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Understanding and building upon pioneering work of Nobel Prize in Physics 2021 laureates Syukuro Manabe and Klaus Hasselmann: From greenhouse effect to Earth system science and beyond

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Abstract The Nobel Prize in Physics 2021 was awarded jointly to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi for their groundbreaking contributions to our understanding of complex systems. This is the first time that climate scientists were awarded the Nobel Physics Prize. Here, we present the evolution of climate science in the past ~200 years and highlight the landmarks of the developments in advancing our understanding of climate change, placing the pioneering contributions of Manabe and Hasselmann into a historical perspective. The backbone of modern climate science is further discussed in the context of the development of the discipline from the discovery of the greenhouse effect to the formation of Earth system science. Perspectives on the future development of climate science are also presented.

Keywords Greenhouse gases, Climate change, General Circulation Model, Detection and attribution, Climate science, Earth system science

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1. Introduction

Syukuro Manabe from Princeton University and Klaus Hasselmann from the Max Planck Institute for Meteorology shared the 2021 Nobel Prize in Physics "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming". While the award is a public recognition of Manabe and Hasselmann's seminal personal contributions to "laying the foundations of our knowledge of the Earth's climate and its influence by human activities", their findings, together with the contribution of the climate research community, inform the public that the entire world, including humans and ecosystems, is affected by climate change and that this will continue.

The pioneering work of Manabe and Hasselmann on the causes and signs of human-induced climate change are honored together with Giorgio Parisi's contribution to disordered physical systems. The three laureates' contributions are combined under the umbrella of complex systems. The climate system is a prime example of a complex physical

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system since it features all the typical characteristics of a complex system (Slingo et al., 2009). The interactions among physical, chemical, and biological processes and various components, at a wide range of spatial and temporal scales, have generated complex behaviors in the Earth's climate. The contributions of Manabe and Hasselmann to the understanding and predictions of Earth's climate behavior are reasonably honored as "groundbreaking contributions to our understanding of complex systems".

It has been 195 years since Joseph Fourier uncovered the greenhouse effect in 1827 (Fourier, 1827). The role of the greenhouse effect in global warming is now understood in the context of climate system science and has been extended to Earth system science. Based on improved observational datasets to assess historical warming, as well as progress in scientific understanding of the response of the climate system to human-caused greenhouse gas (GHG) emissions, the UN Intergovernmental Panel on Climate Change (IPCC) concludes in its 6th assessment report from Working Group I that human influence has warmed the climate system, including the atmosphere, ocean and land, unequivocally (IPCC, 2021). Climate change is already one of the greatest challenges facing the world and humanity. This is, however, the first time that climate scientists have been awarded the Physics Nobel. Here, we briefly review the history of climate science and interpret the contributions of Syukuro Manabe and Klaus Hasselmann from a historical perspective. We also provide a perspective on discipline development from the greenhouse effect to the climate system and Earth system science.

2. The history of climate science

The development of climate change science has passed through the following important stages (see Archer and Pierrehumbert (2011) for a review and a depiction in Figure 1). In 1827, Joseph Fourier found that the atmosphere is largely transparent to solar radiation but is relatively opaque to infrared radiation, leading to a warmer planet than it would have been if sunlight were the only warming factor (Fourier, 1827). Subsequently, the warming effect of the Earth's atmosphere was termed "the greenhouse effect" for the first time by Nils Gustaf Ekholm in 1901 (Ekholm, 1901). In 1861, John Tyndall demonstrated the greenhouse effect in the laboratory. His laboratory studies were driven by questions of the Earth's climate and the greenhouse effect. His study implied that most GHG effects in the atmosphere are due to a few trace gases, such as water vapor and CO_2 (Tyndall, 1861).

In 1896, Svante Arrhenius calculated the warming caused by doubling CO_2 concentrations based on a one-layer model under the constraints of energy balance (Arrhenius, 1896), which is named "climate sensitivity" at present. This paper is regarded as the birth of modern climate science since the importance of satisfying the energy balance both at the top of the atmosphere and at the surface was identified. Arrhenius also described the water vapor feedback and the ice albedo feedback. In 1956, Gilbert Plass accurately calculated the radiative forcing of CO_2 for the first time and determined the infrared cooling rate and the net outgoing radiation at the top of the atmosphere caused by CO_2 (Plass, 1956). One year later, Charles David Keeling began to measure the atmospheric CO_2 concentrations at the Mauna Loa Observatory in Hawaii. This is the first time that human society recorded atmospheric CO_2 concentrations based on instrumental measurements (Keeling, 1960, 1970).

In 1967, Syukuro Manabe and Richard Wetherald made the first fully sound estimate of the magnitude of warming caused by a doubling of CO_2 concentrations based on a simple radiative-convective equilibrium model (Manabe and Wetherald, 1967), which represents the modern era of global warming research. In 1975, Manabe and Wetherald further developed the first credible three-dimensional atmospheric climate model (Manabe and Wetherald, 1975), which is known as the General Circulation Model (GCM). It was the first GCM to be able to deal with a doubling of CO_2, which reproduced the "polar amplification" phenomenon of global warming originally indicated by Svante Arrhenius.

In 1979, Jule G. Charney organized and compiled the first comprehensive assessment of Earth's climate change due to fossil fuel CO_2 emissions, which was entitled "Carbon Dioxide and Climate" and is now known as the famous "Charney Report" (Charney et al., 1979). The synthesis report stated that there was no doubt that a doubling of atmospheric CO_2 concentrations would lead to significant global climate change, resulting in global warming by 1.5–4.5°C, which is similar to the latest results given by the IPCC AR6 (Chen et al., 2021). The synthesis report of Charney yielded new insights and understanding that are central to the climate sciences.

In 1984, James Hansen provided a quantitative analysis of climate feedbacks, which was one of the early indications that cloud feedbacks have significant influences on climate sensitivity (Hansen et al., 1984). The paper of Hansen et al. (1984) thus represents a landmark in the development of climate models with regard to the quantitative analysis of climate feedbacks. Another important finding of the paper was the delayed warming of the ocean due to ocean heat storage (i.e., so-called "committed warming"). In 1986, strong observational evidence was provided to confirm global warming. This was typically represented by the Jones et al. (1986) paper entitled "Global Temperature variations between 1861 and 1984".

Despite the recognition of global warming and the greenhouse effect, further evidence is needed to link the observed

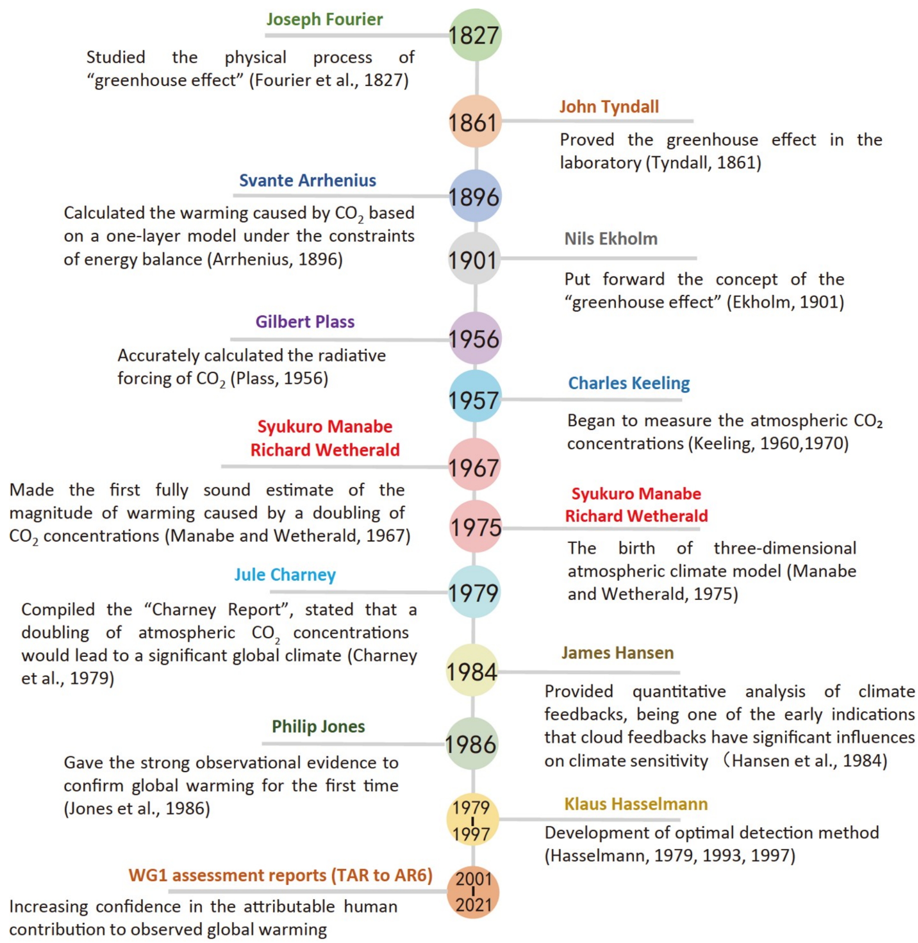

Figure 1 Key landmarks in the history of climate change science.

global warming to human-induced GHG emissions. The observed climate change is composed of internal variability and externally (both naturally and anthropogenic) forced changes. Understanding how a predictable climate system response emerges from chaotic behavior, detecting climate change and identifying its natural and anthropogenic causes have been challenging to climate science. Klaus Hasselmann developed the optimal detection method in a series of studies (Hasselmann, 1979, 1993, 1997) to identify climate change signals from the noise of internal variability. His methods of identifying "fingerprints" now allow the IPCC to assess whether the climate change observed over the past years is dominated by human activities. Through the years with growing evidence from detection and attribution studies, the IPCC WG1 assessment reports have concluded with increasing confidence on the human contribution to observed global warming, which is assessed as "*likely*" in TAR (2001), "*very likely*" in AR4 (2007), "*extremely likely*" in AR5 (2013), and "*unequivocal*" in AR6 (2021). This comes as a result of multiple factors, including the intensification of anthropogenic climate change signals associated with the increasing concentration of GHGs, the increases in observational data and development in climate models, improvements in detection and attribution techniques, and progress in the physical understanding of climate change.

In summary, the century-long development of climate science, including the pioneering contributions of Syukuro Manabe and Klaus Hasselmann, is the fundamental basis for the breakthroughs in our physical understanding of global warming. The award of the Nobel Prize in Physics to climate scientists also indicates that climate change science, with a solid mathematical and physical basis, is receiving more attention from the scientific community.

3. Syukuro Manabe's contributions

To address the global warming problem since the industrial revolution, scientists need to answer two core questions. One is how to physically elucidate the role of CO_2 in global climate warming and exactly predict the impact. The other is to what extent human activities contribute to global warming. Manabe's studies settled the first question, being the first to credibly compute the global temperature change under a doubling of CO_2 concentration. Here, two of his major academic contributions are highlighted.

First, Manabe, together with his cooperators, credibly predicted global warming under a doubling of CO_2 concentration by modeling the equilibrium between radiative and convective processes and involved the greenhouse effect of water vapor.

In 1967, Syukuro Manabe and Richard Wetherald collaborated on a paper entitled "Thermal equilibrium of the atmosphere with a given distribution of relative humidity", published in the *Journal of the Atmospheric Sciences*, operated by the American Meteorological Society (Manabe and Wetherald, 1967). In this paper, they developed a one-dimensional radiative-convective equilibrium model based on the latest advances in atmospheric radiation transfer theory. The energy in each layer from the bottom to top is redistributed by the adjustment between radiative cooling and convection; therefore, the observed atmospheric temperature profile is realistically reproduced in the single-column model. Based on the model, they calculated the near-surface temperature changes when setting CO_2 concentrations from 150 to 300 ppm and to 600 ppm and found approximately 2.3°C warming under every doubled CO_2 concentration (1 ppm=1 μL L^{-1}). This work pioneered realistic modeling of the temperature profile response to radiative forcing and reasonably estimated CO_2-induced global warming. They creatively used outgoing longwave radiation curves to intuitively explain how CO_2 changes could lead to surface warming and how water vapor feedback could increase climate sensitivity.

Second, Manabe, together with his cooperators, developed the first three-dimensional sophisticated GCM of the globe, which was the starting point of the modern climate model. This work initiated the development of a three-dimensional climate model based on global fluid dynamics and thermodynamic principles, which play indispensable and crucial roles in climate change research (Figure 2).

Manabe and Wetherald's radiative-convective model treated the Earth as a single column, in which the temperature distribution is subjected to vertical heat exchange from radiation and convection. However, the temperature change on Earth's surface is far from uniform. To obtain a complete picture of climate change, we need to predict the geographic distribution of warming and precipitation changes, and so on. To this end, the hydrological cycle and complex feedbacks related to water vapor, sea ice and snow cover should be included comprehensively. A three-dimensional GCM, which can adequately represent the above processes, is required to solve the three-dimensional fluid dynamic and thermodynamic equations that control the global heat, moisture and momentum transportations, as well as to realize the coupling between fluid equations and other equations that control physical processes such as radiation, convection and surface heat exchanges.

In 1975, Manabe and Wetherald published a paper titled "The effects of doubling the CO_2 concentration on the climate of a General Circulation Model" in *Journal of Atmospheric Sciences* (Manabe and Wetherald, 1975). This paper is credited with the birth of the General (Global) Circulation (Climate) Model (Figure 2). In this work, they constructed an atmosphere-ocean coupled model with an ideal land-sea distribution, in which the ocean was simplified as marsh and oceanic circulation and heat transport were ignored. By using such an idealized GCM, they demonstrated that CO_2-induced global warming was stronger than that in the simple radiative-convective model. They also showed the polar amplification phenomenon and intensification of the global hydrological cycle under global warming. The birth of the first GCM opened a new era of climate modeling. The present-day climate models are becoming increasingly sophisticated, but their ancestries are traced back to the model created by Manabe and his colleagues.

4. Klaus Hasselmann's contributions

Klaus Hasselmann has made fundamental contributions to understanding climate change from two aspects.

First, Hasselmann developed stochastic climate models to link weather and climate, in which the slowly varying climate variability on long time scales is interpreted as the response that emerges from rapidly varying weather disturbances on short time scales. By connecting the chaotic and random weather system and slow climate variations, his theory explains the origin of internal climate variability.

Inspired by his research experience in turbulence and ocean waves, as well as using the analogy of Brownian motion, Hasselmann proposed a generalizable stochastic description of climate variability. In 1976, he established stochastic climate models to explain the origin of internal climate variability, demonstrating that rapidly varying weather disturbances (i.e., the white noise of the atmosphere) can integrate to form slow variations in climate, thus allowing us to understand natural climate variability as red noise (Hasselmann, 1976). Taking the ocean response to the atmosphere as an example, the rapidly varying atmospheric system can disturb the temperature in the ocean mixed layer. The ocean mixed layer, working as a damper, delays the response of ocean temperature to the atmosphere, consequently resulting in slow variations in the ocean on long (even on decadal) time scales, such as the Pacific decadal oscillation (PDO; Yang et al., 2004). The ocean variations, subsequently, can lead to long-term variations in the atmosphere. His simple but elegant model explains how slow variations in the ocean emerge from chaotic weather behavior in the atmosphere, which has important implications for

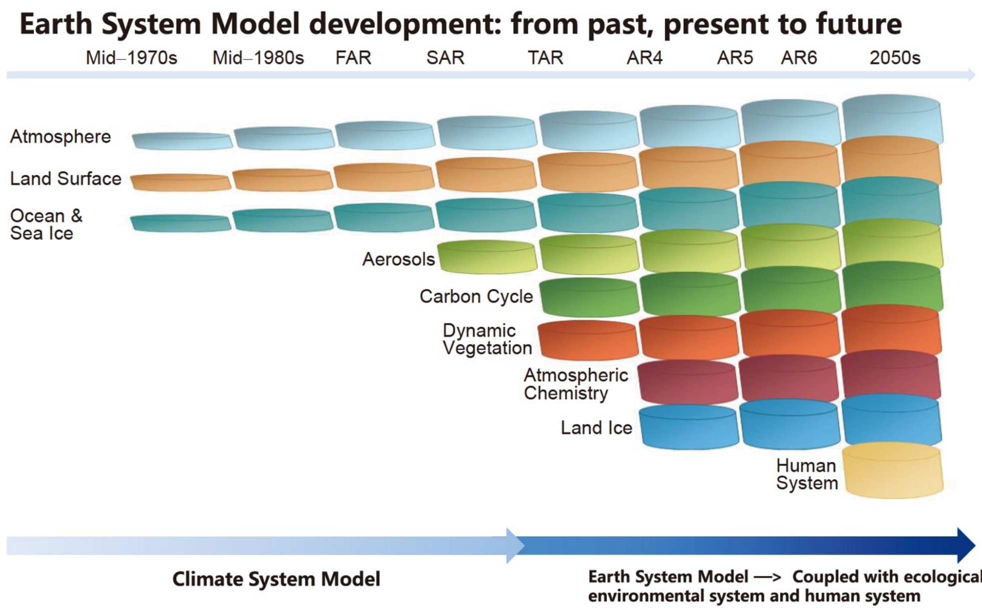

Figure 2 Past, present and future of Earth system model development. The figure shows the development from the climate system model to the Earth system model, which will be coupled with the ecological environmental system and human system in the future. The height of the cylinder indicates the complexity and improvement of the component (modified based on Figure 1.13 of IPCC AR5).

short-term climate predictions in theory.

Second, Hasselmann established the theoretical foundation of climate change detection and attribution. He developed methods for identifying the 'fingerprints' of external forcings, including greenhouse gases, on climate systems, which then allows detecting and attributing observed climate change to human influence.

The existence of internal climate variability means that any attempt to detect climate change is essentially a question of signal versus noise, i.e., whether the observed change ('signal') is outside the 'noise' of internal variability. In the book '*Meteorology Over the Tropical Oceans*' published in 1979, Hasselmann suggested that the identification of atmospheric responses to external forcings from atmospheric internal variability can be treated as the detection of distributions. With the release of the IPCC FAR in 1990, the detection and attribution of climate change became increasingly important. In his work published in *Journal of Climate* in 1993, he found that external forcings, including greenhouse gases, leave unique signals —fingerprints—in climate series, which can be identified. In this work, he proposed the concept of optimal detection, i.e., using 'optimal' techniques to increase the signal-to-noise ratio by looking at the component of the response away from the direction of highest internal variability, which can consequently increase the detectability of forced climate changes. Through years of development, this method was further extended to climate change attribution. To implement optimal detections, in addition to the optimal fingerprints, other approaches, including optimal weighting and optimal filtering, have also been developed (Hegerl and North, 1997). Despite different mathematical forms, these approaches share the same essential concept (Hegerl and North, 1997). With the concept of multiple regression being introduced later (Allen and Tett, 1999), the optimal detection method became easier to understand and more widely used, including the detection and attribution studies of Chinese climate changes (Ma et al., 2017; Sun et al., 2014; Zhou et al., 2020a; Zhou and Zhang, 2021; Sun et al., 2021, among many others).

The two major contributions of Hasselmann, i.e., explaining the origin of the slow-varying internal variability of the climate system and developing methods for identifying climate change signals from noise, laid the foundation for estimating human contributions to climate change. The methods of climate change detection and attribution provide strong scientific support for the conclusion reached by the IPCC AR6 that "*It is unequivocal that human influence has warmed the atmosphere, ocean and land. The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C*" (Figure 3).

From the establishment of stochastic climate models to the development of detection and attribution methods, Hasselmann has made fundamental contributions to addressing to what extent human activities have affected climate change. The conclusion that human influence has unequivocally contributed to the observed climate warming provides a solid scientific basis for international actions targeting climate change adaptation and mitigation.

In addition, from a methodological perspective, the es-

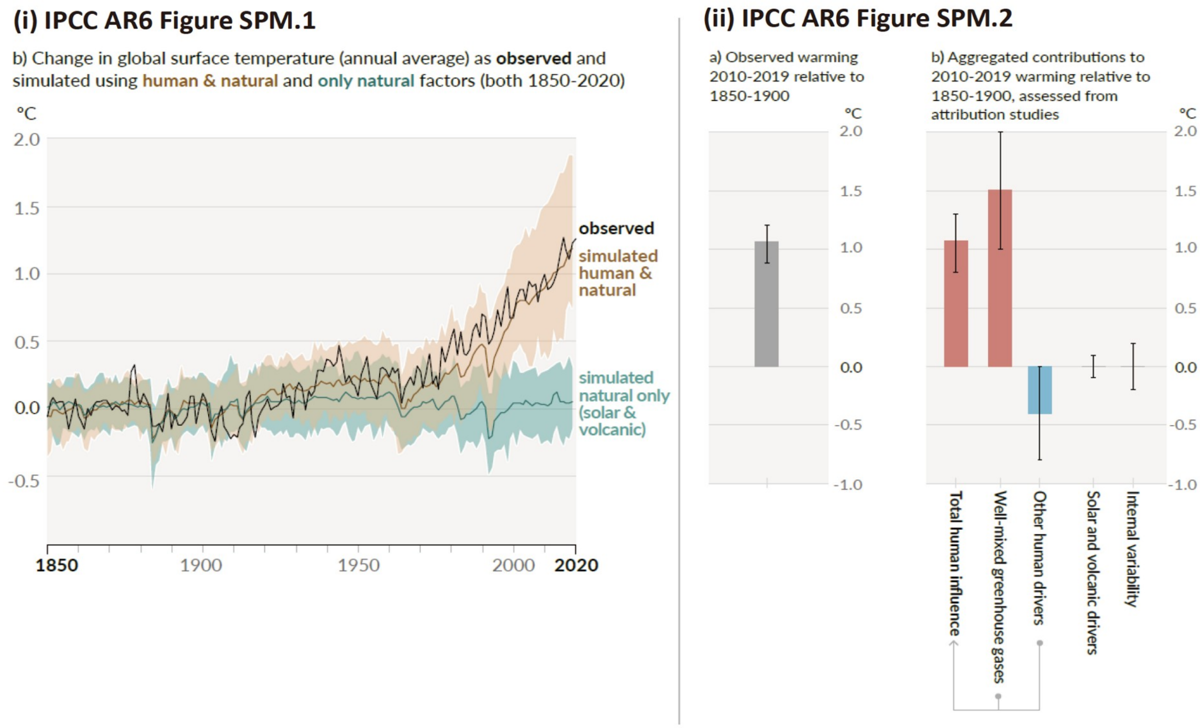

Figure 3 (i) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to CMIP6 climate model simulations of the temperature response to both human and natural drivers (brown), and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the very likely range of simulations (cited from panel b of Figure SPM.1 of IPCC AR6). (ii) Assessed contributions to observed warming in 2010–2019 relative to 1850–1900. (ii-a) Observed global warming (increase in global surface temperature) and its very likely range. (ii-b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to total human influence, changes in well-mixed greenhouse gas concentrations, other human drivers due to aerosols, ozone and land-use change (land-use reflectance), solar and volcanic drivers, and internal climate variability. Whiskers show likely ranges (cited from panels a and b of Figure SPM.2 of IPCC AR6).

tablishment of stochastic climate models was inspired by his research in turbulence, and the development of the detection and attribution method was inspired by the process of signals in information science. As such, Hasselmann has perfectly shown the benefits of multidisciplinary research efforts.

5. The backbone of climate science development

Supporting the evolutionary development of the discipline from the greenhouse effect to the climate system and Earth system are the following interrelated foci that drive climate science forward: observations, the theory of climate physics, the concept of the climate system, the emergence of Earth system science, synthesis such as IPCC assessment reports, and computer simulations of the climate system from the past to the future. They form the backbone of modern climate science.

First, the observations have provided solid evidence of global warming and have served as a testbed of theory and prediction. From John Tyndall (1861) and Svante Arrhenius (1896) to Manabe and Wetherald (1967) and the release of the famous Jule G. Charney Report in 1979, the fundamental physical processes that govern the role of GHGs, particularly CO_2, in causing global warming are mostly well understood. However, theoretical studies and predictions are only high-brow academic questions. When expensive decisions related to climate adaptation and mitigation activities are balanced, we need observations from the real world to test both the theory and the prediction. For this purpose, high-quality and reliable past and contemporary changes evinced by observations at a wide range of spatial and temporal scales are crucial. The famous *Keeling Curve*, which is an ongoing measurement of atmospheric CO_2 concentration at the Mauna Loa Observatory, Hawaii, started in 1957, has depicted the continuously increasing CO_2 concentrations and underpins the observational evidence of how humans are influencing the climate (Keeling, 1960, 1970; Pales and Keeling, 1965). The global average temperature of the Earth compiled by Jones et al. (1986) has shown evidence that the temperature rise began in the 1970s. The use of proxy measurements of temperature to extend the climate record back through the historical era of the last millennium and slightly further pioneered by Mann et al. (1998) provides evidence that the present-day temperatures are warmer than they have been over 1000 years. Based on evidence from both observations and proxy data, it was assessed in IPCC AR6 that "*Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (high confidence)*. *Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period*, *around 6500 years ago [0.2°C to 1°C relative to 1850–1900] (medium confidence)*" (IPCC, 2021).

Second, the recognition of climate change is built upon the development of the theory of climate physics. If we look at the timeline illustrating the development of climate physics from the beginning of the 19th century to 2021, when climate scientists were awarded the Nobel Prize in Physics for the first time, it has taken 195 years. Milestone studies during this period include the following (see also the summary in Figure 1). The greenhouse effect was first discovered by Joseph Fourier in 1827 and then demonstrated in the laboratory by John Tyndall in 1861. Having identified the greenhouse warming effect, scientists were devoted to estimating the warming that would result from a doubling of CO_2 concentrations, with the first estimate by Svante Arrhenius in 1896 based on a one-layer energy balance model and the first sound estimate by Manabe and Wetherald (1967) based on a simple radiative-convective equilibrium model. With Manabe and Wetherald (1967), the study of global warming entered the modern era. A few years later, the work by Manabe and Wetherald in 1975 landmarked the birth of the GCM, with which they for the first time showed a surface warming pattern due to a doubling of CO_2 concentration. All these efforts were synthesized into the famous Charney report in 1979, which concluded that there is no reason to doubt that doubling atmospheric CO_2 would lead to a significant change in the global average temperature. Hansen et al. (1984) presented landmark work with regard to the quantitative analysis of climate feedbacks. This provided the earliest indications that cloud feedbacks had the potential to greatly affect climate sensitivity. All these achievements have fostered international concern about climate change and eventually led to the establishment of the IPCC in 1988. Since the discovery of the greenhouse effect in 1827, nearly 200 years ago, the time is right for the resurgence of climate science.

Third, the concept of the climate system has emerged as a new scientific endeavor, triggered by the growing recognition that we need to understand global warming based on how the atmosphere, ocean, land surface, and cryosphere operate as an integrated system. Climate has been traditionally defined as a long-term average of meteorological elements, including temperature, pressure, humidity, etc. Starting from the 2nd half of the 20th century, with the recognition of the climate system concept, the study of climate change has entered the modern era. By the late 1960s, scientific concern about climate change began to mount due to the increasing carbon dioxide concentrations evident from the early observations at Mauna Loa and the devastating Sahelian drought of the 1960s. This brought the implications of climate variability and change back to the attention of the United Nations. In 1974, the sixth special session of the General Assembly called on the World Meteorological Organization (WMO) to undertake a study of climate change. Later, the First World Climate Conference (WCC-1) was held in Geneva from 12 to 23 February 1979 as "*a world conference of experts on climate and mankind*". The WCC-1 is regarded as one landmark that has greatly promoted studies of climate variability and change and their implications for society and the environment. It called on all nations to strongly support the proposed World Climate Programme. Closely following the recommendations of the WCC-1, it formally established the World Climate Programme with four components, including the World Climate Research Programme (WCRP) (initially entitled Climate Change and Variability Research Programme) (Zillman, 2009). In the past 40 years, the WCRP has been a leading initiative dedicated to coordinating international climate research. This was achieved as a result of the efforts of the international scientific community organized through four WCRP core projects, including CliC (Climate and Cryosphere), CLIVAR (Climate and Ocean-Variability, Predictability and Change), GEWEX (Global Energy and Water Exchanges), and SPARC (Stratosphere-troposphere Processes And their Role in Climate). The WCRP has played a crucial role in promoting our understanding of climate variability and change from the perspective of climate system science. The implementation of the WCRP fostered the establishment of the joint WMO-UNEP (the United Nations Environment Programme) IPCC in 1988. In the third assessment report (TAR) of the IPCC, the climate system is clearly defined as "*an interactive system consisting of five major components: the atmosphere*, *the hydrosphere*, *the cryosphere*, *the land surface and the biosphere*, *forced or influenced by various external forcing mechanisms*" (IPCC, 2001). The concept of the climate system has connected traditional disciplines, which typically examine the component changes in isolation, to build a unified understanding of the complex climate system, including their coupling processes and feedback mechanisms.

Fourth, the emergence and evolution of Earth system science have extended the research scope of climate change from physical science to interdisciplinary and transdisciplinary research. The emergence of Earth system science is built upon the recognition that life exerts a strong influence on the Earth's physical and chemical environment. The International Geosphere-Biosphere Programme (IGBP) addressed the challenge of disciplinary integration in 1986 by organizing several core projects on biogeochemical aspects of the Earth system. The implementation of IGBP core projects has fostered the convergence of disciplines, which in turn accelerated the evolution of Earth system science. This is evident in the transition from isolated process studies to interactions between these processes and increasing global-level observations, analyses, and modeling. The concept of the Anthropocene, introduced by P. J. Crutzen, the laureate of the Nobel Prize in Chemistry in 1995 for his work on the ozone layer, to describe the new geological epoch in which humans are the primary determinants of biosphere and climate changes, has built the foundation for deeper integration of the natural sciences, social sciences, and humanities (Crutzen and Stoermer, 2000). The 2001 Amsterdam conference, "Challenges of a Changing Earth", cosponsored by the four international global change programs, including the IGBP and WCRP, introduced the Amsterdam Declaration and finally led the IGBP to define the term "Earth system" as the suite of interlinked physical, chemical, biological and human processes (Steffen et al., 2020).

The famous Bretherton Diagram, a landmark of the Earth system concept, was the first systems-dynamics representation of the Earth system to couple the physical climate system and biogeochemical cycles through a complicated array of forcings and feedbacks. It provides a clear visual representation of the interacting physical, chemical and biological processes that connect components of the Earth system. The diagram highlights that human activities are significant driving forces for change in the system. In the World Climate Research Programme Strategic Plan (2019–2028), the classical Bretherton Diagram is used as a schematic to depict the components of the Earth system and their interactions.

Although there is still no generally accepted definition of an Earth system, in the WCRP Strategic Plan (2019–2028), the Earth system is clearly defined as "*Earth's interacting physical*, *biogeochemical*, *biological*, *and human systems*, *including the land*, *the atmosphere*, *the hydrosphere*, *and the cryosphere*", while the climate system is defined as "*the part of the Earth system that is relevant to climate*; *that is*, *the atmosphere*, *ocean*, *land surface*, *and cryosphere*, *their coupling processes and feedback mechanisms*" (WCRP, 2019). While the concept of the climate system focuses on the internal dynamics, external forcing and feedbacks among the components, the concept of the Earth system highlights the flows of carbon, energy, and water, in particular biogeochemistry cycle processes and their feedback (Figure 4). The definition by the WCRP focuses on the planetary surface, where the majority of energy, water cycle, and materials are cycled within the Earth system at the time scales considered by the WCRP. The emergence of the Earth system concept has extended the scope of climate research from ocean-atmosphere interactions, land-air interactions, and climate feedback processes associated with energy and water cycle exchanges to carbon feedback associated with complex biogeochemistry cycles.

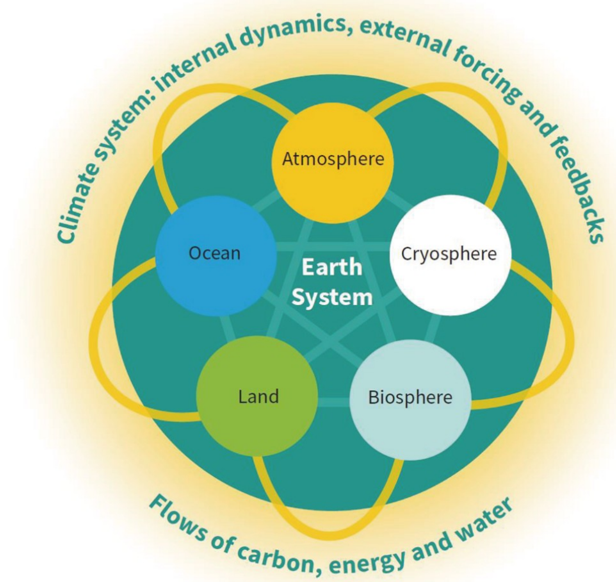

Figure 4 Climate relevant aspects of Earth system science (cited from WCRP Strategic Plan 2019, Figure 1).

Fifth, the IPCC has prompted the development of climate science by providing regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. The IPCC was created by the WMO and the UNEP in 1988. From 1990 to 2021, the IPCC produced 6 assessment reports, as well as a number of special reports and technical papers, by using increasingly rigorous and comprehensive assessment and review processes. Although the assessment of the IPCC is policy relevant and does not have a remit to prescribe policies, the science in the report has clearly influenced policy development as a gold standard for our current understanding of climate science. Meanwhile, the policy sectors have also prompted new research approaches for the climate sciences. The IPCC report has acted as a broker between the scientific and policy-making communities, facilitating new directions in climate research following feedback from the policy-making sectors (Zillman, 2009; Steffen et al., 2020). The IPCC was awarded the Nobel Peace Prize in 2007 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*".

Sixth, climate modeling supported by the quick development of supercomputers has driven modern climate science forward together with observations and theoretical investigations. Since the birth of the first GCM in 1975 (Manabe and Wetherald, 1975), climate models based on the fundamental mathematics, physics and chemistry of the climate system have since developed rapidly (see Figure 2 for a historical view). (1) Atmospheric General Circulation Model (AGCM) has been developed quickly since the mid-1970s. (2) AGCM has been coupled with land surface model since the mid-1980s. (3) AGCM was coupled with slab ocean model at the beginning of the 1990s and was used in climate projection in the IPCC First Assessment Report. (4) Starting from the mid-1990s, both sulfate aerosols and volcanic aerosols were included in AGCM. Additionally, the Oceanic General Circulation Model (OGCM) was used to establish a fully coupled model, and the fully coupled ocean-atmosphere-land-sea ice model was used in climate projections in the IPCC Second Assessment Report. (5) Since the beginning of the 2000s, the land surface model has improved in the context of runoff representation, the aerosol module in the AGCM has improved in the treatment of both direct and indirect effects, and the Atlantic meridional overturning circulation has improved in the OGCM. The fully coupled models used in climate projection supporting the IPCC Third Assessment Report have been generally improved in terms of physics. The carbon cycle process was included in some models. (6) Dynamic vegetation module was included in the land surface model, while atmospheric chemistry module was included in the AGCM since 2007, and the technique of direct ocean-atmosphere coupling without the employment of flux adjustment was used in establishing a fully coupled climate system model. (7) Earth system models with the inclusion of terrestrial and oceanic biogeochemical cycle processes have emerged in climate modeling since 2013. (8) Higher resolution climate models with an atmospheric horizontal resolution of 100 km and oceanic horizontal resolution of 75 km are widely used in climate models and projections that support IPCC AR6. A high-resolution climate system model with both AGCM and OGCM components employing a horizontal resolution of 10–25 km emerged. The convection-permitting model (CPM) was used in some pioneering climate modeling centers (see Figure 2 and Zhou et al., 2019 for a review; the most recent progress is in Chen et al., 2021).

The development of the Earth system model (ESM) from the global climate model is a landmark of model development. The global climate model generally represents the physical climate system components and considers biogeochemical and human systems as external forcings or impacts. Historically, these models were restricted to the physical aspects of the atmosphere and ocean. The ESM represents both the physical climate and the biogeochemical systems and their interactions as a single coupled system. In most ESMs, the human system is treated as external, as is natural forcing (solar and volcanic eruptions) (WCRP, 2019).

Following the improvement of climate and Earth systems models in the representation of physical and chemical processes, the representation of biogeochemistry, including the carbon cycle, and the increase in model resolution, the number of climate centers or consortia that engage in model development has also increased. The wider international community engaged in climate modeling is evident if we contrast the Charney report with its successors, the various IPCC reports. When the famous Charney report was published in 1979, the review of results was only based on two models from Hansen and Manabe. The number of climate centers or consortia that carry out global climate simulations and projections has grown from 11 in the first CMIP to 19 in CMIP5 and 28 in CMIP6. The recently published IPCC AR6 is built upon the output of 39 climate model versions, among which 11 state-of-the-art Earth system models include carbon cycle processes (IPCC, 2021). The climate models developed by Chinese institutions or universities have made great contributions to all six rounds of IPCC assessment (Figure 5). In CMIP1, the climate model developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences, was the only model from China, while in CMIP6, there are 8 climate/Earth system models from the mainland of China (see Zhou et al., 2019, 2020b for reviews).

Climate and Earth system models are among the most sophisticated simulation tools developed by humankind. They are based on the mathematical formulations of the natural laws that govern the evolution of climate-relevant systems, including the atmosphere, ocean, cryosphere, land, biosphere, and carbon cycle (Flato, 2011). Climate models are built on the fundamental laws of physics (e.g., Navier-Stokes or Clausius-Clapeyron equations) or empirical relationships established from observations and, when possible, constrained by fundamental conservation laws (e.g., mass and energy) (Chen et al., 2021). The availability of climate models helps us to compute the evolution of climate-relevant variables numerically using high-performance computers. Since the birth of the first climate model in 1975, more than 40 years ago, the resurgence of climate modeling has resulted in more complex and sophisticated climate models. Climate modeling has and will continue to play crucial roles in understanding past climate change, the detection and attribution of anthropogenic climate change, and the projection of future change under various scenarios.

6. Concluding remarks

Since the discovery of the greenhouse effect in 1827, almost 200 years have passed. Building upon the achievements of the scientific community in global warming and climate change relevant studies in the past ~200 years, including the pioneering work of Nobel Prize in Physics 2021 laureates, Syukuro Manabe and Klaus Hasselmann, we now have solid physical knowledge of Earth's climate. Combined evidence from observations, theoretical studies, climate modeling, climate change detection and attribution studies has con-

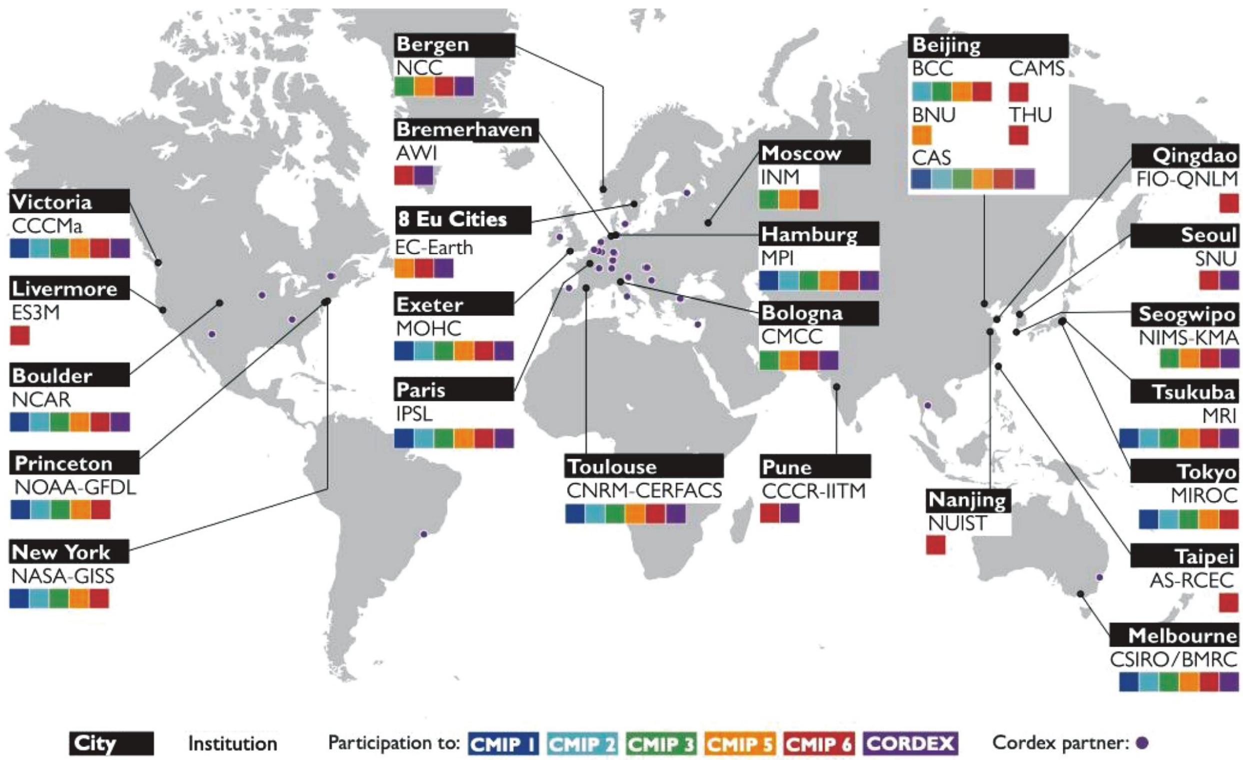

Figure 5 Global distribution of the modeling centers contributing to CMIP and CORDEX. Different colors indicate participation in different phases of the CMIP, more colors indicate a longer participation history (modified based on Figure 1.20 of IPCC AR6; the contribution of climate models developed by the Chinese Academy of Sciences were affiliated with "IAP-LASG" from CMIP1 to CMIP3 and were not included in the original figure of AR6 that only reviewed the contribution of climate models affiliated with the "Chinese Academy of Sciences").

firmed the unequivocal role of human influence on the observed climate warming (IPCC, 2021).

What is next? Certainly, this will not be the last time that climate science is recognized by the Nobel Prize. Looking forward, there is a high probability that the next question to the climate community from the public will be "how should we adapt to and mitigate the ongoing climate change?". Reliable information on climate change prediction from global to regional and even local scales is needed to support the full range of planned adaptation and mitigation actions (Martin et al., 2021). Climate models will provide critical information for both mitigating and adapting to climate change, including understanding the implications of various mitigation strategies (e.g., Zhang and Zhou, 2020) and informing adaptation strategies and long-term resilience. Nonetheless, reliable simulation and prediction of precipitation as well as climate extremes at a regional scale remain a challenge to current state-of-the-art climate models (Zhou, 2021). Higher model resolution is an important step forward for a further increase in confidence in simulations. Added values are expected from very high-resolution convection-permitting models. New generations of kilometer-scale, global storm-resolving climate models are expected to revolutionize the quality of information available for mitigation and adaptation, from global climate and regional climate impacts to risks of unprecedented extreme weather and dangerous climate change (Slingo et al., 2021).

The climate system is a complex, adaptive system (Slingo et al., 2009). The extension of the climate system to the Earth's system calls for understanding the coevolution of the biosphere, including both terrestrial and marine ecosystems and human activities as social-ecological systems (Steffen et al., 2020). To achieve this, the science of climate prediction should be extended to a more multifaceted Earth system prediction that includes the biosphere and its resources (Bonan and Doney, 2018). In the near future, an Earth life system simulator that can predict the multiple relationships between the physical and natural environments, and potentially with society, at both global and national levels, is envisaged (Slingo et al., 2021).

Climate science is built upon physical science and extends to mathematics, chemistry, and the biosphere. Observations, theoretical studies, high-speed computing, and new technologies such as remote sensing, artificial intelligence, and machine learning have powered climate science forward. The extension of climate science to Earth system science has necessitated interdisciplinary and transdisciplinary research. As all these fields are developing rapidly, it is not hard to picture climate science in the spotlight again. To understand the complex Earth system and to further promote future climate predictions that enable society to plan for sustainable development and to keep human and natural ecosystems safe, we expect more achievements from the climate science community to come in the near future.

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References

Allen M R, Tett S F B. 1999. Checking for model consistency in optimal fingerprinting. Clim Dyn, 15: 419–434

Archer D, Pierrehumbert R T. 2011. The Warming Papers: The Scientific Foundation of the Climate Forecast. Oxford: Wiley Blackwell Press

Arrhenius S. 1896. On the influence of carbon acid in the air upon the temperature of the ground. Philos Mag, 41: 237–276

Bonan G B, Doney S C. 2018. Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. Science, 359: 533

Charney J, Arakawa A, Baker D J, Bolin B, Dickinson R, Goody R, Leith C, Stommel H, Wunsch C. 1979. Carbon dioxide and climate: A scientific assessment. Report of an Ad Hoc Study Group on Carbon Dioxide and Climate. Washington D C: National Academy of Sciences Press

Chen D, Rojas M, Samset B H, Cobb K, Diongue Niang A, Edwards P, Emori S, Faria S H, Hawkins E, Hope P, Huybrechts P, Meinshausen M, Mustafa S K, Plattner G K, Tréguier A M. 2021. Framing, context, and methods. In: Masson-Delmotte V, Zhai P, Pirani A, Connors S L, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis M I, Huang M, Leitzell K, Lonnoy E, Matthews J B R, Maycock T K, Waterfield T, Yelekçi O, Yu R, Zhou B, eds. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. In press

Crutzen P J, Stoermer E F. 2000. The "Anthropocene". Global Change Newsletter, 41: 17

Ekholm N. 1901. On the variations of the climate of the geological and historical past and their causes. Q J R Meteorol Soc, 27: 1–62

Flato G M. 2011. Earth system models: An overview. WIREs Clim Change, 2: 783–800

Fourier J B F. 1827. On the temperatures of the terrestrial sphere and interplanetary space. Mémoires de l'Académie Royale des Sciences, 7: 569–604

Hansen J, Lacis A, Rind D, Russell G, Stone P, Fung I, Ruedy R, Lerner J. 1984. Climate sensitivity: Analysis of feedback mechanisms. In: Hansen J E, Takahashi T, eds. Climate Processes and Climate Sensitivity. AGU Geophysical Monograph 29, Maurice Ewing Vol. 5. American Geophysical Union. 130–163

Hasselmann K. 1976. Stochastic climate models Part I. Theory. Tellus, 28: 473–485

Hasselmann K. 1979. On the signal-to-noise problem in atmospheric response studies. In: Shaw B D, ed. Meteorology Over the Tropical Oceans. Bracknell: Royal Meteorological Society Publication. 251–259

Hasselmann K. 1993. Optimal fingerprints for the detection of time-dependent climate change. J Clim, 6: 1957–1971

Hasselmann K. 1997. Multi-pattern fingerprint method for detection and attribution of climate change. Clim Dyn, 13: 601–611

Hegerl G C, North G R. 1997. Comparison of Statistically Optimal Approaches to Detecting Anthropogenic Climate Change. J Clim, 10: 1125–1133

IPCC. 1990. Climate Change. In: Houghton J T, Jenkins G J, Ephraums J J, ed. The IPCC Scientific Assessment Contribution of Working Group I to the First Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 1990. 1–365

IPCC. 1992. Climate Change 1992. In: Houghton J T, Callander B A, Varney S K, eds. The Supplementary Report to the IPCC Scientific Assessment. Cambridge: Cambridge University Press. 200

IPCC. 1995. Climate Change 1995. In: Houghton J T, Meira Filho L G, Callander B A, Harris N, Kattenberg A, Maskell K, ed. The Science of Climate Change Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 1996. 1–572

IPCC. 2001. Climate Change 2001. In: Houghton J T, Ding Y, Griggs D J, Noguer M, van der Linden P J, Dai X, Maskell K, Johnson C A, ed. The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 2001. 1–881

IPCC. 2007. Climate Change 2007. In: Solomon S D. Qin M, Manning Z, Chen M, Marquis K B, Tignor A M, Miller H L, ed. The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 2007. 1–996

IPCC. 2013. Climate Change 2013. In: Stocker T F, Qin D, Plattner G K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V, Midgley P M, ed. The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. 2013. 1–1535

IPCC. 2021. Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors S L, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis M I, Huang M, Leitzell K, Lonnoy E, Matthews J B R, Maycock T K, Waterfield T, Yelekçi O, Yu R, Zhou B, eds. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. In press

Jones P D, Wigley T M L, Wright P B. 1986. Global temperature variations between 1861 and 1984. Nature, 322: 430–434

Keeling C D. 1960. The concentration and isotopic abundances of carbon dioxide in the atmosphere. Tellus, 12: 200–203

Keeling C D. 1970. Is carbon dioxide from fossil fuel changing man's environment? Proc Amer Philosoph Soc, 114: 10–17

Ma S, Zhou T, Stone D A, Polson D, Dai A, Stott P A, von Storch H, Qian Y, Burke C, Wu P, Zou L, Ciavarella A. 2017. Detectable anthropogenic shift toward heavy precipitation over Eastern China. J Clim, 30: 1381–1396

Martin M A, Sendra O A, Bastos A, Bauer N, Bertram C, Blenckner T, Bowen K, Brando P M, Rudolph T B, Büchs M, Bustamante M, Chen D, Cleugh H, Dasgupta P, Denton F, Donges J F, Donkor F K, Duan H, Duarte C M, Ebi K L, Edwards C M, Engel A, Fisher E, Fuss S, Gaertner J, Gettelman A, Girardin C A J, Golledge N R, Green J F, Grose M R, Hashizume M, Hebden S, Hepach H, Hirota M, Hsu H H, Kojima S, Lele S, Lorek S, Lotze H K, Matthews H D, McCauley D, Mebratu D, Mengis N, Nolan R H, Pihl E, Rahmstorf S, Redman A, Reid C E, Rockström J, Rogelj J, Saunois M, Sayer L, Schlosser P, Sioen G B, Spangenberg J H, Stammer D, Sterner T N S, Stevens N, Thonicke K, Tian H, Winkelmann R, Woodcock J. 2021. Ten new insights in climate science 2021: A horizon scan. Glob Sustain, 4: e25

Manabe S, Wetherald R T. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J Atmos Sci, 24: 241–259

Manabe S, Wetherald R T. 1975. The effects of doubling the CO_2 concentration on the climate of a general circulation model. J Atmos Sci, 32: 3–15

Mann M E, Bradley R S, Hughes M K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature, 392: 779–787

Pales J C, Keeling C D. 1965. The concentration of atmospheric carbon dioxide in Hawaii. J Geophys Res, 70: 6053–6076

Plass G N. 1956. The influence of the 15μ carbon-dioxide band on the atmospheric infra-red cooling rate. Q J R Met Soc, 82: 310–324

Slingo J, Bates K, Nikiforakis N, Piggott M, Roberts M, Shaffrey L, Stevens I, Vidale P L, Weller H. 2009. Developing the next-generation climate system models: Challenges and achievements. Phil Trans R Soc A, 367: 815–831

Slingo J, Bauer P, Bony S, Christensen J H, Cox P, Flato G, Hegerl G, Hurrell J, Jakob C, Kattsov V, Kimoto M, Krishnan R, Marotske J, Shepherd R, Stephens G, Stevens B, Stocker T, Sutton R, Zhou T. 2021. Next generation climate models: A step change for Net Zero and climate adaptation. Royal Society Science and Technology for Climate Action Briefing

Steffen W, Richardson K, Rockström J, Schellnhuber H J, Dube O P, Dutreuil S, Lenton T M, Lubchenco J. 2020. The emergence and evolution of Earth System Science. Nat Rev Earth Environ, 1: 54–63

Sun Y, Zhang X, Ding Y, Chen D, Qin D, Zhai P. 2021. Understanding human influence on climate change in China. Natl Sci Rev, 9: nwab113

Sun Y, Zhang X, Zwiers F W, Song L, Wan H, Hu T, Yin H, Ren G. 2014. Rapid increase in the risk of extreme summer heat in Eastern China. Nat Clim Chang, 4: 1082–1085

Tyndall J. 1861. on the absorption and radiation of heat by gases and vapours, and on the physical connection of radiation, absorption, and conduction. Philos Trans R Soc, 152: 59–98

WCRP Joint Scientific Committee (JSC). 2019. World Climate Research Programme Strategic Plan 2019–2028. WCRP Publication 1/2019

Yang X, Zhu Y, Xie Q, Ren X, Xu G. 2004. Advances in studies of Pacific Decadal Oscillation (in Chinese). Chin J Atmos Sci, 28: 979–992

Zhang W, Zhou T. 2020. Increasing impacts from extreme precipitation on population over China with global warming. Sci Bull, 65: 243–252

Zhou T, Chen Z, Zou L, Chen X, Yu Y, Wang B, Bao Q, Bao Y, Cao J, He B, Hu S, Li L, Li J, Lin Y, Ma L, Qiao F, Rong X, Song Z, Tang Y, Wu B, Wu T, Xin X, Zhang H, Zhang M. 2020b. Development of climate and earth system models in China: Past achievements and new CMIP6 results. J Meteorol Res, 34: 1–19

Zhou T, Zou L, Chen X. 2019. Commentary on the Coupled Model Intercomparison Project Phase 6 (CMIP6) (in Chinese). Clim Change Res, 15: 445–456

Zhou T, Zhang W, Zhang L, Zhang X, Qian Y, Peng D, Ma S, Dong B. 2020a. The dynamic and thermodynamic processes dominating the reduction of global land monsoon precipitation driven by anthropogenic aerosols emission. Sci China Earth Sci, 63: 919–933

Zhou T, Zhang W. 2021. Anthropogenic warming of Tibetan Plateau and constrained future projection. Environ Res Lett, 16: 044039

Zhou T. 2021. New physical science behind climate change: What does IPCC AR6 tell us? Innovation, 2: 100173

Zillman J W. 2009. A history of climate activities. WMO Bull, 58: 141–150

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