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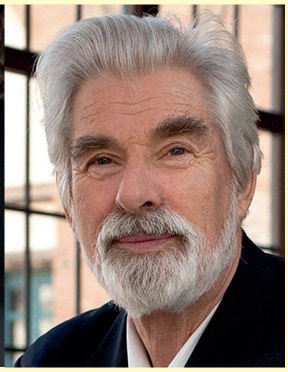
Nobel Prize in Physics 2021

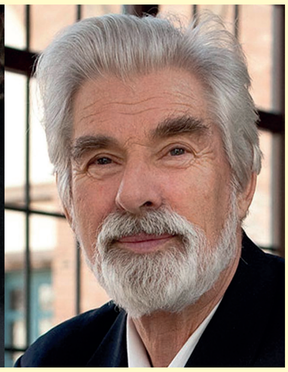


The citation of the Nobel committee

The Nobel Prize in Physics 2021 was awarded ***for groundbreaking contributions to our understanding of complex systems*** with one half jointly to Syukuro Manabe and Klaus Hasselmann ***for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming*** and the other half to Giorgio Parisi ***for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales***.

The Swiss Physical Society expresses its sincere congratulations and best wishes to these colleagues and 2021 Nobel Laureates.

Nobel Prize in Physics 2021



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Syukuro Manabe and Klaus Hasselmann

Thomas Stocker, Climate and Environmental Physics, Physics Institute,
and Oeschger Centre for Climate Change Research, University of Bern, stocker@climate.unibe.ch

It came as a surprise to most of us that the 2021 Nobel Prize in Physics was awarded to Giorgio Parisi, Syukuro Manabe, and Klaus Hasselmann, for their groundbreaking contributions to our understanding of complex physical systems. Nobel Prizes for environmental science are rare: In 1995 the Nobel Prize in Chemistry was awarded for the understanding of the observed ozone depletion in the stratosphere over Antarctica and the demonstration that this is due to the complex chemical reactions triggered by the massive emissions of chlorofluorocarbons from industrial activity. It took the Nobel Prize Committee a full 26 years to acknowledge that also Physics has played a crucial role in providing the tools to understand the complex climate system. The fundamental contribution of Giorgio Parisi to enable generalized predictions of complex systems, on scales from molecular to galactic, will be discussed in a separate article. Here I focus on the area of physical climate modelling, where the two colleagues Syukuro Manabe and Klaus Hasselmann have made foundational contributions that are now timely acknowledged by the Nobel Prize in Physics 2021.

To physically describe the climate system one needs to solve the complete Navier-Stokes equations on a rotating sphere, for both the ocean and the atmosphere. These momentum equations are supplemented by conservation equations for mass of air and water in the atmosphere, water and salt in the ocean, and energy in both domains. Equations of state for moist air and saline water, as well as a set of parameterizations that describe the effects of smaller-scale motions in the atmosphere and ocean are implemented in the climate model. Moreover, the coupling of ocean and atmosphere requires formulations of mass, momentum and energy fluxes at the atmosphere-ocean interface. This also includes physical descriptions of sea ice, snow cover, and land surface processes. It is evident that this is a formidable problem that involves a large range of time and space scales, about 14 orders of magnitude in each. A large body of experience, in particular regarding the numerical solution of the partial differential equations of geophysical fluid dynamics, stems from numerical weather prediction that was made possible by the advent of the first electronic computers in the 1940ies. It is in this environment, that the development of three-dimensional coupled climate models began in the early 1960ies.

Manabe's work started in one dimension only: To simulate the vertical temperature structure in the Earth's atmosphere, he considered radiative transfer and convective adjustment in an atmosphere that also contained the major greenhouse gases H_2O, CO_2 and O_3 and their effect on the vertical fluxes of energy. In this paper [1] Manabe and his colleague were explicit about about their scientific agenda. In the acknowledgement they wrote: "*This work constitutes part of an effort to construct an advanced general circulation model …*", and they published such a model only a year later [2]. Manabe was early in recognizing the problem of increasing CO_2 concentrations in the atmosphere. Their one-dimensional model simulated the response of the atmosphere to a doubling of CO_2: global surface warming of 2°C and concomitant stratospheric cooling [3]. This is a remarkable fingerprint of anthropogenic global warming that is observed today and is due to the effect of the rapidly increasing CO_2 concentration caused by the burning of fossil fuels.

Suki, as called by his friends and colleagues, spent his entire career at the Geophysical Fluid Dynamics Laboratory, a government institution next to Princeton University. In the same lab, Kirk Bryan lead the equivalent effort to build a numerical model of the ocean circulation [4]. The two scientists teamed up and constructed the first coupled climate model [5]. They boldly chose a very idealized domain for their model: a 120°-slice of the planet, half of which was land from 66.5°S to 66.5°N, the rest ocean and periodic boundary conditions in the atmosphere. This configuration captured the essential elements of the global climate system while still being computationally feasible with the computer and storage infrastructure available at the time. The work was more than a proof-of-concept: It marked the beginning of a rapid evolution in climate model development that continues till today. Manabe has always been interested in the applica-

tion of the ever imperfect models to global problems. He had a keen eye for tractable problems and entertained intensive scientific contacts with geochemists and paleoclimate scientists in search of challenging problems.
One example with a Swiss connection concerns rapid climate change. Hans Oeschger (1927 - 1998), physicist at the University of Bern, and Willy Dansgaard (1922 - 2011), from Copenhagen University, found evidence in their isotopic analyses of lake sediments in Gerzensee, and of ice cores from Greenland, that during the last ice age, climate could change rapidly between a warm and a cold state, resembling a physical flip-flop system [6]. This hypothesis motivated a test with the comprehensive climate model that Manabe and colleagues had developed. They showed, that indeed their model could simulate two different equilibrium states [7]. One state was characterized by a strong overturning circulation in the Atlantic Ocean transporting heat northward and warming Greenland. In the second state, this circulation was substantially weaker and caused a relative cooling in Greenland, qualitatively in agreement with the findings of Oeschger and Dansgaard. Multiple equilibria were well known from the analysis of non-linear dynamical systems. Although the climate system engenders many strong damping feedbacks — for example planetary grey body radiation (the Planck feedback) — it is evidently non-linear and exhibits many of the characteristics of non-linear dynamical systems such as limited predictability, chaotic behavior, or multiple equilibria.

The cessation of this Atlantic circulation, an elegant physical mechanism for abrupt climate change, captured the attention of many researchers, e.g., [8, 9]. Manabe and his colleague Ron Stouffer were interested in the consequence of this finding for the ongoing global warming. They showed that the non-linear atmosphere-ocean system could undergo a bifurcation of the Atlantic overturning circulation depending on the warming caused by the continuing increase of the atmospheric CO_2 concentration [10]. This early work is at the start of simulating critical transitions and irreversibility in the climate system.

The work of Klaus Hasselmann was equally foundational. His interest in the global climate system departed from a more theoretical point. Originally concerned with the dynamics of ocean surface waves and their statistical analysis, he proposed that climate variability could be understood as the action of stochastic weather fluctuations on a slow-responding ocean-land- cryosphere component [11]. In this radically reduced description of the climate system he could invoke scale separation and found that the time evolution of the probability distribution of variability of the slow component can be described by a Fokker-Planck equation. This also allowed basic inferences regarding predictability under stochastic forcing, a deep insight into the complexity of the Earth's climate system. The work opened up a new avenue to utilize methods of theoretical physics, classically applied to problems such as Brownian motion, turbulence and plasma dynamics. Thereby, Hasselmann recognized a link between fundamental physics and climate science.

In order to describe the slow component more realistically, Hasselmann laid out a plan for an efficient ocean model [12], which could be used to simulate climate processes on time scales of centuries to millennia. This ocean model became the early workhorse of the scientific activity of the Max-Planck-Institute of Meteorology in Hamburg, of which Hasselmann was the founding director. It was the first three-dimensional model that also simulated the global carbon cycle and a series of tracers in the world ocean [13]. This opened up new avenues of coupled climate-carbon cycle simulations which today form the core of the latest climate change projections of the Intergovernmental Panel on Climate Change [14, 15]. Both Hasselmann and Manabe, with their collaborators, used coupled models to predict climate change expected for a doubling of the CO_2 concentration in the atmosphere [16] (see Figure 1 and Figure on the cover). These results informed the first assessment report in 1990 [17] which was the scientific basis for the UN Framework Convention on Climate Change of 1992.

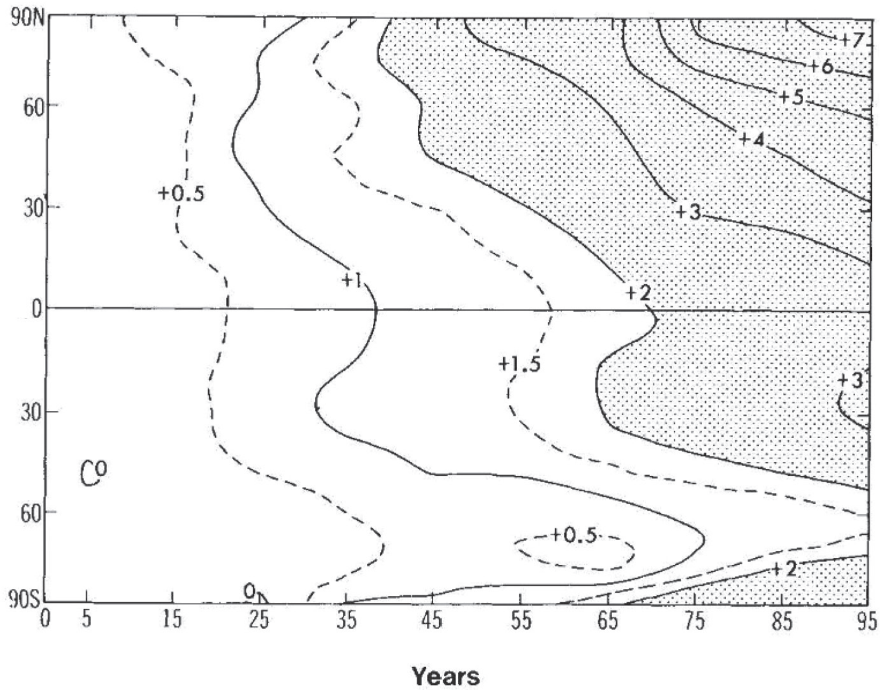

Figure 1: Latitude-time diagram showing the simulated zonal-mean surface warming in a 100-year integration of one of the first coupled atmosphere-ocean models, published in 1989 [16]. In this idealized simulation the CO_2 concentration was gradually increased by 1% per year. See Figure on the cover page for an analysis based on observations.

It is worth to reflect on the realism of this early simulation and its usefulness to estimate the future. Figure 1 emphasizes two salient features of global warming induced by a gradual increase in the greenhouse gas concentration in the atmosphere. First, the model simulates a substantial polar amplification of warming in the northern hemisphere from about 45° to 90°N. This is due to the positive snow-albedo feedback: warmer temperatures melt snow and sea ice and allow the surface to absorb more heat. Second, there is a strongly delayed warming in the southern hemisphere between about 40° to 75°S. This is caused by efficient uptake of heat into the Southern Ocean. In consequence, the coupled model predicts a strongly asymmetric response of the global climate system to the increase in CO_2. More than

30 years after this projection, this characteristic spatial distribution of the warming is unequivocally observed. The Figure on the cover of this issue shows observed zonal mean surface temperatures (HadCRUT5.0 data set), relative to 1850-1900 in decadal running means, as functions of time and latitude. Both the more rapidly evolving heating in the northern high latitudes and the polar area, and the delayed warming in the southern mid- to high-latitudes, are clear patterns of the observed surface temperature changes. In spite of the idealized CO_2 scenario used in 1989, this early model predicted the patterns of warming remarkably well [18].

This realism is also a prerequisite for a further key contribution in climate science. Building on the early statistical work, Hasselmann and colleagues developed new statistical techniques to detect observed climate change and attribute it to different drivers. The approach uses pattern analysis — empirical orthogonal functions, and variants thereof — on fields of observed climate variables such as temperature, precipitation, etc., and their twins in climate model simulations. This fingerprinting method permitted them to individually estimate the contributions of greenhouse gases, aerosols and solar variations to the observed global mean surface warming [19]. Today, detection and attribution has evolved into a new and vigorous field in climate research. Through the combination of the latest satellite and in situ observations with climate model simulations, observed changes in the three-dimensional structure of temperature in the atmosphere, precipitation, sea ice extent, ocean heat content, heat wave occurrence, sea level, and many more, can be quantitatively attributed to the increase in greenhouse gas concentrations and therefore to human activity. Most recently, these techniques have been applied to single extreme events. This event attribution [20] could have serious legal implications regarding liability for loss and damage caused by climate extreme events exacerbated or triggered by climate change.

It is remarkable to see the convergence of the work of these two climate scientists: Syukuro Manabe starting from the radiative fluxes in the atmosphere, and Klaus Hasselmann from the effect of random weather fluctuations on global climate. Both have laid the foundation for the development of comprehensive climate models that have been used to investigate and understand the physical processes that shape the Earth's climate. Since the early 1990ies, significant progress has been made by incorporating the carbon cycle in the ocean and on land, dynamical formulations of vegetation types, the chemistry of the atmosphere and polar ice sheets. This made coupled climate models also attractive tools for interdisciplinary research. Today coupled models include modules of chemistry to investigate tropospheric and stratospheric chemical reactions determining the composition of the atmosphere, modules of biogeochemistry to study the ocean's role in influencing the atmospheric CO_2 concentration both in the past and the future, or modules of biology when questions regarding changes in land vegetation or in marine organisms are addressed.

With the ever growing computer power, the currently most advanced coupled climate models have a grid resolution of 1 km globally, more than 500 times finer than in their infancy. They are now able to simulate local weather systems and impact of climate change with an unprecedented degree of realism. Manabe and Hasselmann, together with countless colleagues, have given us the tools for a physical understanding of our planet. These tools are now available for decisions regarding the future of our Earth system. The significance of their contributions is most appropriately recognized by the Nobel Prize in Physics 2021.

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Figure Cover Page

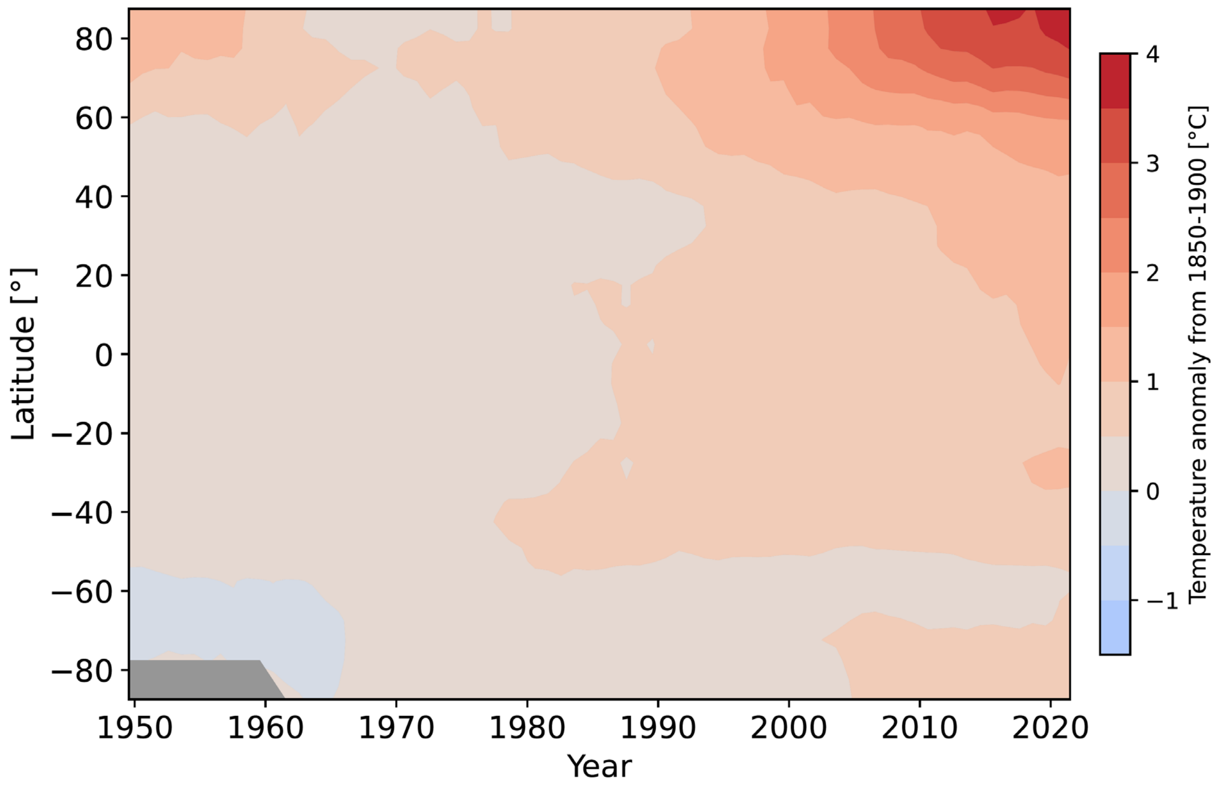

Figure Caption: Observed evolution of zonal mean surface temperature relative to 1850-1900, from 1950 to October 2021 in decadal running means, as functions of time and geographical latitude. The amplification of the warming in the northern hemisphere (ca. 45° to 85°N), and the strongly delayed warming in the south (ca. 40° to 75°S) are observed features that were predicted by climate model simulations already in the late 1980ies. Figure by C. Wirths, Physics Institute, University of Bern, based on the HadCRUT5.0 analysis.

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Annual Meeting of the Swiss Physical Society

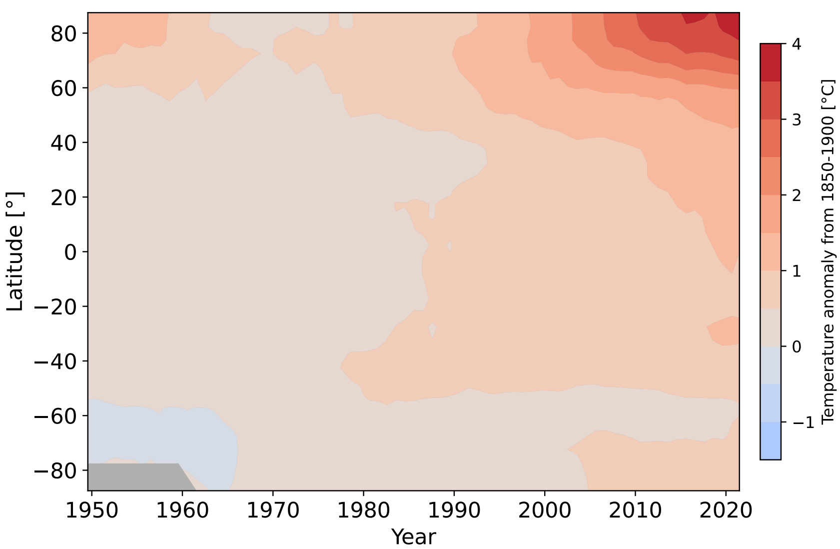
27 - 30 June 2022, Université de Fribourg

in collaboration with

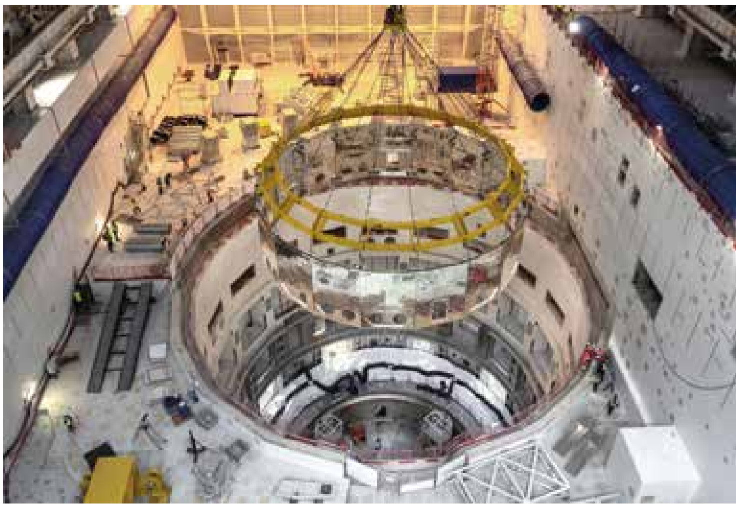
CHIPP, NCCR Bioinspired Materials, SGN,
Département de Physique - Université de Fribourg

Call for Abstracts: Submission Deadline 15 March 2022

More information on page 4.



Observed evolution of zonal mean surface temperature change since 1950, relative to 1850 - 1900. For more information see article on p. 22.
(Figure by C. Wirths, Physics Institute, University of Bern)



A joint SPS - EPS delegation had been invited for an amazing visit to the ITER construction site (p. 28). This image shows the lower cryostat thermal shield being successfully lowered in the tokamak pit and inserted into the cryostat base, begin of 2021. © ITER