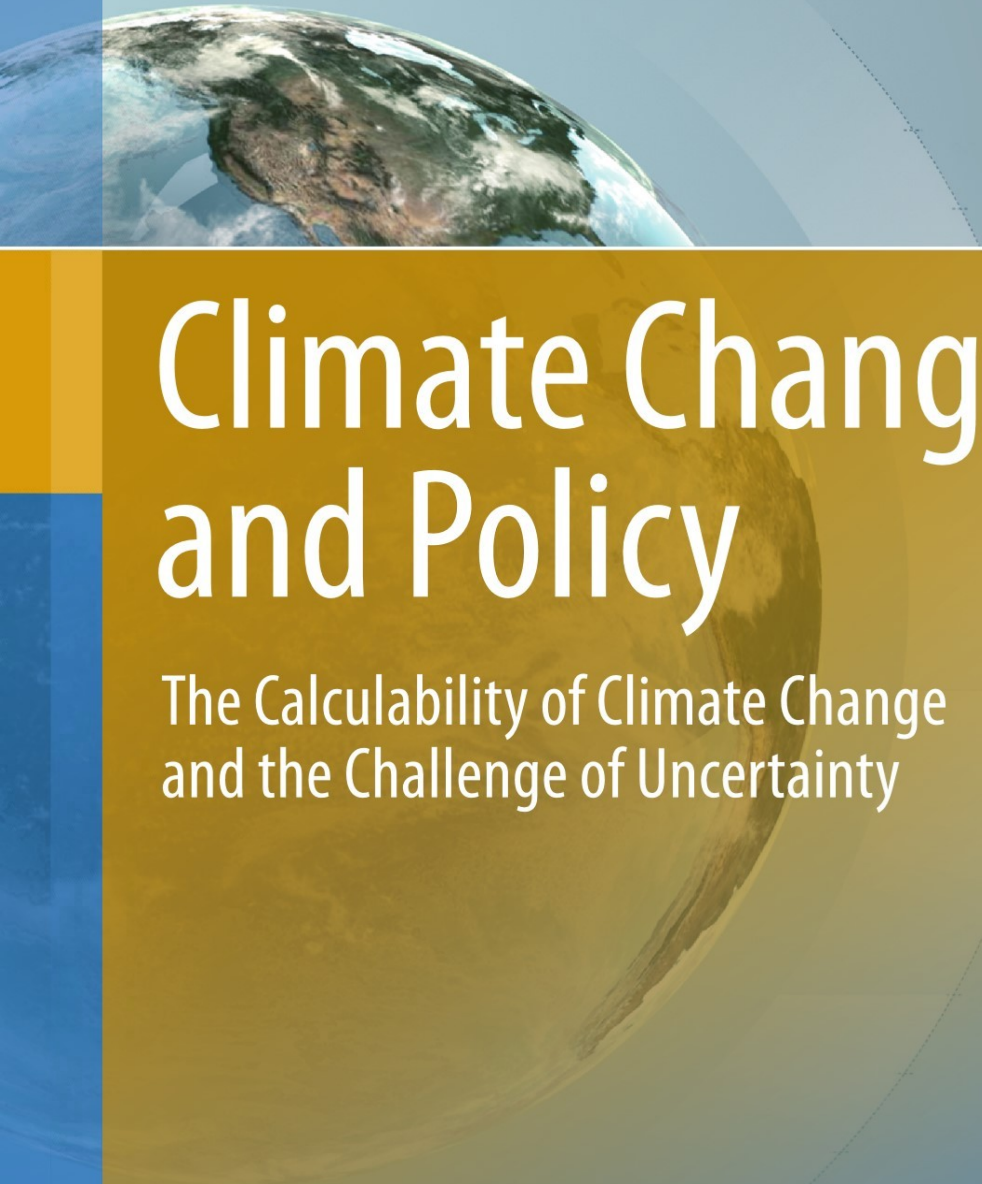
Gabriele Gramelsberger
Johann Feichter *Editors*



Climate Change and Policy

The Calculability of Climate Change and the Challenge of Uncertainty

Springer

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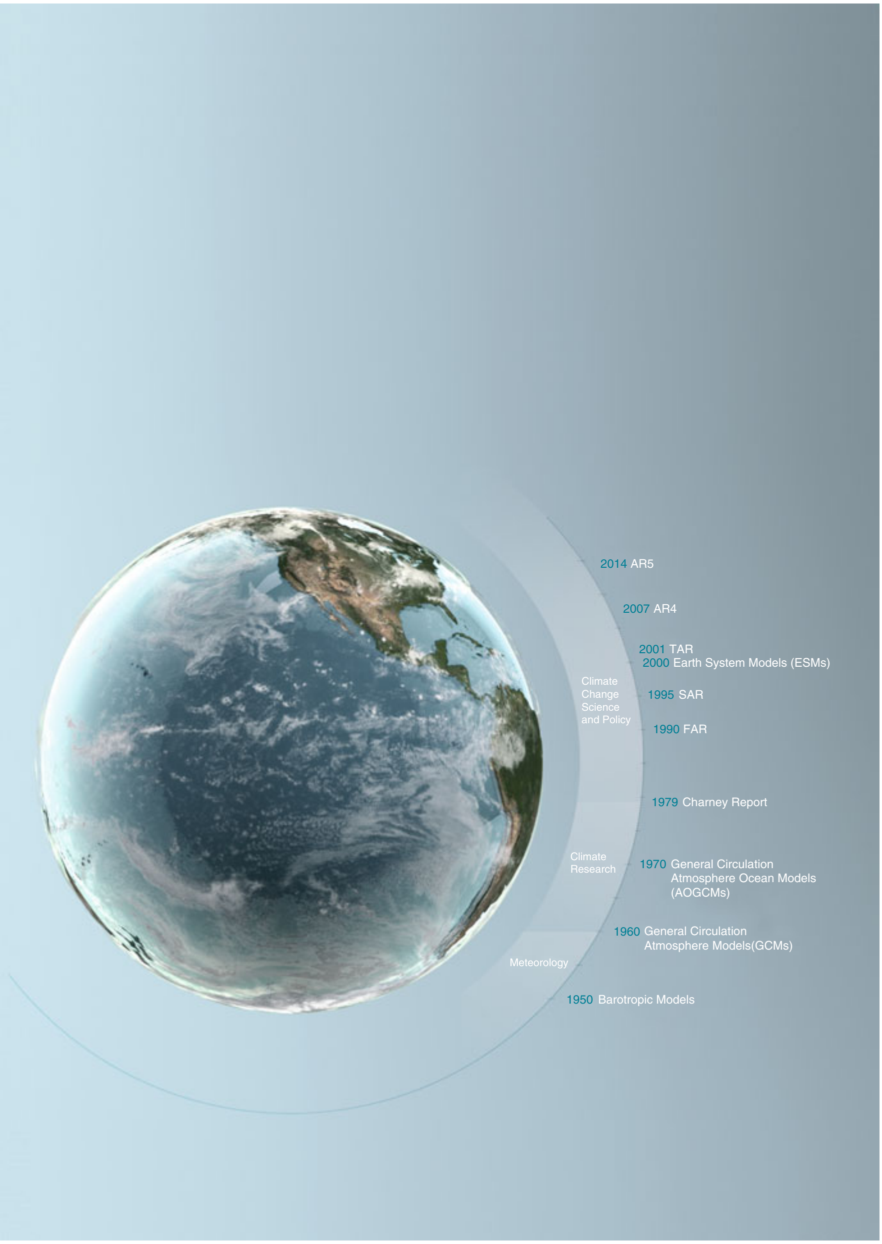
2014 AR5
2007 AR4
2001 TAR
2000 Earth System Models (ESMs)
Climate Change Science and Policy
1995 SAR
1990 FAR
1979 Charney Report
Climate Research
1970 General Circulation Atmosphere Ocean Models (AOGCMs)
1960 General Circulation Atmosphere Models(GCMs)
Meteorology
1950 Barotropic Models

Gabriele Gramelsberger • Johann Feichter
Editors

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Editors
Dr. Gabriele Gramelsberger
FU Berlin
Inst. Philosophie
Habelschwerdter Allee 30
14195 Berlin Berlin
Germany
gab@zedat.fu-berlin.de

Dr. Johann Feichter
MPI für Meteorologie
The Atmosphere in the Earth System
Bundesstr. 55
20146 Hamburg
Germany
johann.feichter@zmaw.de

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Foreword

The uncertainty in projecting climate effects is a contentious issue in science and society. On the one hand, decision-makers require certainty about the future consequences of today’s behaviour. On the other hand the complexity of the climate system, of human behaviour, and global interactions, combine to make such certainty impossible. Although it has turned out that the world is not exactly predictable, advanced strategies of calculability and measurement have been developed that enable to establish ‘rational prognosis’. Thus forecasting future scenarios and dealing with uncertainty has become everyday business for meteorologists ever since automatic computing machines crossed the threshold of a million operations per second in the 1970s.

Since then rational prognosis based on scientific principles has become an essential part of decision-making both in economics and in politics–challenged by the problem of uncertainty. New methods and advanced strategies fuel hopes of managing uncertainty as economics, politics, and society increasingly bank upon rational prognoses, especially where the impact of climate change is concerned. For instance, insurance companies recently converted from retrospective to prospective regulation of insurance policies using simulation-based forecasting, and industrial investments increasingly rely on scientific reports predicting future developments.

Therefore the present volume is guided by two goals. Firstly, to give firsthand insights into the calculability of climate change. Outstanding efforts have pushed meteorology into a pioneering leading role in dealing with rational prognosis as well as uncertainty. One outcome of these efforts is an internationally organised system of evaluation and model comparison–unique in science, which has been established over the last three decades to ensure the quality and validity of scientific results. In this the Intergovernmental Panel on Climate Change and other supranational organizations play a crucial role. The second aim of this volume is to explore the influence of rational prognosis and of the accompanying uncertainty on various socio-political and economical spheres, but also on the public and on science itself. Therefore we are delighted to present a selection of papers written for this volume by leading researchers.

The volume is the result of over six years of transdisciplinary collaboration between Johann Feichter (Climate Research) and Gabriele Gramelsberger (Philosophy of Science). Both this collaboration and the volume were generously supported by the Max Planck Institute of Meteorology in Hamburg.

Gabriele Gramelsberger
Johann Feichter

Contents

Chapter 1
Introduction to the Volume

Johann Feichter and Gabriele Gramelsberger

In 1979 meteorologist Jule Charney and colleagues published a globally recognized report on *Carbon Dioxide and Climate: A Scientific Assessment* (Charney et al. 1979). They finished the report with the conclusions that "our best estimate is that changes in global temperature on the order of 3°C will occur and that these will be accompanied by significant changes in regional climatic patterns" (p. 17). The estimates of the so-called Charney report were based on two, at that time state-of-the art, general circulation models of the atmosphere that carried out numerical studies on the impact of doubling carbon dioxide on the global mean temperature. This measure, called climate sensitivity, was introduced by Charney et al. and were supposed to provide some insight into the 'vast geophysical experiment' mankind was about to conduct (Revelle and Suess 1957). A full two decades before the release of the Charney report, Charles D. Keeling had begun measurements of atmospheric carbon dioxide concentration at Mauna Loa Observatory in Hawaii in order "to make sure that man's 'vast geophysical experiment' would be properly monitored and its results analyzed" (Keeling 1978, p. 38). The 'Keeling Curve', a time series of annual departures from 1958 on, clearly shows the increased CO_2 concentration in the atmosphere. This curve has become one of the icons of man-induced climate change today. However, this kind of 'vast geophysical experiment' should be subject to a digital climate, not to nature. Therefore climate models are indispensable tools for the emerging climate change science. Rooted in simple barotropic models of the atmosphere,[1] first computed by Charney and colleagues on ENIAC in 1950, these models have developed into complex Earth system models—incorporating knowledge from not only meteorology, but also oceanography, hydrology, biology, geochemistry, economy, and other fields. Within the last six decades,

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[1] Barotropic models idealize atmospheric flow insofar that the air pressure only depends on the air density.

J. Feichter (✉)
Max Planck Institute for Meteorology, The Atmosphere in the Earth System, Hamburg, Germany
e-mail: johann.feichter@zmaw.de

G. Gramelsberger
Institute of Philosophy, Free University Berlin, Berlin, Germany

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climate models have turned from purely meteorological into multidisciplinary objects of Earth science. Similarly, forecasts of changes in air pressure fields based on barotropic models have developed into projections of climate change and its impact on ecology using vast software machineries.

The 1979 Charney report provided a numerical study on climate change that was not only outstanding for its time, it marked a watershed that transformed climate change into a public policy issue—interlinking climate science and politics by establishing a growing number of international research programs, conferences, working groups, intergovernmental panels, and committees. The list of activities undertaken since the early 1980s to establish an infrastructure of worldwide coordination and negotiation for dealing with climate change is impressive, as politicians and the public have become increasingly aware what the alteration of climate could mean for mankind's future. Unrestricted change in land cover and pollution on the one side, and reduction of ecological resilience, the loss of biodiversity, regional inequity and vulnerability on the other, characterize the challenge and impact of climate change as a global phenomenon with regional effects. The effort of a global response to climate change by the United Nations involves three main endeavours: better knowledge of the current situation (measurement campaigns), better understanding of relevant processes and future trends (modelling and projecting), and a framework for negotiating the adequate response to climate change (a property rights regime for human use and modification of the carbon cycle). Numerous regional responses to climate change by governments and NGOs in terms of mitigation and adaptation are supplementing international and intergovernmental activities.

However, the link between climate change science and climate change policy are projections of future climate change and impact. As scientists are denied the possibility of conducting experiments with the real climate, only climate models can give insights into man-induced climate change, by experimenting with digital climates under varying conditions and by extrapolating past and future states into the future. But the 'nature' of models is a purely representational one. A model is good if it is believed to represent the relevant processes of a natural system well. Whether it does so can be evaluated by comparing the output of the model with observations. This empirical method of scientific evaluation assumes that when a prognosis inferred from a set of hypotheses (as modelled) concurs with observations from the field or experiments, the accordance corroborates the adequacy of the underlying hypotheses (model). This method holds only for sets of hypotheses among which the relation is clearly defined and among which feedback is limited to linear influences exerted on each other. In other words: Only very simple models can be verified. Most models, and in particular climate models, which interconnect countless hypotheses, are only to some extent testable. This situation of increasing model complexity and dissatisfactory methods for the evaluation of such complexity characterizes climate change science. As there is no way back to over-simplified models, which in any case do not sufficiently represent nature due to their simplicity, the development of advanced evaluation strategies and uncertainty metrics responding to the increasingly advanced style of modelling is a current challenge for science. This challenge involves strategies of model intercomparison, ensemble prognoses, uncertainty metrics on the system and component levels, uncertainty assessment, new ways of learning, and other strategies as outlined in this volume.

The challenge of developing advanced evaluation strategies can also be reformulated as the challenge of dealing with uncertainty in science. But this challenge of uncertainty is in conflict with socio-political expectations. Climate change policy requires accurate information for decision-making, and climate change science needs accurate information on economic development. Since neither of these can be achieved, climate change policy has to learn decision-making under uncertainty, and climate change science has to base its projections on possible scenarios and storylines. For a while climate change policy tended to deal with uncertainty by requiring scientists to eliminate all uncertainties before any policy action could be considered. However, this approach has changed as it has been recognized that inaction on climate change is a form of action in itself—resulting in the unmitigated pollution of the atmosphere and changes to land surface properties—and that complexity and uncertainty go hand in hand. Neither can be avoided without avoiding the other, and certain predictions belong to the realm of desires and ideals rather than to applied science. Today's attempt to define and classify uncertainty in terms of likelihood and confidence reflect this awareness of uncertainty as an integral part of human knowledge, in particular on knowledge about possible future developments. It is now up to society to come to decisions on reductive and adaptive activities as one thing is certain: every year of inaction marks an increase in atmospheric carbon dioxide concentration.

Against this backdrop the volume addresses various aspects of an emerging climate change science and policy, in particular the calculability of climate change and the challenge of uncertainty. Calculability and uncertainty are two sides of the same coin, and this coin constitutes the currency of climate change science and policy (Gabriele Gramelsberger and Johann Feichter, Chap. 2). In order to understand the idea of climate prediction, the possibilities and limits of the calculability of temporal and spatial developments of a system based on physical laws has to be explored. During the late nineteenth and early twentieth centuries, meteorology turned from a descriptive and purely empirical science into one based on theory and models. This shift resulted from conceiving the atmosphere as a mechanical and physical object—a giant 'air mass circulation and heat engine' driven by solar radiation and gravitational forces expressed in terms of local differences in velocity, density, air pressure, temperature, and humidity. The main advantage of subordinating the atmosphere to physical laws is that it can be mathematically modelled so that forecasting algorithms for the computation of future states can be inferred from the mathematical model. As these computations require recourse to enormous computing power, meteorology could take advantage of these forecasting algorithms only when automatic calculating machines came into use during the late 1940s. In 1950 Charney and his colleagues computed the first weather forecast—a forecast of air pressure change for a 15 × 18 grid of 500-mbar contour surface—and in 1956 Norman Phillips computed the first climate experiment for the northern hemisphere, successfully reproducing the global circulation cells (Charney et al. 1950; Phillips 1956). Both experiments were based on simple barotropic models of the atmosphere, marking the beginning of numerical modelling in meteorology. Since the 1950s modelling as well as available computer power have advanced by leaps and bounds. This allowed the increasingly advanced models—general circulation models (GCMs) and later, coupled atmosphere-ocean general circulation models (AOGCMs)—to be used for specific experiments, and climate science to be applied to practical problems, e.g. for investigations on the impact of doubling CO_2, on deforestation, and on other environmental problems. With these experiments meteorology turned into climate change science, and purely scientific interest in the field was complemented by sociopolitical demands. Growing efforts to coordinate climate modelling and climate change response negotiations on an international level have accompanied this shift. Today, Earth system models (ESM), model intercomparison, advanced evaluation methods, and the IPCC Assessment Reports are the cornerstones of an internationally organized climate change science and policy. This development has opened up the community of GCM/ESM modellers—more than a dozen institutes around the globe—to new and rapidly growing groups of model users, model output users, and modellers that have extended the variety of climate models by adding regional models, Earth system models of intermediate complexity, integrated assessment models, and other types of climate change and impact models.

A driving force of this development has been the Intergovernmental Panel on Climate Change (IPCC) and the regular release of the IPCC Assessment Reports. Since the early 1990s the reports have reviewed and accumulated state-of-the-art knowledge on climate change and given projections of possible future developments. Furthermore, they have introduced an international rhythm of model development, improvement, evaluation, and intercomparison which is unique in science. This concerted cycle has substantially improved the new method of computer-based simulation for knowledge production. However, the IPCC Assessment Reports play a crucial role on both sides: climate change science and climate change policy (Arthur C. Petersen, Chap. 3). As a 'boundary organization' the IPCC has introduced procedures and rituals for interconnecting science and policy, but also ensures the stability of the boundaries between the two. The most decisive and urgent task of IPCC is the mediation of 'robust conclusions' on climate change. Therefore, the main types of uncertainties had to be identified: unpredictability (the evolution of society, chaotic components of climate system), structural uncertainty (inadequate and incomplete modelling of processes, ambiguous system boundaries, lack of knowledge on significant processes and relations among variables, etc.), and value uncertainty (inaccurate, missing, and non-representative data due to inappropriate spatial and temporal resolution). Furthermore, the uncertainty of climate change projections had to be assessed on scales of confidence and likelihood in order to support decision-making under uncertainty for policy makers. This process of identification and assessment of uncertainty is an integral part of the extended review process of the IPCC Assessment Reports. Hundreds of authors and reviewers, considering ten thousands of statements from the community on the assessment of results, take months and years to prepare the scientific basis and conclusions until the Summary for Policymakers is finally approved line by line by the participating governments. This extended review process and the ritual of wording is unique in science, though not without its critics. The example of the Summary for Policymakers in the third IPCC Assessment Report shows the careful and complex process of adequately incorporating information and wording it carefully, in particular for the uncertainty level of the statements. From this perspective, the IPCC Assessment Reports are seen less as instruments to create 'scientific consensus' than as 'policy-relevant assessments acknowledging uncertainty'.

Such an uncertainty assessment is indispensable for policy options, as there is social pressure for robust advice (Hermann Held, Chap. 4). Therefore a paradigm shift from deterministic to probabilistic climate projections, new data sources, and new forms of learning are required. The last of these refer to a concept of uncertainty that is seen more as a 'catalyst for self-awareness on silent assumptions within disciplines'—accepting the challenge of uncertainty—than as an unsolvable problem. This awareness stimulates constructive interaction among disciplines, in particular among climate science, economic, and statistics. Over the course of the IPCC Assessment Reports scientists have further developed the debate on uncertainty. In particular during the work on the third report, they began discussing the problems of intra-model uncertainty, of climate sensitivity (CS) as a key uncertain property, and of system-immanent response time scales. This stimulated the exploration of new methods such as Bayesian statistics for intra-model uncertainty, strategies for retro-reduced CS uncertainty, and the study of restoring mean time scales in historical records—following the idea that, if climate's main response time could be reconstructed, the uncertainty about global mean temperature could be reduced. However, besides these scientific efforts to deal with uncertainty, society has to decide which view should be assumed with regard to climate change: that of a 'climate-impact-pessimist' following the 'precautionary principle', or that of a 'climate-impact-optimist'. The second view takes the scattered knowledge on climate change into account, mainly the positively known information. Combining both views recently led to the debate on the '2°C-target' and on the economic costs to realistically achieve at least this target.

The debate on how mankind should respond to climate change is diverse, as the appropriate strategy depends on local and regional circumstances. Besides mitigation and adaptation, the concept of geo-engineering emerges on and off the agenda, although most scientists do not regard geo-engineering as an appropriate strategy. However, the more interesting question is not necessarily what can be done, but which concrete mechanisms are needed in order to realize a diverse set of strategies. These mechanisms will decide whether at least the 2°C-target will be achieved. Therefore Chaps. 5–8 of this volume explore a mix of exemplary mechanisms, which can help, or not, to respond to climate change: the market mechanism for reducing greenhouse gas emissions, the possibilities and limitations of insuring risk, and the awareness that is created by such insurance policies, the disillusioning lessons which can be learned from weather modification in order to assess climate engineering, and the utilization of participatory approaches to design proactive responses to regional climate impacts. The case studies demonstrate the sensitive interdependency between climate change science, climate change policy, and the various mechanisms. This interdependency is influenced by different types and sources of uncertainty and, depending on the specific mechanism, requires specific ways of dealing with uncertainty.

Probably the most ambitious attempt at a global response to climate change is the introduction of market mechanisms for reducing greenhouse gas emissions by the United Nations Framework Convention on Climate Change, outlined in the Kyoto Protocol of 1997 (Alex Vasa and Axel Michaelowa, Chap. 5). This global response is based on various market mechanisms: trading Certified Emission Reductions (CERs), and the components of Joint Implementation (JI), Clean Development Mechanism (CDM), and International Emission Trading (IET). IET allows governments to sell unused shares of their emission budget; JI permits the generation of emission credits through emission reduction, and the CDM allows projects that reduce emissions to generate emission credits. In this system one CER is considered to be equivalent to one metric ton of CO_2 emissions. The Kyoto Protocol stipulated an ‘orientation period’ from 2008 to 2012, which has to be extended by a post-2012 strategy. After the disappointing results concerning a reliable post-2012 strategy of the UN Climate Change Conference (COP-15) at Copenhagen in 2009, the next UN conferences will show whether agreement can be achieved. Although managing emissions is one of the fastest-growing segments in financial services, the key uncertainty is whether such an international regime is manageable and how long it will last. Therefore the post-2012 strategy will decide how market participants will behave. Besides the uncertainty of the inconsistent application of the rules of these market mechanisms by the institutions governing the market mechanisms, these uncertainties influence the prices on the Kyoto market and the carbon market. However, only a long-term orientation on global climate policy can lead to substantial effects on reducing greenhouse gas emissions.

Another market-relevant aspect is addressed by the question of the insurability of climate change and its relation to climate change policy (Michael Huber, Chap. 6). Of course climate change itself cannot be insured against, but various effects of climate change which can be transformed into a set of insurable risks are insurable. As losses due to disasters are measures of economic costs, and as these losses are increasing significantly, insurance and reinsurance companies as well as policy makers are paying increasing attention to these developments. Between 1990 and 2008 a total of 600,000 people died as a direct consequence of more than 11,000 extreme weather events, and economic losses of 1.7 trillion USD were insured (Harmeling 2010). Local communities have to rely on insurance solutions to be more resilient to climate risks. But this would privatize climate change effects, which is not really advisable due to the size and global scale of the problem. As flood risk insurance has shown, states tend to shirk responsibility for effective climate policy by offloading the costs of climate change onto insurance companies. The problem is exacerbated because insurance fosters adaptive strategies, while climate change requires preventive policies. Another problem is the state-dependency of insurance regimes, which establishes an unequal treatment of climate change effects. The various regimes, in turn, influence the political weight of events.

Besides market mechanisms for greenhouse gas emissions and insurance solutions, another segment of an emerging climate change market seems to be preconceived: climate engineering (William Cotton, Chap. 7). Most scientists are extremely cautious in considering climate engineering as an option, and there are good reasons for this wariness as climate is a complex and multifaceted system of feedback interaction. Nevertheless, there is a fear that climate engineering could be considered as a 'last gasp' measure to prevent the catastrophic consequences of climate change because political decision-making fails—and COP-15 was a good example. Such a scenario could be the case notwithstanding the unforeseeable side effects of climate engineering, which would trigger a risk spiral of quasi-infinitely regressive human interventions in the climate. Climate engineering would involve major uncertainties. At present the effects of climate engineering cannot even be evaluated, as the cause-and-effect chains of global warming are not sufficiently known, and because an accurate benchmark for natural climate variability is lacking. Obviously, there is no trial-and-error method available to figure out appropriate climate engineering designs. However, the history of weather modification in the US shows that while operational programs were supported with considerable resources, scientific research to study the possibility and impact of weather modification decreased to a low level in the 1980s. This led to commercial applications without the guidance of sound scientific investigations.

The fear of the catastrophic consequences of climate change is engaging scientists and policy makers to search for solutions on a global scale. Nevertheless, global climate change is the sum of countless local interventions like pollution, deforestation, extensive agriculture, urbanization, traffic, and others. In fact, a possible success in achieving the 2°C-target is rooted in an appropriate way of linking mitigations and adaptations on the local scale in an integrated and participatory manner (Livia Bizikova, Sarah Burch, John Robinson, Alison Shaw, and Stephen Sheppard, Chap. 8). The case studies from British Columbia show how a participatory scenario-building process for local, proactive responses to climate change can be developed, and how uncertainty can be communicated in this process. In accounting for the human dimension, scales of likelihood are not very useful to support decisions and choices. Instead, diverse tools like storylines, 3D visioning, and backcasting are used to explore plausible futures. The results of these attempts indicate that uncertainty can be addressed efficiently. In particular visualizations, for instance of rising snowlines or sea levels, help to develop a typology of resilience for local scenarios.

Participation directly involves local communities in climate change response activities. This direct engagement is urgently needed as citizens are otherwise restricted to public media as their source of information about climate change. Such a restriction forces citizens to passively monitor the activities of policy makers, which seems less than beneficial for proactive responses. Furthermore, it puts them at the mercy of the media's image politics of climate change (Birgit Schneider, Chap. 9). As the case studies from British Columbia indicate, visualizations are important tools for envisioning possible effects of climate change and for assessing decisions and choices together with local communities. Images are considered to have a pedagogical ability to show complex connections in an easy way. But this view of images is misleading, as climate images are highly complex knowledge sources, overloaded with information that require ‘visual literacy’ in order to decipher the incorporated information. As climate itself is not a perceptible phenomena but a scientifically constructed object, images on climate and climate change, such as the well-known ‘hockey stick graph’, are also highly constructed objects—in particular those images that picture possible futures. The main question here is how uncertainty about these possible futures can be communicated within images. Various designs like blurred areas, bifurcated curves and others have become common elements in climate visualizations. However, the human necessity for visioning in order to comprehend possible developments endows images with power. The media benefit from this fact. The fever curve of global warming and the lonely polar bear drifting on a sheet of ice seem to bear witness to the impact of climate change.

Summing up, climate change and policy have turned the physics of the atmosphere and the ocean into a multifaceted picture of the Earth system. Although the physical models based on hydro- and thermodynamics are still at the core of climate change science in order to achieve computability, the applicability of these models has introduced various sources of uncertainty, e.g. the intra-model uncertainty of parameter values. These uncertainties propagate into the output of the models and into policy options. However, as these uncertainties are an integral part of human knowledge, in particular on possible future developments, rather than capitulating, it is time to develop strategies for dealing with uncertainty. As the papers in this volume indicate, various strategies and mechanisms are on their way to constituting not only an international arena of climate change science and policy, but also a climate change market and a framework for local and proactive responses. A balanced mix of strategies and mechanisms, accompanied by scientific progress in understanding climate change, will decide whether at least the 2°C respectively 450 ppmv target can be achieved.

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Chapter 2
Modelling the Climate System: An Overview

Gabriele Gramelsberger and Johann Feichter

A Google search for the keyword ‘climate’ on a cold summer day in August 2010 delivered more than 150 million links in 0.23 s, and ‘climate change’ brought another 58 million. Obviously it is no problem to find floods of information about these topics on the net, yet understanding the scientific concept of climate and climate modelling is not so easy. The trouble with ‘climate’ starts when it is mixed up with the idea of weather, and when extreme weather events and short-term trends in temperature or precipitation are interpreted as effects of climate change. Usually, these interpretations are linked to an individual’s memory of experiences in childhood and other periods of life. But the trouble results not from this individual definition, which does not accord with the World Meteorological Organization’s official definition of climate as the statistics of weather.[1] The trouble is raised by the scientific concept of climate as a mathematical construct that cannot be experienced directly. This problem is hitting science now that socio-political demands are coming into play. For responding to such demands, science has to break down its statistical and general concepts into individual and local conclusions, but this is—at the moment at least—not possible. The reason lies in the top-down approach of modern science, which uses globally valid equations to achieve increasingly higher resolution. The great challenge for meteorology during the next years and decades will be to translate statistical and general results into individual and local knowledge. Or in other words, science has to connect its global view with local

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[1] “Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system”. (IPCC 2007a, p. 249).

G. Gramelsberger (✉)
Institute of Philosophy, Free University Berlin, Berlin, Germany
e-mail: gab@zedat.fu-berlin.de

J. Feichter
Max Planck Institute for Meteorology, The Atmosphere in the Earth System, Hamburg, Germany

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circumstances. Regional modelling and downscaling are just the beginning, although these methods are still far removed from any particular individual or local view of a particular city or area. Of course, one can ask why humans do not simply get used to the scientific concept of climate. But when concrete environmental activities are required, individual needs and local effects play the main role, not the annual mean global temperature.

In order to set the stage for this challenge to meteorology, the present chapter will provide an introductory view on its background: the current practices of climate modelling and predictions, and their roots in the development of science. First of all, in Sect. 2.1 the scientific view on the climate and Earth as systems will be outlined. Section 2.2 will then give a historical retrospective in order to show why science is so dependent on numerical models and, in Sect. 2.3, how the climate is modelled today. Section 2.4 will continue with insights into the extensive structure for the international coordination of climate modelling, and in Sect. 2.5 the purpose of undertaking these huge efforts will be questioned. The answer, of course, is: to project future trends, but this poses another question. What kind of projections are provided and what can we expect from them—especially considering the uncertainties associated with this computable view into the future? Finally, in Sect. 2.6 limits of scientific arguments will be discussed.

2.1 Understanding the Climate System

2.1.1 Climate Stability

Paleo-data show that for the last 12,000 years we have lived in a relatively stable climate period called the Holocene (Stott et al. 2004). This stability supported the development of civilization based on the Neolithic Revolution around 10,000 B.C., when agriculture and cities were invented and the population multiplied (Gupta 2004). But history also demonstrates the sensitivity of particular human civilizations that collapsed upon encountering regional climate changes, as the ancient Mayan culture proved. This sensitivity to environmental conditions—both stable and unstable—has long shaped regional knowledge about the climate, but it took several thousand years before mankind reflected on the differences between climate zones. Based on a spherical world concept, in the sixth century B.C. the Greek philosopher Parmenides classified different zones from torrid and temperate to frigid climates. The term ‘κλιμα’ thereby referred to the slope of the Earth. Various theories on the number of zones followed—Parmenides listed five, Ptolemy later seven—, as well as on the portion of the world that is habitable, on the climatic influence of the length of days, and finally, on the synonymy of climate and latitude on maps by Ptolemy in the first century A.D. Ptolemy, in particular, became quite influential in the Arabic world as well as in Medieval and Renaissance Europe (Sanderson 1999). Climate zones were used as marks of orientation on maps until degrees of latitude were introduced in the sixteenth century. From the eighteenth century on, measurables such as temperature and precipitation were employed to indicate climate zones. But even though such measurables were used, the Ancient classification persisted.[2]

However, climate was seen as a stable phenomenon that shaped the form of climes. At the beginning of the nineteenth century a major debate on the origin of surface deposits, from clay to boulders, began among geoscientists. The dominant belief at this time was that the deposits were witnesses of the Biblical deluge. Consequently this period was coined ‘Diluvium’, the Latin word for deluge. Apart from the Biblical narratives, nature was considered to be invariant, inspired by the belief that only invariance provides objective truth. Later, in 1813, George Cuvier proposed that several catastrophic events could have been responsible for the deposits. In 1840 Charles Lyell hypothesized that floating icebergs might have dropped the erratic boulders rather than marine currents. Finally, the concept of widespread continental multiple glaciations gained ground at the end of the nineteenth century, giving rise to the idea that climate can change. But what were the reasons? In 1864, James Croll proposed an astronomical theory, speculating that changes in the earth’s orbital parameters might have triggered the sequence of cold and warm periods (Odroyd and Grapes 2008). The geophysicist Milutin Milankovic developed a mathematical model to calculate the changes in solar insolation due to orbital variations. His results were published in 1941, but the computed changes in insolation were too small to significantly perturb the climate system. Therefore, his theory was ignored for some decades until observational evidence from deep-sea sediment data taken in the 1960s was found to support his hypothesis. Numerical climate models have demonstrated that the Milankovic cycles initiate a suite of positive (amplifying) feedbacks in the climate system, which finally result in the occurrence of glacial and warm periods (Berger 1988; Ganopolski et al. 1998). Milankovic’s theory of celestial mechanics, causing changes between Warm Ages and Ice Ages, influenced the perception of climate research as an exact science. It fueled the hope that future climate developments were predictable.

2.1.2 The Physical and Mechanical Understanding of Climate

In order to understand this paradigm shift from an invariant climate to the perception of climate as a kinetic system, a physical and mechanical understanding of climate, as it is common for today’s science, is required. This understanding is

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[2] “The first quantitative classification of world climates was made by the German scientist Wladimir Koeppen in 1900. Koeppen was trained as a plant physiologist and realized that plants could serve as synthesizers of the many climatic elements. He chose as symbols for his classification the five vegetation groups of the late nineteenth-century French botanist De Candolle, which was based on the climate zones of the Greeks: A, the plants of the torrid zone; C, the plants of the temperate zone; D and E, the plants of the frigid zone, while the B group represented plants of the dry zone. A second letter in the classification expressed the moisture factor (an Af climate is tropical and rainy)” (Sanderson 1999, p. 672; see also Koeppen 1936).

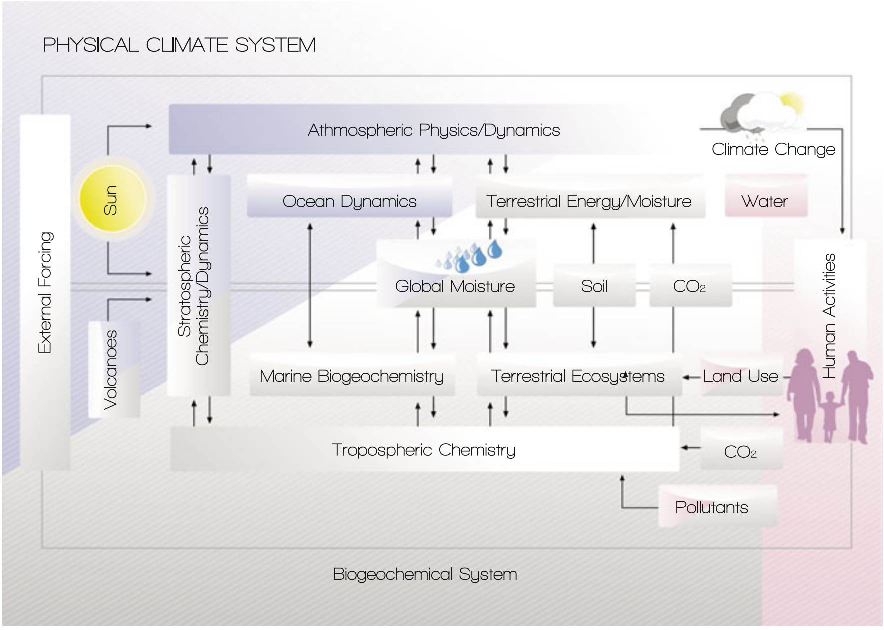

Fig. 2.1 Bretherton diagram. Various interactions and driving forces of climate change
Source: Replotted by the authors from *Earth System Science Challenges*, *The Strategic Plan 2003–2010*, Max Planck Institute for Meteorology 2003

based, on the one hand, on a view of nature as a complex system compounded of various components, each ruled by a set of interacting entities (see Fig. 2.1).[3] While climate used to be connected mainly to the atmosphere, today's approaches include the atmosphere, the ocean, the cryosphere (sea-ice and the large ice shields and glaciers), the pedosphere, and the marine and terrestrial biospheres. On the other hand, the physical and mechanical understanding combines two views which are two faces of the same coin: energy and motion. Driven by solar radiation, the atmosphere and the Earth absorb, transform, reflect and emit incoming energy.[4]

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[3] The system approach was introduced into science in nineteenth-century thermodynamics by the physicist Nicolas L.S. Carnot. He envisioned the relations between heat and work done by heat in an ideal heat engine, i.e., in a closed body. In 1824, his experiments led him to the following theorem: "When a gas changes in volume without change of temperature the quantities of heat which it absorbs or gives up are in arithmetical progression when the increments or reductions of volume are in geometrical progression" (Carnot 1824, p. 28).

[4] The relevant electromagnetic spectrum of radiation ranges from short-wave radiation emitted by the sun mainly as visible light (about 400–780 nm), to long-wave radiation emitted by the Earth and the atmosphere, mainly as heat (infrared light about 780 nm–1 mm). According to Wien's law the wavelength of emitted radiation is indirectly proportional to the absolute temperature. Thus, solar radiation is in the short-wave range (the sun's temperature ~5,800 K) and the infrared radiation emitted by the surface or the atmosphere is in the long-wave (or thermal) range. The increase in wavelength goes along with a decrease in energy.

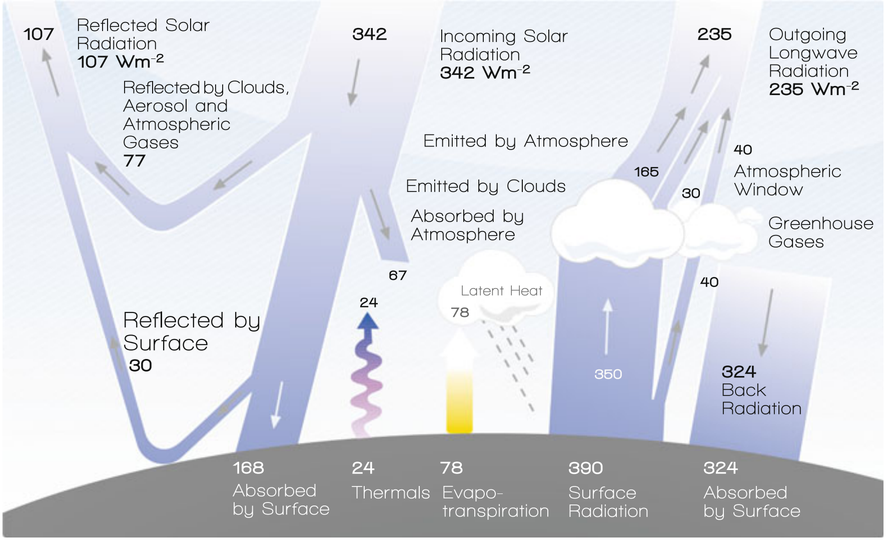

Fig. 2.2 Estimate of the Earth's annual and global mean energy balance. As displayed above, the planetary albedo, which is the fraction of solar radiation reflected, amounts to about 31%. The other 69% are used to heat the Earth-atmosphere system (20% the atmosphere and 49% the Earth's surface). The energy leaves the Earth-atmosphere system by conduction (rising hot air), as latent heat (energy is used to evaporate water which condensates in the atmosphere, where the energy is released again and carried from the surface to the atmosphere) and by thermal radiation. The thermal radiation from the surface is absorbed by greenhouse gas molecules in the atmosphere and radiated back to the surface, enhancing the temperature or escaping into space. The Earth remains at a constant temperature if averaged over a longer period, because the outgoing radiation equals the incoming
Source: Replotted by the authors from Kiehl and Trenberth 1997, p. 206

The view on energy focuses on the balance of energy flows by reflection, absorption and emission. These energy flows are based on the reflection of incoming solar radiation by air molecules, water droplets, ice crystals, and other particles; the absorption and transformation of incoming solar radiation into heat by the same particles; the reflection by the different surfaces of various albedos like water, vegetation, and snow;[5] the absorption of the energy not reflected and transformation into heat by these surfaces; the horizontal energy flow between the poles and the tropes by advection; and the latent heat flow of the water cycle (see Fig. 2.2). The overall energy radiated by a surface, according to Stefan-Boltzmann's law, is directly proportional to the fourth power of their absolute temperature. These energy flows are influenced by the behaviour of greenhouse gases and clouds. An atmosphere without greenhouse gases would lead to a surface temperature of –18°C. The greenhouse gases—the most important among them water vapour—act like a shield that keeps the surface temperature of the Earth at a lively +15°C.

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[5] Albedo is the fraction of reflected solar radiation to the total incoming solar radiation; A = 1 means all radiation is reflected.

If we neglect feedbacks, it is easy to calculate a rough estimate of the temperature change due to an increase in carbon dioxide (CO_2). The equilibrium surface temperature can be derived as

$$T_G = \sqrt[4]{\frac{S_0(1-A)}{2\sigma(2-\alpha)}},$$

with S_o the solar constant, the incident solar radiation at top of the atmosphere; A the planetary albedo, or $(1-A)$, the fraction of solar radiation absorbed by the Earth's atmosphere; α the long-wave absorptivity of the atmosphere as controlled by greenhouse gas concentrations; and σ the Stefan-Boltzmann constant. According to this equation, the surface temperature increases if the solar constant or the absorptivity (or the greenhouse gas concentrations of the atmosphere) increases, and decreases if planetary albedo increases. Short-wave radiation heats up the Earth's surface and to a smaller extent the atmosphere, and is emitted back to the atmosphere as long wave-radiation. Carbon dioxide, methane, and other gases as well as water vapour, clouds, and aerosols absorb and emit radiation within the thermal infrared range. Thus, a complex flow of energy, depending on the Earth's surface properties and the chemical composition of the atmosphere and modified by numerous feedback processes, determines the thermodynamic state of the atmosphere.

Energy causes motion. The view on motion focuses on the dynamics of the atmosphere caused by the effects of local differences in energy input and output, which create mechanical work in terms of motion.[6] Spatial and temporal variations in the energy balance drive the motions of the atmosphere as well as the ocean. For instance, the annual amount of energy received at the equator is a factor of 2.4 greater than that at the poles. This difference in solar radiation in polar and tropical zones lead to global circulation: Warm air in the tropics expands, becomes lighter, rises, drains off to the side in higher regions of the atmosphere (air pressure falls), and causes a vertical flow which drives the global circulation. Conversely, cold air sinks and becomes heavier (air pressure rises). Thus differences in temperature result in differences in air pressure and, in turn, differences in air pressure result in mechanical work, that is, motion based on the air's expansion and contraction. The gradients in temperature and pressure decisively influence the atmosphere's circulation, but other factors also play a role. The deflective effects on air masses by the Earth's rotation, angular momentum, gravity, and the Coriolis effect contribute to the global circulation and form typical wind patterns (see Fig. 2.3). Furthermore, global circulation interacts with regional conditions like surface properties and mountains to produce regional patterns such as the monsoons. Variations in local energy budgets are controlled by land-sea distribution, by soil type, by vegetation cover, by clouds and by the chemical composition of the atmosphere. In turn,

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[6] Because about 90%of the atmosphere's mass is located in the troposphere—from the ground up to an altitude of 16 km (about 1,000–100 hPa)—most circulation takes place here.

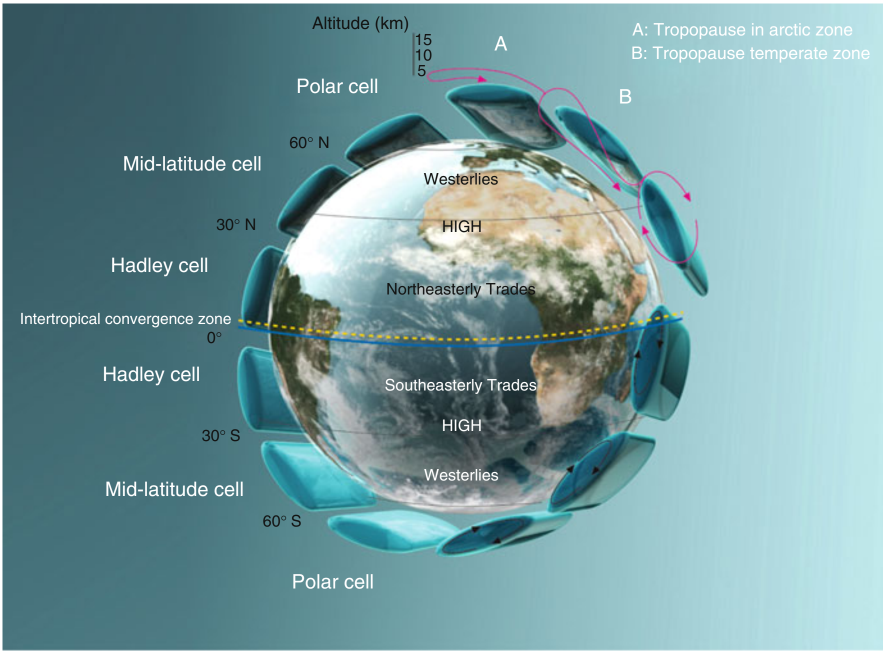

Fig. 2.3 The global circulation of the Earth: The polar cells, the mid-latitude cells (about 30°N to 60°N and 30°S to 60°S with the westerlies) and the Hadley cell (about 30°N to 30°S latitude with the northeasterly and southeasterly trade winds). When shipping increased in the sixteenth century, a scientific understanding of wind patterns became important. At the beginning of the seventeenth century it was known that around 30° latitude there is a 'torrid zone' with weak winds, and that south of this zone regular, northwesterly winds, called Trade Winds, exist (Persson 2006)
Source: Replotted by the authors from NASA, http://sealevel.jpl.nasa.gov/overview/climate-climatic.html

clouds, vegetation and chemical composition are influenced by the energy fluxes and other meteorological parameters.

While motion is caused by energy differences, it is slowed down by friction. Differences in wind velocity cause eddies, which propagate energy down to micro turbulences and molecular motion—where motion is transformed into heat. Both sides of the coin, energy and motion, are reunited within a general circulation model (GCM) which interconnects the two in terms of differences in velocity, humidity, density, pressure, and temperature, and thus models the complex physical and mechanical system of the atmosphere.

2.1.3 Greenhouse Effect and Climate Sensitivity

As mentioned above, without greenhouse gases the atmosphere would provide us with a mean surface temperature of –18°C instead of a lively +15°C. But this energy balance is a fragile one. Back in 1896 the physicist Svante Arrhenius already recognized that CO_2 supports a greenhouse effect. The meteorologists of that period first discussed the question as to whether "the mean temperature of the ground [is] in any way influenced by the presence of heat-absorbing gases in the atmosphere?" (Arrhenius 1896, p. 237). According to Arrhenius, "Fourier maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground" (p. 237). This absorption of heat "is not exerted by the chief mass of the air, but in a high degree by aqueous vapour and carbonic acid, which are present in the air in small quantities" (p. 239; Rodhe et al. 1997). It was not today's motivation of understanding and preventing anthropogenic greenhouse effect that posed the above question, but the interest in the cause of Ice Ages that drove climate research in the late nineteenth century. The basic hypothesis at that time was that mankind will face a new Ice Age; therefore an increase of temperature was welcomed. In 1938, the British engineer Guy S. Callendar published his groundbreaking studies on the increase of CO_2 concentration in the atmosphere. He pointed out that since the 1880s more than 150,000 million tons of CO_2 had been added to the air, and estimated that this would cause an estimated increase in temperature of about 0.003°C per year. For Callendar, this increase was embraced because the "return of the deadly glaciers should be delayed indefinitely" (Callendar 1938, p. 236). Therefore "the combustion of fossil oil [. . .] is likely to prove beneficial to mankind in several ways" (p. 236).

However, this opinion changed once scientists recognized the trend towards global warming. But it took another two decades before scientists became alarmed about the release of CO_2, because their main hypothesis was that the oceans would absorb it. The study by Roger Revelle and Hans E. Suess in the 1950s showed that the oceans cannot absorb CO_2 as rapidly as it is produced by mankind and that mankind was about to conduct "a vast geophysical experiment" (Revelle and Suess 1957). In 1957 Bert Bolin and Erik Erikson investigated the buffer and exchange mechanisms of the ocean en detail. Taking the rapid increase of fossil fuel emissions into account, they argued that the CO_2 content in the atmosphere would rise about 25% or more by 2000—in agreement with a study by Callendar at the same time (Bolin and Eriksson 1959; Callendar 1958).[7] Thus, the plan for a worldwide network of CO_2 monitoring stations was broached in the 1950s. The measurement of CO_2 concentrations began in Scandinavia back in 1955 (Bischof 1960), and in 1958 Charles D. Keeling begun measurements using an infrared CO_2 gas analyzer at the Mauna Loa Observatory in Hawaii as part of the International Geophysical Year.[8] This new instrument, as well as the site of Mauna Loa, allowed the collection of highly accurate results. Today the 'Keeling Curve', a time series of annual departures from 1961 on, clearly shows the increase of CO_2 concentration in the

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[7] A seminal study on *The Discovery of Global Warming* and a substantial bibliography is provided by Spencer Weart: URL: http://www.aip.org/history/climate/bib.htm (Weart 2003).

[8] Keeling's measurements were supported by Revelle, who "wanted to make sure that man's 'vast geophysical experiment' would be properly monitored and its results analyzed" (Keeling 1978, p. 38).