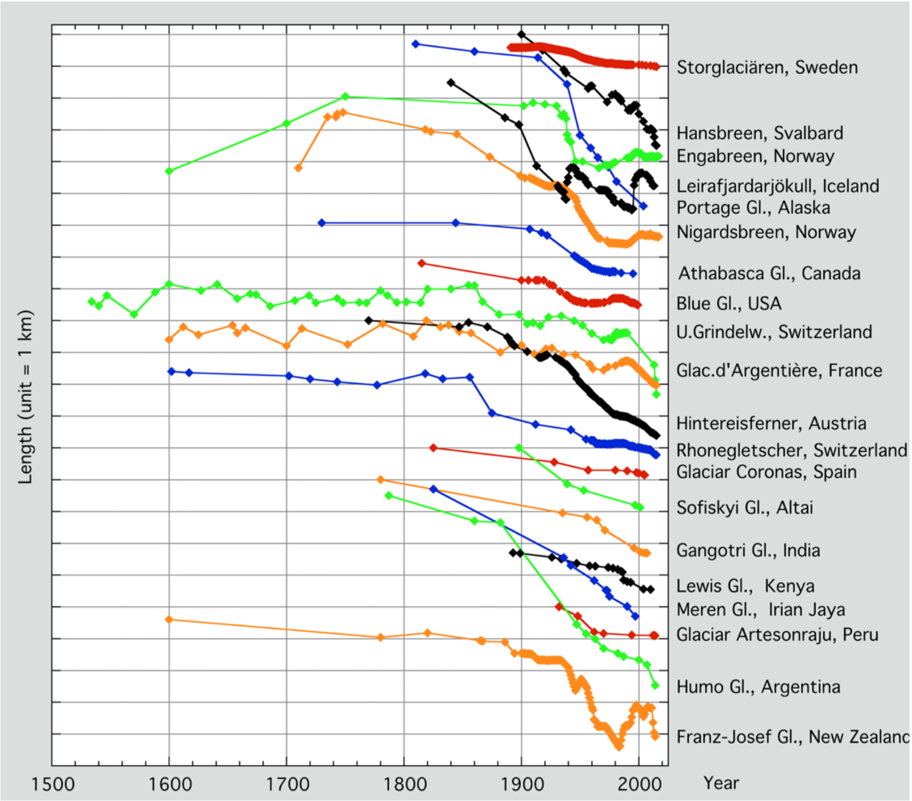

Fig.8: A selection of glacier length records since 1500 AD. The records are loosely ordered according to latitude.

The 500 records (and this is just a little selection of 20 of them) show what glaciers did over the past 500 years. There is a strong coherence across the globe. The records are ordered from northern latitudes all the way to New Zealand. On smaller time scales there are differences. It is the job of a glaciologist to make a distinction between fluctuations due to climatic forcing and fluctuations that are related to the specific glacier geometry.

Next, we turn to a more general discussion on the predictability of climate change. In terms of the predictability of the climate system, we have to make a distinction between different quantities. There are certain elements we can predict very well (e.g., global mean temperature) and certain elements are very hard to predict (e.g., local precipitation). In general terms, quantities that are more directly related to the energy budget of the global system, like the global mean, annual mean temperature, are more predictable than quantities that involve dynamics (the flow in the atmosphere and the ocean). For instance, when the forcing is very strong – like the annual cycle in the insulation – the result is quite predictable. It is not difficult to predict that in summer in Italy it is warmer than in winter. But we want to go much further.

I was involved in the first IPCC assessment. The establishment of the IPCC was mentioned as a big step by the Chairman, and I think he is right. It was 35 years ago that IPCC came with the first established prediction of climate change in the future, as illustrated in Fig. 9. The carbon dioxide concentration in 1990, when this prediction was issued, was 353 ppm. IPCC predicted for the current year (2025) 425 ppm, and actually we have 427 – so a very accurate prediction. The prediction for temperature was very accurate as well. However, this concerns the global annual mean temperature.

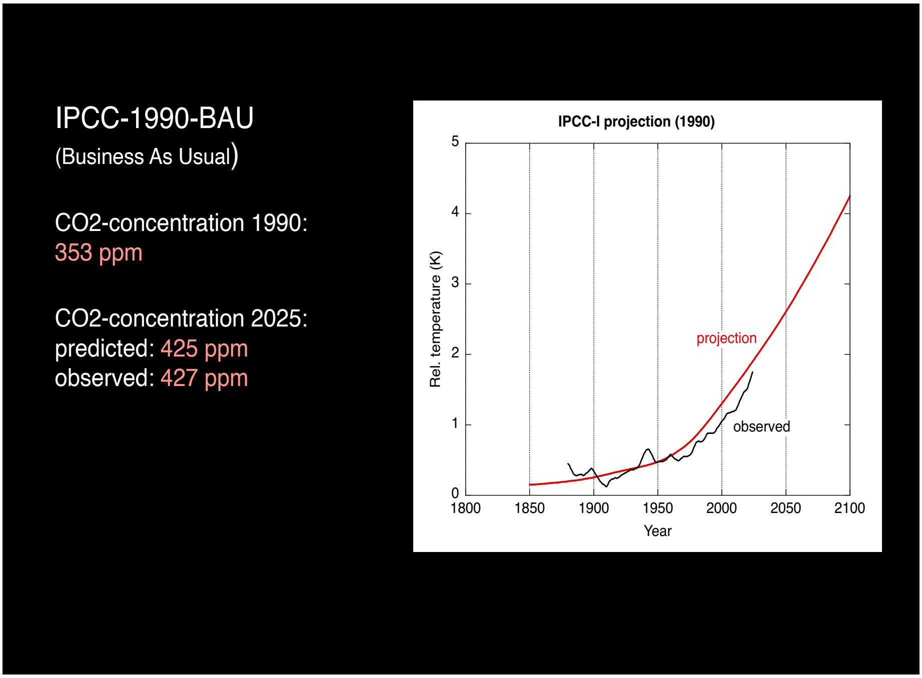

Fig. 9: Carbon dioxide concentration and global mean temperature as predicted by IPCC in 1990, compared to measurements.

I investigated a lot of model outputs from different climate models and came to a few additional conclusions. First of all, climate models have underestimated polar amplification. The changes in the polar regions we see today are considerably larger than those predicted by climate models in the past. The enormous decline in sea ice in the Arctic region was also underestimated. So surprises are coming all the time. Of course, once things happen and we adjust the models and start to work on the tuning buttons, we can make it all fit. But that does not imply predictability.

Land-ocean contrast is another delicate issue. In Switzerland and probably also in Northern Italy, the warming we see is 2.5 times the global mean. If you look into this a bit more carefully, you will see that mid-latitude land masses warm more markedly than the global mean. This was not predicted or barely predicted by climate models. The underestimation of severeness of extreme weather events is something else. This is related to the limited resolution of models. The water vapor cycle also is a big player. In a way one does not need complex models to understand that thunderstorms, tornadoes, and hurricanes become more violent when it gets warmer. As most of you will probably know, the amount of water vapor in the atmosphere follows the so-called Clausius-Clapeyron equation, which means that the amount of water vapor increases exponentially with the temperature. It is the water vapor that condenses and delivers energy to atmospheric systems. So even from a simple physical point of view you can predict that thunderstorms and so on will be more severe. But where will there be more thunderstorms or more severe ones – in Switzerland? Perhaps less in Spain? That is the type of answer people want to have, but in my view are impossible to give.

I've tried to make a qualitative ordering of what we can predict and what we cannot predict [Fig. 10].

Fig. 10: Overview of predictability for various climatological quantities (qualitative).

Temperature is simpler than precipitation, because precipitation has to do with dynamics in the ocean and atmosphere. Annual mean is the best predictable quantity. Polar amplification is a little bit less, but especially climate change on a regional scale is very difficult and will probably never be achieved for fundamental reasons. When I read something like this on the bottom line of Fig. 11, "Understanding these regional differences is essential not only for scientific accuracy, but for shaping local adaptation strategies in the face of a warming world," I think this sentence is wrong. It suggests that if we put enough satellites in space and make the computers bigger and bigger, we will be able to make regional climate change predictions. I think it has been demonstrated that this is fundamentally impossible.

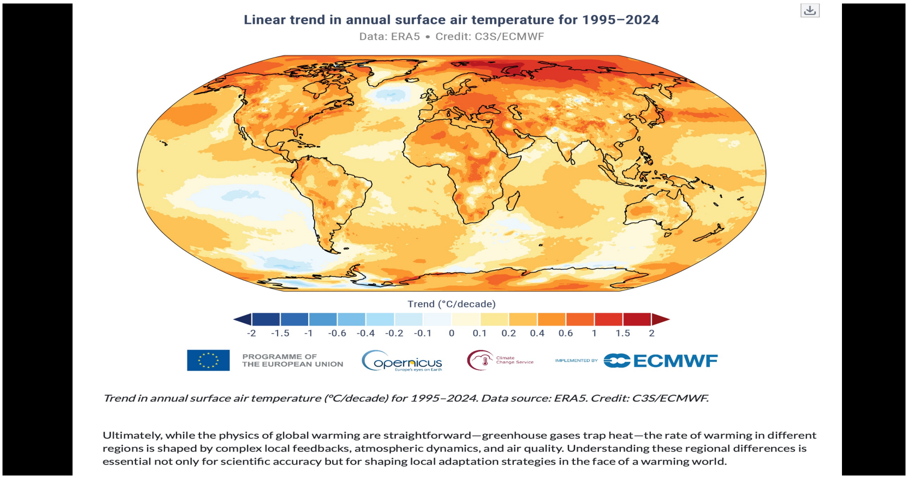

Fig. 11: Linear trend in annual surface air temperature for 1995-2024. Note the large differences on regional scales, part of which will reamin unpredictable.

So what do we do? Fig. 12 is perhaps the most dramatic graph that has ever been produced by climate science, namely carbon dioxide concentration in the atmosphere over the past 800,000 years, as found in bubbles in ice cores. If we consider these 800,000 years, we see that carbon dioxide concentration varied between glacial and interglacial periods, but never exceeded 280 parts per million. Now we are at 430! This is a huge push to the system – to the atmosphere – and a huge push by means of changing the concentration of the gas that is most active in the radiative sense in the atmosphere.

Fig. 12: Atmospheric carbon dioxide concentration over the past 800 000 years, obtained from analysis of air bubbles in Antarctic ice cores, and compared with the present-day value.

Obviously, making such a huge push to a system we do not know very well – and which is to some extent unpredictable – is dangerous. But of course, you can reverse the argument and say, “Well, if we don't know anything or very little, we can't do anything!” So precaution is my key word, as well as respect for the natural system. But it is true that we do not know the answer to the simple question: if there were no people on the globe would there be no climate change? What would the climate do? It will not stay the same – that is for sure. There is always evolution, long memory in the ice and in the ocean. So this is the tension we have. As scientists we have to admit that we cannot predict everything, but we still advise to take action. So for me PRECAUTION remains the key word.