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Climate change is physics

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Two founding fathers of climate science and climate modelling were honoured with the Nobel prize in physics this year. They led early climate research towards both fundamental and societally relevant research, which is now as vital as it was then.

The Nobel Committee awarded the physics prize this year "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming". Two of the three laureates—Klaus Hasselmann and Syukuro Manabe—pioneered climate modelling, from elegant conceptual explanations of observed climate properties to the comprehensive modelling based on numerical fluid dynamics used today. Climate modelling now transitions (almost) seamlessly from weather forecasting to decadal climate prediction and projection of future climate, and will eventually encompass digital Earths (https://www.wcrp-climate.org/digital-earths). Modelling is our best window into the future. As such, it is a key element of understanding and mitigating climate change.

Importantly, the award of the Nobel prize highlights that climate modelling is physics. This renders the question 'do you believe in global warming' meaningless: whether the globe warms in response to greenhouse gas increases is determined by the physics of energy balance. It is not subject to belief systems. Through their scientific work, both Hasselmann and Manabe established the scientific foundation for concern about increasing concentrations of greenhouse gases, particularly, the increase of CO_2 in the atmosphere arising from the burning of fossil fuels. The path of scientific enquiry they pioneered leads straight to the series of United Nations Climate Change Conferences of the Parties that seek to limit global climate change. The 26th meeting in the series, COP26, brought together world leaders in Glasgow in November 2021.

Two champions, two hubs

Syukuro ("Suki") Manabe worked as a senior researcher at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton. From the 1960s onwards, he played a leading role in developing the first climate model. His initial atmospheric modelling work explained the vertical temperature structure of the atmosphere as a response to radiatively active trace gases and explored convection and the fluid dynamics of the atmosphere[1]. Many of Manabe's papers are now classics that climate scientists (including myself) still use in teaching. His modelling work provided fundamental insights into the physics of the coupled climate system on all timescales, from ice ages to the response to human-caused greenhouse gas increases since the Industrial Revolution[2,3].

Klaus Hasselmann (pictured in Fig. 1) is the founding director of the Max–Planck Institute for Meteorology (MPI-M) in Hamburg. He initially focused on theoretical work: One of my favourite papers written by Klaus, and his most cited paper[4], is on 'stochastic climate models'. The theory is complex, based on the statistics of Brownian motion, but the fundamental idea is simple: short-term weather variability leads to long-term climate variability. This occurs because the slow components of the climate system, particularly, the ocean, integrate weather variability on daily to monthly scales into climate variability on annual and multi-decadal timescales. His paper on stochastic climate models is beautiful and explains the origin of unforced long-term climate variability, including its spectral shape, which is clearly visible in observed sea surface temperatures[5] and also in the variability of today's climate models. The concept reaches to even longer timescales: large ice sheets, analogously, integrate variability on ocean timescales to

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Fig. 1 Klaus Hasselmann. Photo credit: Julia Knop, MPG.

variability on timescales of thousands of years. This recognition of the stochastic nature of climate variability has changed our understanding of observed climate.

A few years after his seminal 1976 paper, Klaus' group began a major climate modelling approach based on fluid dynamics equations for atmosphere and ocean. The GFDL and MPI-M research groups applied climate models to simulate the effect of increasing greenhouse gas concentrations. Researchers from both groups warned[3,6,7] that substantial long-term warming is expected in response. These early models were rather simple due to limitations in available computational power, yet they already featured many aspects of future climate change that are still predicted today. They simulated a sensitivity to sustained CO_2 doubling that is consistent with that in today's models and in the most recent assessment report by the Intergovernmental Panel on Climate Change (IPCC)[8]. Key features of the expected pattern of change in surface temperature also have remained consistent: the Arctic warms more than the tropics, the land more than ocean. Across the lower atmosphere (the troposphere) we expect warming, whereas the stratosphere cools in response to stronger absorption by greenhouse gases in the troposphere and in response to human-cause depletion of ozone in the lower stratosphere.

Detective work

Yet the big test of the models' accuracy in predicting human influence on climate is to identify a predicted change in observational data. Klaus turned to the question of what it would take to detect warming in response to increasing greenhouse gases against the background of pronounced climate variability on all timescales that his statistical model predicted. Rather than searching for a needle in the haystack of multi-dimensional climate variability, the approach he proposed was to search, in observational data, for the pattern of climate model-simulated change in response to greenhouse gases that have been robustly predicted by climate models. The clue to success is to identify and then focus on the aspects of the pattern that are most distinct from natural climate variability, called the 'optimal fingerprint' of climate change[9]. This involves a noise-reducing metric based on the inverse covariance matrix of climate variability.

Under Klaus Hasselmann's and Hans von Storch's guidance, I applied the method to observe trends in global surface temperature data, following Klaus' argument that one of the distinctive features expected in the response to greenhouse gas increases is a rapid warming trend[10]. In parallel, Ben Santer applied a closely related approach to radiosonde and satellite data of the vertical profile of atmospheric temperature change. Based on Suki's early modelling work and on signal-to-noise studies from Ben's collaboration with Klaus[11] the vertical profile was expected to show a strong signal of combined tropospheric warming and stratospheric cooling.

By the 1990s, both the surface temperature and atmospheric temperature profile data indicated that climate was indeed changing in a statistically significant way: they showed a change that exceeded estimates of the unforced or 'internal' climate variability that were available at the time. Since then, these results have been confirmed and strengthened: the observed human-induced change has become stronger, and both models and observations themselves have improved. The divergence of the observed changes in climate and internal climate variability now exceeds the statistical threshold that is used for the detection of elementary particles in physics[12]. The identification of anthropogenic warming is now "unequivocal"[8]. Klaus further proposed a method to distinguish explicitly between different possible causes of climate change[13], which we applied to show that the observed warming is consistent with the combined effect of greenhouse gases and aerosols, but could not be explained by solar variability nor by greenhouse gas effects without aerosols[14].

Inspiring leaders. In addition to leading research groups that developed climate models, both Klaus and Suki used these models to address fundamental questions about how the climate system works, how it varies, how it evolved over time, and how increases in greenhouse gases may affect it. This age of early climate modelling was marked by a multitude of exciting new discoveries about mechanisms of climate variability and causes of observed change. Palaeoclimatic studies used models to explain the past, and past data were increasingly used to evaluate the models. At MPI-M, the intellectual atmosphere was one of exciting, pioneering science where new insights emerged from applying new modelling tools to understand climate variability and change (see, for example, Fig. 2). We looked at all timescales—from the possible effects of large changes in ocean configurations that happened over the course of thousands to millions of years, way back in Earth's history, to the future consequences of greenhouse gas increases over the coming decades to centuries.

At MPI-M, the founding director gave the science a direction and asked exciting questions. The group then attempted to answer these questions, challenged and directed by Klaus, in a golden time of discovery that the people involved look back on fondly (see this account[15]). From talking to people who worked at GFDL I get the sense that the scientific atmosphere there was similar. Both Klaus and Suki were recognised as truly exceptional scientists by their colleagues and coworkers, as well as impressive human beings and interesting people to be around: enthusiastic, joyful, and optimistic.

Klaus kept optimistic not only about scientific enquiry, but also about the ability of humanity to deal with climate change. I very much hope that his optimism is well-placed, and that moving away from fossil fuels will bring new opportunities. Klaus has always advocated to try new things in science, too.

Into the future. Climate science continues. We do not yet fully understand or predict all processes involved in the interactions of atmosphere, ocean, land surface, and biosphere. These interactions are particularly important in terms of the carbon cycle. Considering societal interactions with the Earth system is even trickier, yet critically important. Many climate problems—such as the availability of water—are fundamentally altered by human actions. Our choices in terms of water management, irrigation, and planting or removal of vegetation have implications for climate. As climate change unfolds, stronger evaporation may fuel droughts and enhance extreme heat, and enhance fire activity, and then in turn a changing vegetation may affect our ability to slow emissions. Melting glaciers and large ice

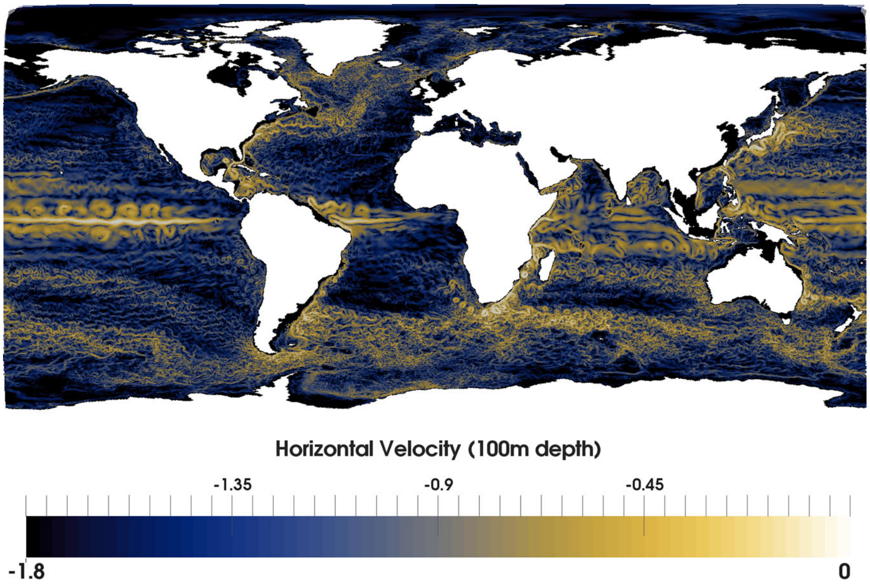

Fig. 2 Recent high resolution ocean model output, visualising ocean currents in 100 m depth. Simulations are performed with the ICON ocean model (https://www.dkrz.de/de/kommunikation/galerie/Vis/ozean/icon-ocean-experiments). Note the Western Boundary currents, and turbulent flow in the tropical Pacific and near the South tip of Africa, features that have only recently been resolved in models.

sheets influence the climate around them but also have ramifications for sea level rise and water availability over the summer. There are nonlinearities and tipping points that we had better understand well and avoid (see https://www.wcrp-climate.org/safe-landing-climates). We also need reliable information for decisions on how to adapt to climate change.

The two new Nobel laureates led us through the early days of climate research with great success, and opened a broad field of scientific enquiry. Climate science will continue to both provide exciting discoveries about how the planet works, and actionable information on the human footprint on the planet.

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Competing interests

The author declares no competing interests.

Additional information

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