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Climate Change:
From the Greenhouse Effect to High-Resolution Climate Modeling

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Climate change is one of the most pressing societal and economic issues, but also one of the most complex scientific challenges. There is overwhelming evidence that anthropogenic climate change is already happening. Global mean temperatures are rising, polar sea ice is decreasing, glaciers are retreating, sea level is rising, and the atmospheric water content is increasing. The most recent European summer fits well into this pattern. Over the Swiss Plateau, the summer 2018 ranked as the third warmest in the long-term data series. Detailed analysis demonstrates that the summer warming of the last decades has been very pronounced (Fig. 1). The temperatures of the last decades (1991-2018, red bars in bottom panel) exhibit a shifted statistical distribution in comparison to the past (1864-1990, blue bars). Between the two periods there has been a mean summer warming of 1.8 K. This warming amounts to about 2 standard deviations of the 1864-1990 distribution. Even the coldest summer since 1991, the summer 1996, is significantly warmer than the 1864-1990 mean. These observations, along with many others, demonstrate that the climate system is experiencing a pronounced shift far beyond natural variations.

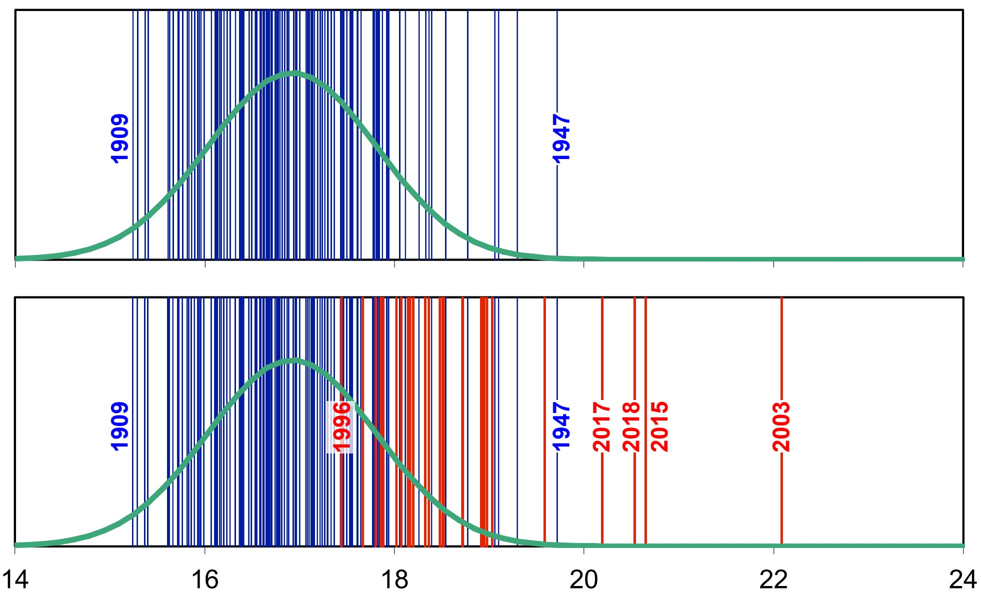

Fig. 1: Summer temperatures over the Swiss plateau (average of stations Geneva, Basel, Bern and Zurich) from 1864-1990 (blue, both panels) and 1991-2018 (red, bottom panel). Extreme summers are annotated. The green curve shows a Gaussian fit for the 1864-1990 period. The warming between the two periods is evident: even the coldest summer of the 1991-2018 period (the summer 1996) is warmer than the 1864-1990 mean. (updated from Schär et al., 2004, http://dx.doi.org/10.1038/nature02300

While 30 years ago there has been a vigorous debate regarding the reasons behind this warming, all recent assessments of the UN Intergovernmental Panel on Climate Change (IPCC) conclude that the prime reason behind global warming is due to the anthropogenic greenhouse emissions.

The physical principles behind the greenhouse effect are now well understood. Early studies of Joseph Fourier (1824) and John Tyndall (1861) identified the role of greenhouse gases for the climate system, and isolated H_2O and CO_2 as the most important atmospheric gases able to absorb infrared radiation. Already in 1896, Svante Arrhenius provided a first estimate of the effects of increasing atmospheric CO_2 concentration. His model of the Earth's energy balance was the first of its kind. It accounted for incoming solar and outgoing terrestrial (infrared) radiation, included the forth-power Stefan-Boltzmann law (then referred to as Stefan's law), and considered absorption by H_2O and CO_2 gases. Arrhenius estimated that a doubling of CO_2 would lead to a warming of about 5.4 K. In discussing his results, he did focus on the role of CO_2 variations for the ice ages, but he also mentioned that "the world's present production of coal reached in round numbers 500 millions of tons per annum [...]. Transformed into carbonic acid, this quantity would correspond to about a thousandth part of the carbonic acid in the atmosphere." According to current estimates, the emissions in 1895 amounted to about 406 million tons of carbon.

Today's annual anthropogenic emissions of carbon are estimated to about 10 billion tons of carbon, about 25 times more than in 1895. The prime reason of these emissions is the exploitation of fossil fuels. While some fraction of the emissions are absorbed by the oceans and the land surfaces, about 50% remain in the atmosphere and contribute to the accumulation of atmospheric greenhouse gases. Consistent with these figures, the atmospheric CO_2 concentration is currently rising by about 0.5%/year.

While the evidence for a man-made influence on the climate system is rapidly mounting, uncertainties in climate change projections have remained staggeringly large. For instance, current estimates of the equilibrium global-mean warming in response to a doubling of atmospheric CO_2 concentrations amount to 3 ± 1.5 K. During the last 40 years, this estimate has neither significantly shifted nor narrowed. The main cause behind the slow progress in projecting climate change is the representation of clouds in climate models, especially of small-scale convective clouds (i.e. thunderstorms, rain showers, shallow convective cloud layers). While the projected geographical patterns of climate change are converging across different climate models, the amplitude of these patterns is sensitive to the representation of clouds. These uncertainties make it difficult to plan and develop adequate response strategies, which are essential to reduce global warming and adapt to climate change.

With the advent of high-resolution climate models, there are now promising prospects, as it becomes feasible to formulate the models much closer to first principles and to refine the horizontal resolution of global climate models from today 50-100 km to 1-2 km in the future. In essence, this will allow resolving convective clouds explicitly, and thereby representing crucial physical processes and feedbacks on a physical basis rather than using semi-empirical parameterization schemes.

The potential of high resolution is demonstrated by regional climate models, which show that the mesoscale structure of atmospheric phenomena is much more credibly simulated at high resolution (Fig. 2). The forthcoming increase in resolution is also important in the context of extreme events (e.g. heavy precipitation and flash flood events), which are characterized by small spatial and temporal scales and thus require high resolution. Recently it has become feasible to conduct such simulations at continental scales over decadal time periods.

Models of this type are currently used to better understand and project heavy precipitation events in a future climate. Previous theoretical studies have suggested that heavy hourly events increase by between 6 and 14% per degree warming. Results from high-resolution climate models suggest that the increase in extreme precipitation intensity will likely be near the lower value of 6% per degree warming, corresponding to the Clausius-Clapeyron rate. Assuming a warming of 5°C by the end of the century under a business-as-usual scenario (IPCC RCP8.5), this would yield intensity increases of about 30%. Such results are essential for the dimensioning of critical infrastructures with long life times, for instance bridges, dams and hydrological runoff systems.

Currently major initiatives are underway to expand the computational domains of high-resolution regional climate models to global scales, or to refine the horizontal resolution of global models to km-scale. Estimates show that about a 100-fold increase in computational power will be needed. In addition, new approaches are required to handle input/output, as the memory bandwidth is increasingly becoming the crucial bottleneck (as opposed to the computational power in the past), and it is essential to better exploit future hardware architectures (such as GPU-based supercomputers). It appears feasible that within 10-20 years computers and models will enable km-scale global simulations over centennial time periods, and it is hoped that these advanced modeling systems will help to reduce current uncertainties in climate change projections.

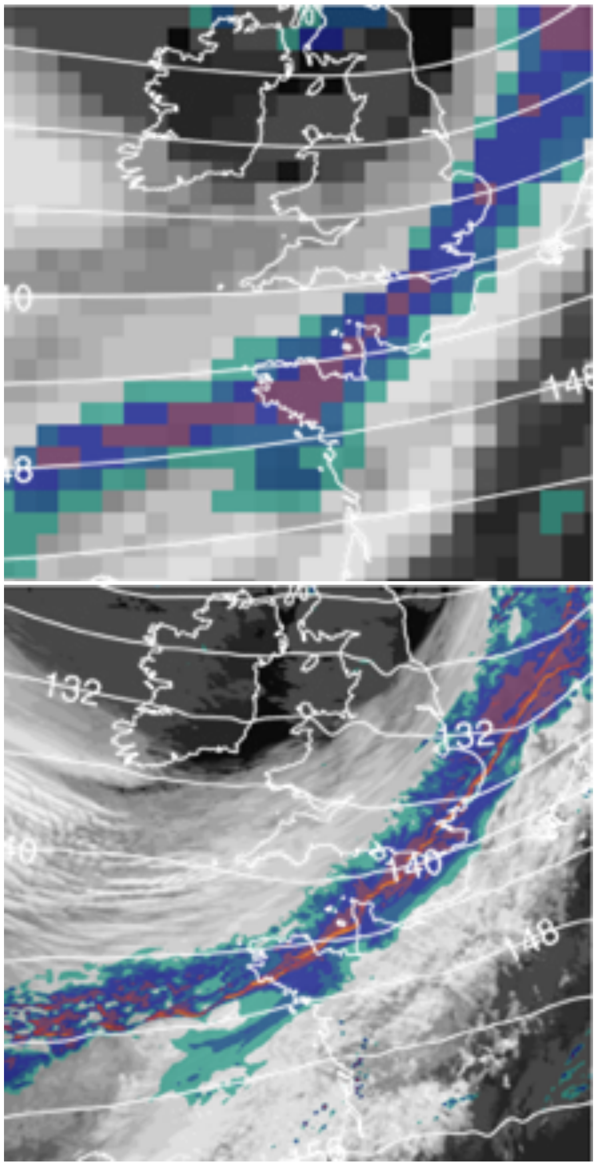

Fig. 2: Zoomed snapshots of a simulated cold front at horizontal resolutions of 50 and 2 km, respectively, showing visualizations of simulated clouds in grey, and precipitation intensity in color. The 2 km simulation (lower panel) is able to represent the narrow cold-frontal rainband (the reddish band of heavy precipitation), which is responsible for halting the scale collapse. Decade-long simulations of this type are currently used to better understand and project the fate of heavy precipitation events in a changing climate. (from Leutwyler et al., 2017, http://dx.doi.org/10.1002/2016JD026013).