Complex and yet predictable: The message of the 2021 Nobel Prize in Physics

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Syukuro (Suki) Manabe, Klaus Hasselmann, and Georgio Parisi were awarded the 2021 Nobel Prize in Physics. At first blush, this prize appears to recognize unrelated work in disparate fields. Even one of the Nobel Committee members acknowledged in the postannouncement press conference that it looks like a “split prize.” Upon reflection, however, there is a common thread running through the works of the awardees. Simply put, this year’s prize in physics acknowledges that disordered systems are predictable and that systems that behave chaotically can respond predictably to changes in external parameters. Earth’s climate is one such complex system, and it is of great importance to humanity. Its future must be predicted to guide policy. The prize also acknowledges that changes in the climate, like the properties of disordered condensed matter, are predictable using methods grounded in sound physics. Therefore, it is very appropriate to jointly recognize the foundational work done by these three visionary researchers with the Nobel Prize in Physics.

This Nobel Prize in Physics is very different from the earlier Nobel Peace Prize awarded in 2007 to former Vice President Al Gore and the Intergovernmental Panel on Climate Change (IPCC), which recognized the importance of human-induced climate change and the actions needed to understand and mitigate it. It is also different from the 1995 Nobel Prize in Chemistry to Profs. Rowland, Molina, and Crutzen for their work on a global environmental problem arising from ozone depletion by manufactured chemicals, some of which were also major greenhouse gases. In contrast to those two earlier awards, the 2021 Nobel Prize in Physics recognizes the fundamental scientific basis of climate predictability, detection of change due to known external forcings, and the predictability of disordered condensed matter.

Climate scientists Syukuro Manabe and Klaus Hasselmann were recognized “for the physical modelling of Earth’s climate, quantifying variability and reliably predicting global warming,” according to the Nobel citation (1). Manabe’s early work was carried out at the General Circulation Research Section of the US Weather Bureau, which later became the National Oceanic and Atmospheric Administration’s Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. Manabe focused on “simple models” of the well-understood fundamental physics of radiative transfer, atmospheric dynamics, and land and ocean processes (2). These simple models could be run on the computers of the 1960s and 1970s, which were feeble compared to today’s supercomputers. Manabe’s early research showed the importance of radiation and convection for establishing the vertical structure of climate models.

Klaus Hasselmann. Image credit: Julia Knop/Max Planck Society.

Syukuro Manabe. Image credit: Denise Applewhite (Princeton University, Princeton, NJ).

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the atmosphere and the energy balance of the earth system (3).

Manabe’s global warming studies built on the pioneering discoveries of Svante Arrhenius (4) and Guy Stewart Callendar (5). Arrhenius, who received the 1903 Nobel Prize in Chemistry for his work on conductive electrolytes, realized in his 1896 study that carbon dioxide (he used the term “carbonic acid”) is an important greenhouse gas (4). He calculated that its doubling would increase the global-mean surface temperature by about 2 K. Callendar documented in 1938 the anthropogenic increase in atmospheric CO2 and evaluated its radiative influence as a greenhouse gas (5). An important distinguishing feature of Manabe’s model was that it included the powerful effects of cumulus convection, which were omitted in the calculations of Arrhenius and Callendar. Manabe’s results highlighted the vital role of water vapor as a greenhouse gas (4). He calculated that its doubling would increase the global-mean surface temperature and its powerful amplifying feedback on climate change. A few years later, in 1975, Manabe and Wetherald (6) used a more complete version of the model to predict that an increase in CO2 would lead to warming almost everywhere at the Earth’s surface, particularly strong warming in the Arctic, a decrease in the Earth’s ice and snow cover, an increase in the globally averaged rate of precipitation, and a cooling of the stratosphere, all of which are now observed in the latest IPCC assessment of 2021 (7). “Dr. Manabe is very deserving of the Nobel Prize for his early pioneering research,” notes Warren Washington of the National Center for Atmospheric Research in Boulder, Colorado, himself one of the earliest developers in the 1960s of groundbreaking computer models of climate.

Manabe’s predictions of the effect of increasing atmospheric CO2 formed a critical background for the National Academy’s famous “Charney report” (8) (Ad Hoc Study Group on Carbon Dioxide and Climate, 1979). Hansen et al. (9), Washington and Meehl (10), and others (11) later used different models to obtain results consistent with Manabe and Wetherald’s 1975 paper (6). The Charney report and research by Hansen, Washington, and others pointed to a need to mitigate climate change by reducing anthropogenic greenhouse gas emissions. The unequivocal attribution of climate change to anthropogenic activities remained a significant research challenge, however. This is where the research of oceanographer Klaus Hasselmann, at the Max-Plank-Institute for Meteorology in Hamburg, Germany, enters the story.

As Benjamin Santer told us: “Hasselmann (12) launched in 1979 an entire field of scientific inquiry. He provided a statistical roadmap for anthropogenic signal detection.” In later work, Hasselmann (13) demonstrated convincingly how to separate the “fingerprint” of forced climate change (i.e., that caused by increased anthropogenic greenhouse gas emissions) from the noisy unforced variability that is inherent in the climate system (14). Hasselmann’s work led to the unambiguous attribution of large-scale changes in key observed climate parameters, such as surface temperature and precipitation, to human-caused increases in greenhouse gases. Santer further noted that “without Hasselman’s signal-to-noise studies, the IPCC’s 2021 Sixth Assessment Report (7) would not have concluded that human influence on climate is pervasive and unequivocal.”

Hasselmann also showed that aspects of climate variability are predictable despite the chaos of the day-to-day weather (12, 15). The role of chaos in limiting the skill of deterministic weather forecasts was originally highlighted by meteorologist Edward Lorenz in 1963. Lorenz’s foundational research led to the development of chaos theory (16), which shows that minor differences in initial conditions can cause a chaotic system (e.g., the atmosphere) to evolve into very different states and thus limit predictability. Lorenz demonstrated that even simple physical systems could behave chaotically. He also showed that the statistical behavior of chaotic systems is predictable. His work led to today’s probabilistic weather forecasts based on ensembles of simulations. In particular, it showed that even the highly variable climate system is indeed predictable.

In 1976 Hasselman (12) built on Lorenz’s ideas to explore the role of stochastic high-frequency fluctuations
of the atmospheric circulation in producing lower-frequency climate variability. In particular, he developed a very simple model of the upper ocean, in which sea surface temperature (SST) variability is driven entirely by the sea-surface turbulent and radiative fluxes associated with high-frequency, stochastic atmospheric variability. The model assumed that the damping of the SST variability is linearly proportional to the magnitude of the SST anomaly. In this case, there is neither variability in the ocean circulation nor feedback from the SST to the fluxes at the air–sea interface. Despite its simplicity, Hasselmann’s model could account for a remarkably large fraction of the observed variance and persistence of the SST (17).

The Nobel Prize also recognizes physicist Giorgio Parisi of Sapienza University of Rome “for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales” (1). The Nobel citation further notes that “around 1980, Parisi discovered hidden patterns in disordered complex materials. His discoveries are among the most important contributions to the theory of complex systems. They make it possible to understand and describe many different and apparently entirely random materials and phenomena, not only in physics but also in other, very different scientific disciplines, such as mathematics, biology, neuroscience and machine learning” (1). To this list, we add “climate.”

Together, Manabe, Hasselmann, and Parisi have created a foundation for understanding and predicting the behavior of complex systems. Manabe’s early work dealt with the physically based representation of key climate processes in numerical models. Hasselmann’s work showed the viability of statistical predictability in a chaotic system. Parisi’s work dealt with the disorder from atomic to cosmic scales, sometimes self-generated, again taking a statistical view. As Prof. Subir Sachdev of Harvard notes, “Parisi worked on the issue of chaos itself, and he developed a rather intricate model of it, far from that of a Gaussian random process. He applied it to various optimization problems in which one takes a statistical view of an ensemble.”

Scale interactions, across both space and time, are the dominant feature of all aspects of climate predictions, and indeed in predictions involving complex systems. Global models of the atmosphere, ocean, and land surface have been under intensive development for about 60 years, and enormous progress has been made in their representation of Earth’s climate (18, 19). Relative to Manabe’s pioneering model, today’s global models include a far broader range of components (including land, ocean biogeochemistry, and carbon cycle processes, as well as atmospheric chemistry), use more accurate computational methods, and have a much higher spatial resolution. We are entering an era of true “Earth System Models” that will provide the basis for more precisely predicting the human impacts of climate change, guiding adaptation strategies, setting mitigation targets, and providing the detailed information needed to enable robust decision-making.

In the case of anthropogenic climate change, predicting the evolution of the forcing agents (greenhouse gases and aerosols) is just as important. These forcing agents are, in principle, under human control. This is the backdrop for the decisions of the world leaders at the Conference of the Parties meeting on climate (COP26) in October and November 2021, and in the coming years, to maintain a habitable Earth.

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1 The Nobel Prize, Press Release: The Nobel Prize in Physics 2021. https://www.nobelprize.org/prizes/physics/2021/press-release/. Accessed 29 December 2021.
2 S. Manabe, J. Smagorinsky, R. F. Strickler, Simulated climatology of a general circulation model with a hydrologic cycle. Mon. Weather Rev. 93, 769–798 (1965).
3 S. Manabe, R. T. Wetherald, Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. Atmos. Sci. 24, 241–259 (1967).
4 S. Arrhenius, On the influence of carbonic acid in air upon the temperature of the ground. Philosophical Magazine and Journal of Science 41, 237–276 (1896).
5 G. S. Callendar, The artificial production of carbon dioxide and its influence on temperature. Q. J. R. Meteorol. Soc. 64, 223–240 (1938).
6 S. Manabe, R. T. Wetherald, The effects of doubling the CO2 concentration on the climate of a general circulation model. J. Atmos. Sci. 32, 3–15 (1975).
7 IPCC, “Summary for policymakers” in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Masson-Delmotte, et al., Eds. (Cambridge University Press, 2021), in press.
8 J. Charney et al., Carbon Dioxide and Climate: A Scientific Assessment (National Research Council, National Academy of Science, Woods Hole, MA, 1976).
9 J. Hansen et al., Climate impact of increasing atmospheric carbon dioxide. Science 213, 957–966 (1981).
10 W. M. Washington, G. A. Meehl, General circulation model experiments on the climatic effects due to a doubling and quadrupling of carbon dioxide concentration. J. Geophys. Res. 88, 6600–6610 (1983).
11 National Research Council, Carbon Dioxide and Climate: A Second Assessment (Washington, DC, 1982).
12 K. F. Hasselmann, “On the signal-to-noise problem in atmospheric response studies” in Meteorology Over the Tropical Oceans, D. B. Shaw, Ed (Royal Meteorological Society, 1979), pp 251–259.
13 K. Hasselmann, Optimal fingerprints for the detection of time-dependent climate change. J. Clim. 6, 1957–1971 (1993).
14 B. D. Santer et al., Celebrating the anniversary of three key events in climate. Nat. Clim. Chang. 9, 180–182 (2019).
15 K. Hasselmann, Stochastic climate models part I. Theory. Tellus 28, 473–485 (1976).
16 E. N. Lorenz, Deterministic nonperiodic flow. J. Atmos. Sci. 20, 130–141 (1963).
17 M. A. Alexander, C. Deser, M. S. Timlin, The reemergence of SST anomalies in the North Pacific Ocean. J. Clim. 12, 2419–2433 (1999).
18 P. Bauer, A. Thorpe, G. Brunet, The quiet revolution of numerical weather prediction. Nature 525, 47–55 (2015).
19 D. A. Randall et al., 100 years of Earth system model development. Meteor. Mon. 59, 12.11–12.66 (2019).