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Physical modelling of Earth's climate: 2021 Nobel Prize winners in Physics Syukuro Manabe and Klaus Hasselmann

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Abstract: In 2021, the Nobel Prize in Physics was awarded "for groundbreaking contributions to our understanding of complex systems", with half awarded 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". S. Manabe demonstrated for the first time how elevated levels of carbon dioxide in the atmosphere lead to increased temperatures on the Earth's surface. K. Hasselmann created a model that connects weather and climate together, developed methods for determining specific signals that leave an imprint on the climate.

Keywords: complex physical systems; physical modelling of Earth's climate; 2021 Nobel Prize winners in Physics Syukuro Manabe and Klaus Hasselmann.

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Физическое моделирование климата Земли: лауреаты Нобелевской премии по физике 2021 года Сюкуро Манабе и Клаус Хассельманн

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Аннотация: В 2021 году Нобелевская премия по физике присуждена «за новаторский вклад в наше понимание сложных систем», причем половина присуждена совместно Сюкуро Манабе и Клаусу Хассельманну «за физическое моделирование климата Земли, количественную оценку изменчивости и надежное прогнозирование глобального потепления», другая половина Джорджо Паризи «за открытие взаимодействия беспорядка и флуктуаций в физических системах от атомных до планетарных масштабов». С. Манабе впервые продемонстрировал, как повышенный уровень углекислого газа в атмосфере приводит к повышению температуры на поверхности Земли. К. Хассельманн создал модель, которая связывает воедино погоду и климат, разработал методы определения конкретных сигналов, которые накладывают отпечаток на климат.

Ключевые слова: сложные физические системы; физическое моделирование климата Земли; лауреаты Нобелевской премии по физике 2021 года Сюкуро Манабе и Клаус Хассельманн.

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The Nobel Prize in Physics 2021 was awarded "for groundbreaking contributions to our understanding of complex systems". The prize was divided equally: the first half of the prize (5 million SEK) was awarded to Syukuro Manabe, the Japanese professor from Princeton University (USA), and Klaus Hasselmann, the German scientist from the Max Planck Institute in Hamburg, "for physical modeling of the Earth's climate , quantification of variability and reliable prediction of global warming"; the second half wasawardedto Giorgio Parisi from the University of Rome La Sapienza (Sapienza – Università di Roma) "for the discovery of the interaction of disorder and fluctuations in physical systems from atomic to planetary scales" [1–4].

The press release from the Royal Swedish Academy of Sciences dated October 5, 2021 states: "One complex system of vital importance to humankind is Earth's climate. **Syukuro Manabe** demonstrated how increased levels of carbon dioxide in the atmosphere lead to increased temperatures at the surface of the Earth. In the 1960s, he led the development of physical models of the Earth's climate and was the first person to explore the interaction between radiation balance and the vertical transport of air masses. His work laid the foundation for the development of current climate models.

About ten years later, **Klaus Hasselmann** created a model that links together weather and climate, thus answering the question of why climate models can be reliable despite weather being changeable and chaotic. He also developed methods for identifying specific signals, fingerprints, that both natural phenomena and human activities imprint in the climate. His methods have been used to prove that the increased temperature in the atmosphere is due to human emissions of carbon dioxide".[1]

Among all the complex and chaotic physical systems that surround us, the Royal Swedish Academy of Sciences singled out one – the climate of the Earth, especially its rapid change. This is the third Nobel Prize for the study of climate and its effects. In 2007, the UN Intergovernmental Panel on Climate Change (IPCC) and former US Vice President A. Gore were awarded the Nobel Peace Prize "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change." In 2018, the American W. Nordhaus received the Economics Prize "for integrating climate change into long-term macroeconomic analysis." However, these laureates did not directly study the climate, but only used the results of other studies.

Syukuro Manabe (Fig. 1) was born on September 21, 1931 in Ehime, Japan. He completed all stages of education at the University of Tokyo (Bachelor's degree in 1953, Master's degree in 1955, PhD in meteorology in 1958), and then moved to the United States, where in 1975 he received the US citizenship. He worked at the National Oceanic and Atmospheric Administration, taught at Princeton University, where he received a professorship. In 1997 he returned to Japan, where he worked for four years as director of the research program on global warming. Then he again worked at Princeton University (until 2003), and since 2005 he has been working again at the US National Oceanic and Atmospheric Administration. He has been the winner of many prestigious scientific awards in the world.

[1] https://www.nobelprize.org/prizes/physics/2021/press-release.

Fig. 1. Syukuro Manabe and his Nobel Prize
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Fig. 2. Klaus Hasselmann and his Nobel Prize
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Klaus Hasselmann (Fig. 2) was born on April 25, 1931 in Hamburg, Germany. In 1934, he emigrated to England with his family, returned to Hamburg in 1949. He graduated from the University of Hamburg in physics and mathematics in 1955, then until 1957 he studied physics and hydroaerodynamics at the University of Göttingen (PhD in 1957) and Institute of Hydroaerodynamics of the Max Planck Society. In 1961–1964, he worked at the University of California, Los Angeles (USA), then returned to his homeland, and since 1964 taught at the University of Hamburg, where from 1966 to 1975 he held the position of professor. In 1974, he founded the Max Planck Institute for Meteorology and served as director until 1999. In 1988-1999, he was the first scientific director of the German Climate Computing Centre. He is the founder of the European Climate Forum and the winner of several European scientific awards.

The main characteristics of complex physical systems are the emergence of disorder from order and the multitude of scales in space and time. Understanding of the nature of these phenomena is a colossal research task. The most obvious example is the transition from laminar to turbulent flow in a dynamical system: in this system and similar nonlinear systems, the characterization of the boundary between order and disorder is one of the most complex problems in physics. Turbulent thermal convection (for example, when boiling water) is a clear demonstration of the role of multiple scales in controlling the macroscopic mass and heat transfer that occurs in the Earth's atmosphere and is accompanied by internal, external and emergent phenomena.

Many scientists have been studying thermodynamic processes in the atmosphere since the 19th century (J.-B. Fourier, J. Foote, J. Tyndall, Nobel laureate S. Arrhenius and others). In the 20th century, direct observations were supplemented by the results of modeling processes in the atmosphere, based on the assumption of a greenhouse effect caused by solar energy and greenhouse gases, primarily CO_2. Although the famous Keeling curve (named after C. Keeling, who started the monitoring program in 1958) shows a permanent increase in CO_2 concentration by almost 100 units over 50+ years (from 320 to 420 ppm[2]), model spectra show that the most powerful greenhouse gas in the Earth's atmosphere is water vapor, the distribution of which we cannot directly control. Most likely, atmospheric water vapor is controlled by a complex hydrological cycle, and thermodynamic calculations show that for every degree of temperature increase, the atmosphere can contain about 7 % more water. Apparently, it is possible to track the temperature on the Earth's surface by the concentration of other greenhouse gases, but even the simple question of the relationship between CO_2 concentration and global physical climatology has not yet been answered. Nevertheless, even S. Arrhenius in 1896 established that the atmosphere is not saturated. More than a hundred years have passed, and modern spectroscopic measurements also show that CO_2 is far from saturation.

It is clear that any model is a kind of approximation to reality, taking into account many

[2] https://keelingcurve.ucsd.edu.

limitations. Global climate models are also the result of computational approximation of numerous subsystems of the atmosphere, taking into account physical laws. Recent advances in climate modeling are based on the concept put forward by K. Hasselmann in 1976 that the chaotic weather dynamics is based on variability over long time scales and depends on incoming solar energy and outgoing infrared energy. S. Manabe and co-workers were the first to propose a model of the atmosphere in the form of a one-dimensional column with a given profile of relative humidity and greenhouse gas concentration, in which thermodynamic processes were calculated taking into account radiative transfer and convective regulation. They were able to solve model equations for heat, mass, momentum, and radiation over the entire globe, showing that a doubling of CO_2 leads to a warming of 2.3–2.93 °C. In reality, the profile of greenhouse gases changes over time and the climate responds to this. Thus, S. Manabe formulated and substantiated the general circulation climate model (global climate model), which takes into account the processes in the atmosphere and ocean. Later, K. Hasselmann proposed a scheme for a systematic assessment of how models are compared with observations and what underlies the variability in both, modeled a generalized stochastic description of the dynamics of the ocean climate, linking it to the weather (Fig. 3). Now these models are the basis for understanding climate and its changes, as well as for weather forecasting.

No matter how good the models are, but physical cosmology and physical climatology are sciences based on the method of observation, and only what nature allows can be observed. Therefore, climate change models and weather forecasts can only be confirmed in the future. However, K. Hasselmann's idea was to use the models in retrospect, i.e. to answer the question of what circumstances led the climate to its current state whether it was a natural variability or an increase in greenhouse gas concentrations resulting from human activities.

In three papers published in 1979–1997, K. Hasselmann created the basis for a systematic comparison of climate models and observations. He proved that theory, observations and models provide significant information about the properties of the main climate signals and climate noises. It is the unique characteristics of the signal that can be used to distinguish signals from noise. The article by K. Hasselman [6] was a statistical roadmap for hundreds of subsequent studies on climate change and provided strong scientific support for the conclusion made in 2013 by the Intergovernmental Panel on Climate Change (Nobel Peace Prize winner 2007): "human influence… is *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century".

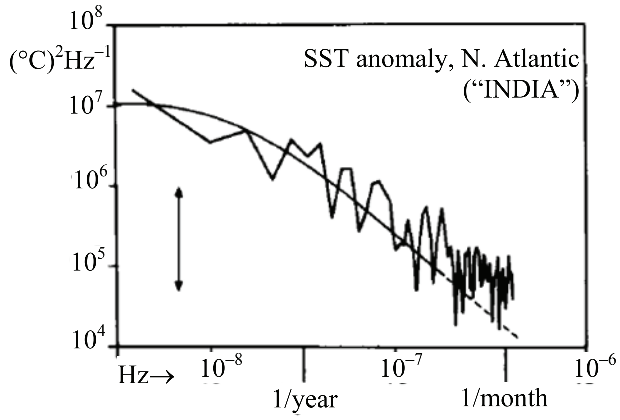

Fig. 3. First application of the stochastic Hasselmann model for climate variability: the sea surface temperature (SST) spectrum of the North Atlantic in 1949–1964. The 95 % confidence interval is indicated by a double-headed arrow [5]

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