Chapter 2
Modelling the Climate System: An Overview

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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

[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).

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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

[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).

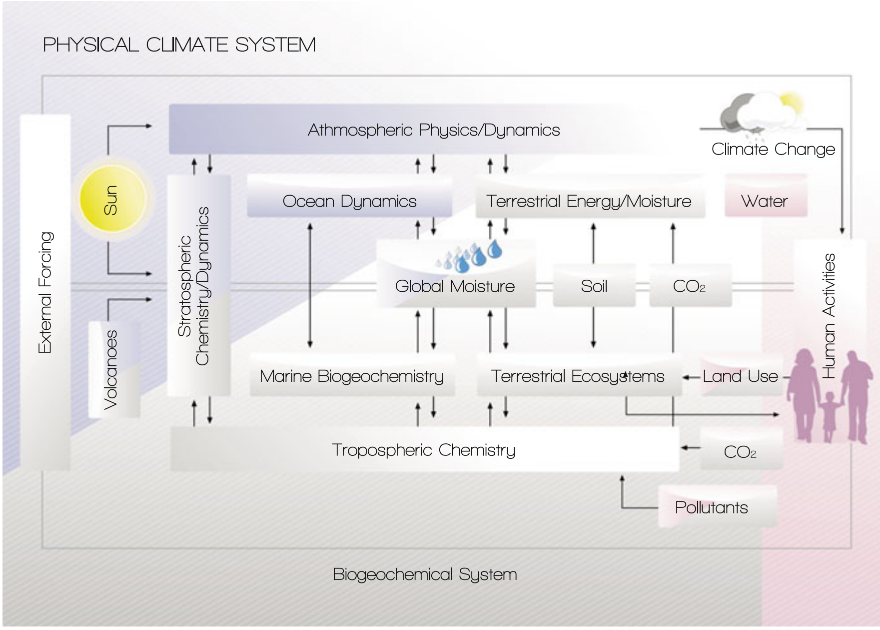

Fig. 2.1 Bretherton diagram. Various interactions and driving forces of climate change
Source: Replotted by the authors from *Earth System Science Challenges*, *The Strategic Plan 2003–2010*, Max Planck Institute for Meteorology 2003

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]

[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.

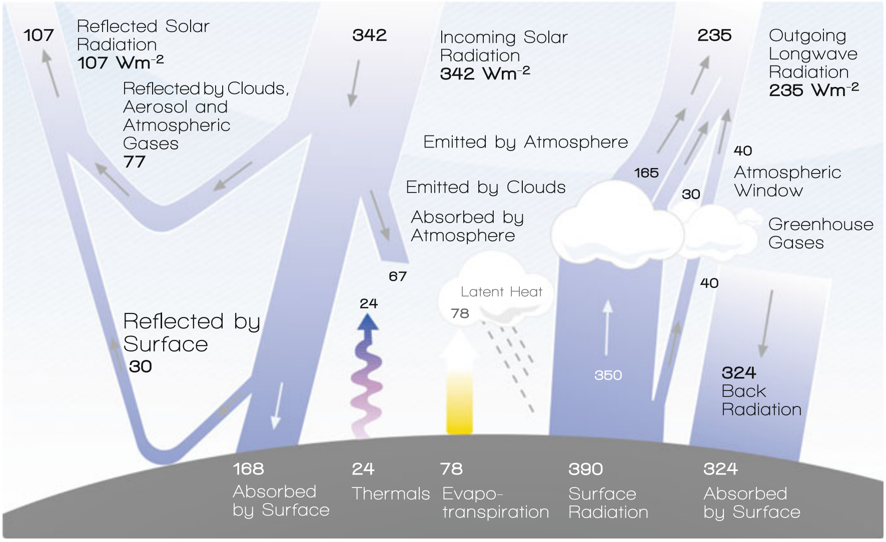

Fig. 2.2 Estimate of the Earth's annual and global mean energy balance. As displayed above, the planetary albedo, which is the fraction of solar radiation reflected, amounts to about 31%. The other 69% are used to heat the Earth-atmosphere system (20% the atmosphere and 49% the Earth's surface). The energy leaves the Earth-atmosphere system by conduction (rising hot air), as latent heat (energy is used to evaporate water which condenses 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,

[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.

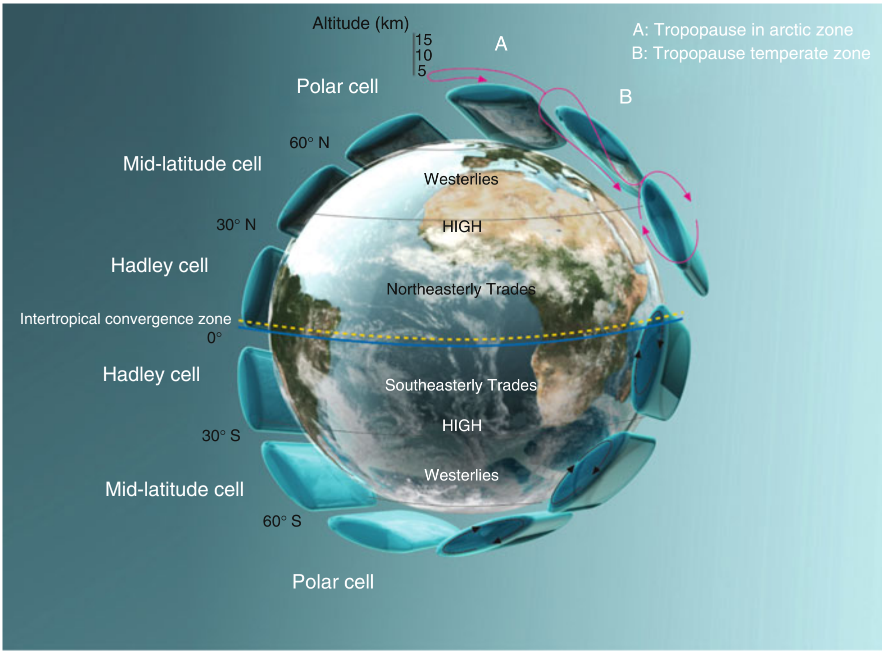

Fig. 2.3 The global circulation of the Earth: The polar cells, the mid-latitude cells (about 30°N to 60°N and 30°S to 60°S with the westerlies) and the Hadley cell (about 30°N to 30°S latitude with the northeasterly and southeasterly trade winds). When shipping increased in the sixteenth century, a scientific 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

[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).

atmosphere at a site that was thought to be unpolluted. This curve has become one of the icons of man-induced climate change (Keeling 1978; Weart 2003; see also Chap. 9 of this volume).

In the 1970s, once simulation methods had gained ground, the question arose as to what temperature would result from a doubled increase of CO_2 concentrations (Charney et al. 1979). This value, called ‘climate sensitivity’, is still one of the key questions in climate research. Climate sensitivity is defined as the globally averaged near-surface temperature change per greenhouse-gas-induced radiative perturbation. It can only be assessed by model-based simulations since controlled laboratory experiments with the atmosphere are not an option, although the model-based estimates of climate sensitivity vary by a factor of three. The main reason for this uncertainty is the fact that only 40% of warming is due to the relatively well-known direct greenhouse gas effect on thermal radiation, with 60% caused by feedbacks within the climate system. For instance, a warmer atmosphere retains more water vapour, and since water vapour is the most important greenhouse gas, this increase in water vapour concentrations enhances warming. The major uncertainty arises from feedback effects concerning clouds. Therefore, in order to diminish uncertainties and to enhance the understanding of the behaviour of the Earth’s system, more and more processes have to be parameterized and implemented in the models.

Ever since Charney posed the ‘CO_2 doubling question’ the endeavour of understanding the complex interplay of atmospheric processes has taken on entirely new dimensions. Today it is known that man’s activities impact the climate system via three mechanisms: by increasing greenhouse gases or ozone (which also absorbs in the solar radiation spectrum) in the atmosphere; by emitting aerosol particles or aerosol precursor gases; and by changing land surface properties. The greenhouse gases emitted by man, ordered according to their importance, are the long-lived species carbon dioxide (CO_2) and methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O, laughing gas) and the short-lived species ozone. Greenhouse gases affect the thermal radiation budget and exert a warming effect. Aerosols are liquid or solid particles in the atmosphere ranging in size between some nanometers to some micrometers. Aerosol particles are either emitted as particles (e.g., soot, dust from industry and road traffic) or formed by the condensation of vapours in the atmosphere (e.g., ammonium sulfate, ammonium nitrate, organics).

The man-made aerosol precursor gases are sulfur dioxide, nitrogen dioxide, ammonia and volatile carbon compounds. These particles absorb or scatter solar radiation and reduce solar insolation at the surface (solar dimming). Thus, in polluted regions we experience the paradox that although temperatures are rising, solar insolation is decreasing. Absorbing aerosols like soot warm the earth-atmosphere system; scattering aerosols like ammonium sulfate, ammonium nitrate and organics cool it. Furthermore, aerosols act as cloud condensation and ice nuclei. Cloud droplets and ice crystals form on aerosols, and the particle number concentration and chemical properties affect the microphysical properties of clouds. Aerosol pollution enhances the albedo of water clouds and thus exerts a cooling effect. The effects of aerosol pollution on ice clouds are not yet well understood and could amount to either warming or cooling. Land-use change, by deforestation and covering soil through urbanization and infrastructure construction, changes the surface albedo, the capacity of soils to hold water, and the evaporation rate. Pastures and cropland have a higher albedo than forests, thus land-use change in temperate and tropical latitudes enhances the amount of solar radiation reflected back to space, exerting a cooling effect. In tropical regions, deforestation reduces the evapotranspiration rate and results in warming. The overall effect of land-use change is to lower temperatures. However, with increasing deforestation in the tropics, the warming effect due to reduced evapotranspiration might dominate in the future.

2.1.4 Climate Variability

Based on this understanding of the fragile balance of direct and indirect feedbacks between the various components of the climate system, climate is defined as a statistical description in terms of the mean values and variability of relevant meteorological quantities over a period of time (WMO 2010). This definition unveils two basic concepts of climate research: averaging and variability. In fact, climate variability refers to changes in the mean state of climate (the standard deviation), or the occurrence of extremes on spatial and temporal scales beyond the variability of weather events. The variability of climate is caused by internal factors (internal variability) and by natural and anthropogenic forcings (external variability). Numerous interactions between the components of the climate system and nonlinear feedback loops induce random climate fluctuations on various temporal scales, a kind of noise in the climate system. Even in the absence of any radiative forcing or perturbation, weather patterns differ from year to year. These fluctuations, also called 'internal variability', are inherently chaotic and thus not predictable—some regions experience stronger, some weaker variability. Furthermore, some parameters are more variable than others; for instance, temperatures at high latitudes show stronger variability than in the tropics, and precipitation fluxes are characterized by higher variability than are temperatures.

External mechanisms cause changes in the state of climate, such as changes in solar radiation, changes in the Earth's orbital parameters, plate tectonics, strong volcanic eruptions, and human influences. The sign and magnitude of these perturbations is expressed in terms of the net radiative imbalance at the top of the troposphere or atmosphere. Man-made perturbations of the radiative imbalance are termed 'radiative forcing', with negative forcing causing cooling and positive causing warming. The radiative imbalances and forcings are calculated using general circulation models of the atmosphere. The radiative forcing due to a man-made increase in CO_2 concentrations between 1750 and 2005, for instance, is +1.66 W/m^2. In contrast, the CO_2 concentration after the eruption of Mount Pinatubo in June 1991, the best investigated volcanic eruption, was in the order of –3 W/m^2 one year after eruption, but dropped to pre-eruption values within few years. Compared to anthropogenic and other natural forcings in the climate system, volcanic radiative forcing acts on a short time-scale.

Knowledge of internal climate variability is mandatory to detect anthropogenic impacts on the climate. As both external forcings and internal variability impact climate, only climate models can separate internal from forced variability. Internal variability might change in a changing climate—and a specific forcing can excite a particular mode of this internal variability, leading to a kind of resonance. The magnitude of the climate response to a specific forcing can thus be weak or very intense, depending on the actual mode of internal variability when the forcing is applied. As a consequence of these chaotic internal fluctuations, the time evolution trajectory of the past climate can never be reproduced exactly by a climate model, because each simulation is just one realization of many possible states. Hence, simulations reproduce past climates only in a statistical sense, that is, models provide the range of possible climate states associated with a specific forcing (Bengtsson et al. 2006). The internal variability of the climate system thus constitutes an upper limit for the detection of anthropogenic climate change. An anthropogenic climate signal is detectable only if it exceeds the noise or the internal variability. The contribution of natural variability in explaining recent temperature increases is one of the key issues in the current climate change debate.

The important outcome of meteorological investigations since Arrhenius is that climate is a complex phenomenon. As such, it denies the application of mono-causal explanations and, more important, mono-causal interventions. The awareness of this complexity is an indispensable result of series of long-term observations, but also of the increasing use of numerical models in meteorology. In particular, numerical models are needed to conduct ‘experiments’ with a digital atmosphere to acquire analytical knowledge. Only models allow scientists to separate internal from forced variability and to run feedback interactions. For instance, according to model simulations, we know that only 40% of the temperature response due to an increase of greenhouse gas concentrations in the atmosphere arises from the greenhouse effect (change in the thermal radiation budget). The other 60% are caused by feedbacks with the water cycle, emphasizing the importance of feedback processes. And these feedbacks can only be studied in a digital atmosphere. But there are other reasons why science needs numerical models.

2.2 The Need for Numerical Models in Science

2.2.1 From Observation to Forecasting

The briefly outlined picture of the physical understanding of climate is rooted mainly in developments of nineteenth and twentieth-century meteorology. The transformation of meteorology into the physics of the atmosphere was accompanied by the increasing use of models. Models have been a common tool of knowledge production for physicists since the seventeenth century, but are newer to meteorologists because meteorology lacked a theoretical foundation in the eighteenth and nineteenth centuries. It was mainly a descriptive science, based on the measurement and recording of empirical data. But pure data provide no insights into phenomena; they need to be interpreted on the basis of theory. Therefore the introduction of physical laws gradually transformed meteorology from a descriptive science into one based on theory and models.[9] This transformation began when meteorologists tried to apply the physical theories of hydrodynamics and thermodynamics to meteorology, with the consequence that the correlation between global circulations and regional patterns was fully recognized. While weather is defined as the actual state of the atmosphere in a period of several hours up to a few days, climate is the statistics of weather over a longer period, of months, years and decades. Therefore the scientific basis—the physics of the atmosphere—is the same for both, but the application of this scientific basis differs for weather and climate models, e.g., in terms of temporal and spatial resolutions, as well as in their boundary conditions.

A look at the history of meteorology unveils the step-by-step transformation of meteorology into a theory- and model-based science.[10] While the measurement and recording of meteorological variables like temperature, air pressure, and humidity dates back to the seventeenth and eighteenth centuries when the thermometer (temperature), barometer (pressure), and hygrometer (humidity) were developed,[11] the theoretical analysis of these data did not begin until the nineteenth century. One reason was that the available records were not comparable with each other, as they were based on individual measurement devices and periods carried out by singular scholars. As early as 1667 Robert Hooke had presented a *Method for Making a History of the Weather* to the audience of the Royal Society at London, where he demanded the standardization of measurement devices, of measurement periods, and of the style of records (Hooke 1667). But it took another century until the Societas Meteorological Palatina finally coordinated internationally standardized measurements for the first time in 1781.[12] By the end of the nineteenth century a growing

[9]Models in this sense are defined as the concretizations of a theory. This so-called semantic view on models is widespread in the theory of science (Fraassen van 1980).

[10]There is an increasing body of historical studies on meteorology (see for example Friedman 1989; Fleming 1990, 1998; Nebeker 1995; Harper 2008). A *Bibliography of Recent Literature in the History of Meteorology* is provided by Brant Vogel (Vogel 2009). A review of *The International Bibliography of Meteorology: Revisiting a Nineteenth-Century Classic* is given by James R. Fleming (Fleming 2009).

[11]In 1597 Galileo Galilei developed a water thermometer which was advanced by Daniel Fahrenheit's mercury thermometer in 1714. In 1643 Evangelista Torricelli developed the barometer, and in the eighteenth century Horace-Bénédict de Saussure invented the hair tension hygrometer when he discovered that hair under tension expands relative to the surrounding humidity.

[12]In 1781 the Societas Meteorological Palatina, located in Mannheim, operated 39 weather observation stations around the globe. Because it took more than 100 years to introduce the standard of the Greenwich Mean Time in 1884 (and Coordinated Universal Time in 1972) to globally synchronize measurements, the Societas introduced the 'Mannheim hour' as a global standard for time measurements. By using measurement devices of identical construction for measurements recorded simultaneously all over the world, at 7, 14, and 21 Mannheim hour, they set a standard for meteorological measurements that would fulfill even today's requirements (Wege and Winkler 2005).

network of weather observation stations covered Europe and the US, but measurement instruments and practices still "remained discrepant, and it was enormously difficult to coordinate them. For years [. . .] the failure of coordination appeared on most weather maps in the form of a wholly artificial cyclone over Strasbourg" (Porter 1995, p. 27). Problems in the coordination and exchange of data were the other reason why the theoretical analysis of measurement data was deferred. The exchange of data, too, was as difficult to achieve as their standardization and synchronization, but it made little sense to study weather or climate as local phenomena, since there is no way to escape their dependence on regional and global conditions. Therefore meteorologists had to exchange data, but before the invention of the electric telegraph in 1835 this exchange was difficult and tedious as it was based on the use of printed weather almanacs. During the 1840s the exchange of data by telegraph increasingly allowed the daily analysis of weather conditions from a wider area, with the expanded data rounding out a regional picture of the actual weather situation.

However, the growing amount of data led to a new problem, because tables started to overflow with digits without providing any synoptic insight. Meteorologists had to develop methods to compile a synoptic view from these singular data, thus forcing them to switch from a purely typographic to a hybrid typographic and graphic medium. This switch resulted in a new epistemic tool—weather maps—about which the Norwegian meteorologist Vilhelm Bjerknes later said that "in the hands of these researchers weather maps have developed into a basic—immaterial—instrument of the physic of the atmosphere, analogous to the material instruments of experimental physics" (Bjerknes 1938, p. 61). Although early weather maps could not do full justice to Bjerknes' claim, they opened up new insights by graphically generalizing singular data with isolines and complex graphical items like wind vectors. For instance, diagrams with overlapping isobars and isotherms presented a picture of the major thermodynamic factors of weather conditions. The combination of these items simultaneously visualized various factors of the weather system, so that meteorologists began to see anticyclones and cyclones: "high- and low-pressure areas roaming over the maps" (p. 50). As they realized that weather was caused by travelling air masses, the development of cyclones (cyclogenesis) became a research topic.

Based on these new insights of synopsis, meteorologists could now think about developing methods for prolonging the synoptic picture into the future. It was Robert Fitzroy, a British Admiral to the Navy, who optimistically promoted the practical utilization of meteorology in his *Weather Book: A Manual of Practical Meteorology* in 1863. As he was particularly interested in forecasting storms, he concentrated on the 'dynametry' of air—the movement, force, and duration of motion—which he intended to extract from local measurement data by combining statistical and mathematical methods.[13] He applied a qualitative knowledge of the

[13]The disastrous Royal Charter storm in 1859, which caused the loss of over 800 lives and the steam clipper Royal Charter, inspired Fitzroy to develop charts for weather forecasts and storm warnings.

atmosphere's dynamics, based on observations and the known physical explanations of the causes of circulation. Back in 1686 Edmund Halley had explained that solar radiation differs for low and high latitudes. Heated tropical air is replaced by cooler air from polar regions, thus causing a north–south circulation. This circulation is, as George Hadley pointed out in 1735, deflected by the Earth's rotation. Because the speed of rotation differs at each point on Earth, as Heinrich Dove explained in 1837, the deflection of air masses differs as well, causing a difference in rotational speed between moving air masses and the places to which these masses have moved. These differences slowly change the direction of the currents, for instance when they come from the North Pole, from north to northeast to east. In 1858 William Ferrel rediscovered the Coriolis effect and applied it to the atmosphere (Halley 1686; Hadley 1735; Dove 1837; Ferrel 1858; Fleming 2002). Fitzroy's dynametry was based on these theories. He took into account the northeast and southwest motion as the 'wind poles', as Dove called them, assimilating all intermediate directions to the characteristics of these extremes. He traced them back to the polar and tropical currents and distinguished them from local effects. He also considered dynamic forces caused by heat or cold, by the expansion of air masses, or other causes. Furthermore, he was aware that changes in weather and wind were preceded and accompanied by alterations in the state of the atmosphere, and that these alterations were indicated sooner in some places than others. Therefore changes in temperature, pressure, and wind direction could be seen as "signs of changes [of weather] likely to occur soon" (Fitzroy 1863, p. 177). On this basis of knowledge and measurement data—compiled from 30 to 40 weather telegrams daily—he introduced his concept of weather forecasting to the newly founded Meteorological Department of the Board of Trade, the forerunner of the British Meteorological Office. Fitzroy coined the term 'weather forecast', defining it as "strictly applicable to such an opinion as is the result of a scientific combination and calculation" (p. 171). In August 1861 the first forecast was published for Scotland, Ireland, and England and he vividly described the practice of this new service in his manual:

> At ten o'clock in the morning, telegrams are received in Parliament Street, where they are immediately read and reduced, or corrected, for scale-errors, elevation, and temperature; then written into prepared forms, and copied several times. The first copy is passed to the Chief of Department, or his Assistant, with all the telegrams to be studied for the day's forecast, which are carefully written on the first paper, and then copied quickly for distribution. At eleven—reports are sent out to the Times (for second edition), Lloyd's, and the Shipping gazette; to the Board of Trade, Admiralty, and Horse Guards (p. 194).

Although Fitzroy was sure that the dynametry of air would become a subject for mathematical analysis and accurate formulas, he had to improve the more accessible tool of weather maps because of the limited capacity of computation at that time. He introduced maps with movable wind markers and 'nodes'–centrical areas around which the principal currents circulate or turn.[14] He used colour gradients to

[14] According to Alexander Dieckmann, the concepts of both Heinrich Dove and Robert Fitzroy should be seen as forerunners of the 'polar front' theory outlined by Vilhelm Bjerknes in 1919 (Dieckmann 1931; Bjerknes 1919).

mark the energy differences in polar (blue) and tropical (red) air streams. These maps and the knowledge of dynamical principles guided meteorologists in their work of forecasting. But this work was more an art than an exact science. It was based mainly on experience and a feeling for the dynamical principles than on computation or geometrical construction. Nevertheless, the method of 'synoptic meteorology' became a promising approach. In 1941 the meteorologist Tor Bergeron pointed out in a retrospect on his domain:

> Synoptic Meteorology based on telegraphic weather reports appeared in practice simultaneously in England and France in 1861, met with the greatest expectations in all Europe. As a consequence meteorological institutes were established in most other European countries in the ensuing 20 years (in Sweden in 1873) with the main object of issuing weather forecast and storm warnings based on synoptic maps [. . .] Meteorology was, however, then only a new-born science and by far not an exact one. [. . . It] had to get on with mainly empirical, formal and one-side methods, which were quite un-fit to the extreme complexity of its main problems (Bergeron 1941, p. 251).

This lack of complexity led to false prognoses and gave synoptic meteorology a bad reputation until the methods of weather analysis and databases advanced in the 1910s.

2.2.2 Meteorology as Physics of the Atmosphere

Synoptic meteorology, which had its heyday during the first half of the twentieth century when concepts of cyclogenesis gained ground (Bjerknes 1919), followed a qualitative approach of physics. While synoptic meteorology applied its approach from the perspective of the synoptic scale to the atmosphere—a horizontal length scale on the order of 1,000–2,500 km, a complementing perspective from the scale of the infinitesimal, applied to the global scale, began entering meteorology at the end of the nineteenth century, known as 'dynamical meteorology'. This new perspective resulted from the purely theoretical area of hydrodynamics. The problem of motion was of practical interest not only for meteorologists. For centuries it had occupied the greatest minds of science. In 1755 the mathematician Leonhard Euler had derived the general equations of motion from Isaac Newton's Second Law of Motion, stating that a body experiencing a force F experiences an acceleration a related to F by, in Euler's notation, $F = ma$. Euler applied Newton's law to fluids—gases and liquids—by mathematically describing the flow of an idealized fluid without friction. In consideration of the conservation of mass and energy, he received a set of five coupled equations and five unknowns—velocity in three directions, pressure, and density. To close this system an equation of state is required, which specifies the state of matter under a given set of physical conditions: e.g., the ideal gas law, which describes the state of a gas determined by its pressure, volume, temperature, and the amount of substance. The Euler equations were among the very first partial differential equations in science to deal with the concept of infinitesimals. They were later expanded by Claude Navier and George

Stokes for viscous fluids.[15] The Navier–Stokes equations are used to describe the flow of a fluid of a certain mass experiencing various forces such as pressure, gravitation, and friction. The Euler equations correspond to the Navier–Stokes equations if viscosity and heat transfer are neglected. Today's general circulation models of the dynamics of both the atmosphere and the ocean are based on the Navier–Stokes equations.

It was the vision of Vilhelm Bjerknes that meteorology should become an exact science, a physics of the atmosphere, based on thermo- and hydrodynamical theory. Trained as a physicist, he was not interested in meteorology at first, but a mathematical problem regarding idealized assumptions in hydrodynamics directed him towards meteorological considerations. In his study *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology*, Robert Friedman describes Bjerknes' situation in the 1890s when he tried to apply hydrodynamic analogies to electric and magnetic phenomena. His results "contradicted the well-established theorems of Helmholtz and Lord Kelvin which claimed vortex motions and circulations in frictionless, incompressible fluids are conserved" (Friedman 1989, p. 19).[16] Bjerknes' results pointed in another direction. He realized that density in a fluid without any restrictions on compressibility depends not only on pressure, as in the concepts of Helmholtz and Kelvin, but on other variables as well, for instance temperature. In 1897, and again in 1898, he presented his results to the audience of the Stockholm Physics Society. The present meteorologists Nils Ekholm and Svante Arrhenius immediately realized the relevance of Bjerknes' "general circulation theorem" for meteorology. The rise of interest in cyclogenesis paved the way for Bjerknes, who started to seriously consider a research program of an exact science of the atmosphere based on the laws of physics—encouraged by the leading meteorologists Cleveland Abbe and Julius Hann.[17] The general circulation theorem laid the basis for a view of the atmosphere as a "turbulent fluid

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[15]George Stokes conceived the motion of a fluid differently than Claude Navier had done. He developed a method that "does not necessarily require the consideration of ultimate molecules [as Navier did]. Its principle feature consists in eliminating from the relative motion of the fluid about any particular point the relative motion which corresponds to a certain motion of rotation, and examining the nature of the relative motion which remains" (Stokes 1845, p. 185).

[16]This claim implied that vortices cannot be created or destroyed in such idealized fluids (Helmholtz 1858). But the appearance and disappearance of vortices was a common phenomenon to meteorologists. Therefore the idealized theoretical and mathematical models of hydrodynamics were not applicable to meteorology.

[17]Bjerknes' concept did not appear out of nowhere, e.g., the meteorologist Sir William N. Shaw had derived equations from physical laws for meteorological problems. In 1866 Julius Hann had already used thermodynamics to explain the warm, dry winds from the Alps. In the mid-1990s the physicists J.R. Schütz and Ludwig Silberstein also extended Helmholtz's vorticity equations to the case of a compressible fluid (Thrope et al. 2003). In 1901 Max Margules calculated the change of pressure within columns of differing temperature, and in 1902 Felix Exner computed a prognosis of air pressure. Bjerknes' outstanding achievement was to consolidate the fragmented field of dynamic meteorology on a sustainable basis of theoretical, practical and computational research (Gramelsberger 2009).

subjected to strong thermal influences and moving over a rough, rotating surface" (Rossby 1941, p. 600).

The concept of such an exact science of the atmosphere was outlined in Bjerknes' seminal 1904 paper, *The Problem of Weather Prediction, Considered from the Viewpoints of Mechanics and Physics*.[18] Rooted in the deterministic approach of physics, Bjerknes stated that

> the necessary and sufficient conditions for a rational solution of the problem of meteorological prediction are the following: 1. One has to know with sufficient accuracy the state of the atmosphere at a certain time. 2. One has to know with sufficient accuracy the laws according to which a certain state of the atmosphere develops from another (Bjerknes 1904, reprinted in 2009, p. 663).

If both are known sufficiently, the future states of the atmosphere can be extrapolated. This is the underlying principle of weather forecasting as well as climate prediction. In opposition to the purely empirical and statistical methods of synoptic meteorology, he understood atmospheric processes to be of a mixed mechanical and physical nature. In his mathematical model the state of the atmosphere was determined by seven variables: velocity (in three directions), and the density, pressure, temperature, and humidity of the air for any point at a particular time. For the calculation of these variables Bjerknes proposed a mathematical model based on the three hydrodynamic equations of motion (describing the relation between the three velocity components, density and air pressure), the continuity equation (expressing the continuity of mass during motion), the equation of state for the atmosphere (articulating the relation between density, air pressure, temperature and humidity of any air mass), and the two fundamental theorems in the mechanical theory of heat (specifying how the energy and entropy of any air mass change in a change of state). Such a mathematical model can be used to compute prospective states of the atmosphere, expressed as the computation of these seven variables into the future.

However, the analytical solution of such a complex mathematical model was, and still is, not achievable. An arithmetical way to calculate it seemed too laborious considering the limited power of human computers at that time. Therefore Bjerknes proposed a mixed graphical and mathematical way for computing future states. In the 1904 paper he outlined some ideas for reducing the complexity of his model by following the principles of infinitesimal calculus with several unknowns.

> For mathematical purposes, the simultaneous variation of several parameters can be replaced by sequential variations of individual parameters or of individual groups of parameters. If this is accompanied by using infinitesimal intervals, the approach corresponds to the exact methods of infinitesimal calculus. If finite intervals are used, the method is close to that of the finite difference and of the mechanical quadratures, which we will have to use here. However, this principle must not be used blindly, because the practicality of the method will depend mainly on the natural grouping of the parameters, so that both

[18]The paper was published in the *Meteorologische Zeitschrift* in January 1904–entitled "Das Problem der Wettervorhersage, betrachtet von Standpunkt der Mechanik und Physik". An English translation is provided in the *Meteorologische Zeitschrift* of December 2009 (Bjerknes 2009).

mathematically and physically well-defined and clear partial problems will result (Bjerknes 2009, p. 665).

According to Bjerknes, a “natural dividing line” of the problem is given by the boundary between the dynamical and the physical processes—separating the hydrodynamic from the thermodynamic problems. Although Bjerknes followed this natural dividing line, he avoided the practice of theoretical hydrodynamicists who, in order to simplify computation, cut the link between both theories by disregarding temperature and humidity in the equation of state. But Bjerknes had already overcome this idealization, which has led others to the simplifying assumption that density is related solely to pressure.[19] Instead of omitting temperature and humidity, his mathematical model of the atmosphere considered both as “parameters for shorter time intervals, using values that are either given by observations or previous calculations” (p. 665).

Although the 1904 paper outlined Bjerknes’ mathematical model and gave a very clear vision of a rational method of weather forecasting, it did not contain any equation or computing plan. Nevertheless, Bjerknes was very optimistic about the possibility of computing his model, which would turn meteorology into an exact science. In fact, in the following years he devoted his work to achieving a way of computing forecasts. He had a mixed graphical and mathematical method in mind for performing the computations directly upon the charts. This, he pointed out in 1911, “will be of the same importance for the progress of dynamic meteorology and hydrography as the methods of graphical statistics and of graphical dynamics have been for the progress of technical sciences” (Bjerknes 1911, p. 69). When Bjerknes became director of the Leipzig Geophysical Institute in 1913 he claimed in his inaugural lecture that “there is only one task: to compute future states of the atmosphere” (Bjerknes 1913, p. 14).[20]

2.2.3 Limitations of Analysis and the Need for Numerical Methods

The idea of computing future states of the atmosphere has become the driving force for meteorology as physics of the atmosphere, or as Bjerknes claimed, as an exact science. The idea of an exact science is related to the use of numbers and laws, the

[19]While hydrodynamics deals with the motion of fluids, thermodynamics studies the energy conversion between heat and mechanical work. “Indeed it can be cut so easily that theoretical hydrodynamicists have always done so in order to avoid any serious contact with meteorology” (Bjerknes 2009, p. 665).

[20]Bjerknes had to give up his ambitious program and successfully developed a more practical way of weather forecasting when he moved from Leipzig to Bergen in 1917. He improved the methods of synoptic meteorology based on an advanced theory of cyclogenesis (the polar front theory), which he had developed together with his son Jacob and others, now called the ‘Bergen school’ (Bjerknes 1919; Friedman 1989).

latter articulated as equations. The basic promise of exact science is: if the current state of a system, e.g., of the atmosphere, is known by measurement and the laws of its behaviour are understood, future states are computable. This promise was largely fulfilled for very simple models in 1846, when the French scientist Urbain Le Verrier forecasted the existence of planet Neptune based solely on calculations. His numerical forecast was confirmed several days later by the Berlin Observatory through observation (Galle 1846). However, predictability is not so easy to achieve, for reasons of complexity and efficiency. In fact, the lack of both led to a stagnation in science which hindered scientific—and, in particular, technological—development in the late nineteenth and early twentieth centuries. Mathematical models like the one Bjerknes suggested for weather forecasting were far too complex to be solved analytically, that is to deduce an exact solution. An exact solution describes the behaviour of a system at any time and place. Exact solutions can be derived for very simple systems like two-body systems without any disturbance. But such systems are extremely idealized and do not occur in nature. In the case of two bodies—e.g.,, planets idealized as the midpoints of perfect spheres—the influence of the bodies on each other is linear and their behaviour can therefore be deduced and predicted. But even a tiny disturbance can cause a non-regular behaviour that is no longer easy to predict. The disturbance introduces a more complex feedback into the two-body system of nonlinear nature. Small changes can produce complex effects, such that the output of the system is no longer directly proportional to the input. For more complex systems it is not possible to derive an exact solution. This limitation of analysis made science 'blind' for the prediction of the behaviour of complex systems like the atmosphere, although they could describe them mathematically. Therefore scientists had to decide whether they wanted to theoretically analyze the behaviour of idealized, i.e. simplified, systems that do not occur in nature, or investigate more complex and realistic ones in a practical way.

This situation of science at the end of the nineteenth and the beginning of the twentieth centuries led to a schism between theory and application in various disciplines. Its effects were felt most prominently in the fields of hydrodynamics and fluid dynamics.[21] The flow of air or water could be studied theoretically without any reference to real circumstances like friction or turbulent flow. Alternatively, scientists and engineers could use experiments to collect particular data for individual cases that did not provide much general insight into the nature of fluid phenomena. Only numerical models and their computation—so-called simulations—are able to overcome this schism, but the price for this is uncertainty

[21]In his study *The Dawn of Fluid Dynamics* Michael Eckert described the situation dramatically: "More than a 100 years after Bernoulli's and Euler's work, hydrodynamics and hydraulics were certainly no longer regarded as synonymous designations for a common science. Hydrodynamics had turned into a subject matter for mathematicians and theoretical physicists—hydraulics became technology. Aerodynamics, too, became divorced from its theoretical foundations in hydrodynamics. [. . .] In all these areas of application, air resistance was the central problem. Aerodynamic theory could not provide a single formula that accounted for the various practical goals" (Eckert 2006, pp. 25, 26).

(see also Sect. 2.5). Nonetheless, at the beginning of the twentieth century science lacked efficient tools for computation and scientists had to find other ways to perform practical investigations of complex systems. One of the methods to overcome the schism was experimentation. Scientists tried to cope with this problematic situation by using experiments for computation and to derive empirical formulae. In particular, wind tunnels and water tanks were used to study the influence of scale models, e.g., of ships or air planes, on the flow of a fluid. A text book for aircraft construction stated in 1929: "Our knowledge of surface air friction is wholly based on experience, but the model rules suggest a convenient formula for its magnitude". These model rules "are of immense practical use, and they refer to all kinds of flow, not only to theoretical ones" (Munk 1929, p. 137). Using experimental devices like analogue computers delivered numerous empirical formulae for all kinds of cases and parameter ranges.[22] But the validity and precision of these experimental devices were limited and often not comparable with results acquired from other devices. It turned out that early wind tunnels produced turbulent flows rather than the uniform flow of air needed. Therefore "the data collected here [Langley Laboratory]", as a report on wind tunnels concluded, "must be considered, primarily, as data concerning the tunnel, and not the models tested here" (Reid 1925, p. 219). Furthermore, such empirical formulae "although fulfilling well enough the purposes for which they were constructed", as George Gabriel Stokes had already pointed out in 1845, "can hardly be considered as affording us any material insight into the laws of nature; nor will they enable us to pass from consideration of the phenomena from which they were derived to that of others of a different class, although depending on the same causes" (Stokes, 1845, p. 76). Science was stuck between idealization and complexity, between the limitation of analysis and the limitation of experiments and empirical formulae.

2.2.4 Introduction of Computers and Forecasting Algorithms

Fortunately, another way of dealing with this schism emerged in the 1940s. When in 1946 Herman Goldstine, an U.S. Navy officer, and John von Neumann, a Hungarian-American mathematician, referred to the situation of analysis and science as "stagnant along the entire front of nonlinear problems" (Goldstine and von Neumann 1946, p. 2), they had in mind numerical models and automatic computing machines that were supposed to help overcome this stagnation. The basic question they posed was: "To what extent can human reasoning in science be more efficiently replaced by mechanisms?" (p. 2). The mechanisms Goldstine and von Neumann had in mind were the integration of differential equations with automatic computing machines.

[22]"In 1896 a textbook on ballistics lists in chronological order 20 different 'laws of air resistance', each one further divided into various formulae for different ranges of velocity. [. . .] No physical theory could provide a logical framework for justifying these empirical 'laws'" (Eckert 2006, p. 26).

These machines should replace “computation from an unquestioned theory by direct measurement. Thus wind tunnels are, for example, used at present, [. . .] to integrate the non-linear partial differential equations of fluid dynamics. [. . .] It seems clear, however, that digital (in the Wiener-Caldwell terminology: counting) devices have more flexibility and more accuracy” (p. 4). In other words: Instead of using experiments for computation, computers should be used for experiments by numbers.

Computation, however, is laborious work. Back in the 1600s Johannes Kepler had already required vast computations to calculate the orbit of Mars. In fact, he needed years for his computations, but at the end he had turned astronomy into a number-crunching science. Before the invention of automatic computing machines, calculation was carried out by humans, called ‘computers’. In his study on *When Computers Were Human* David Grier explored the history of human computing groups, whose work

> might be best described as ‘blue-collar science’, the hard work of processing data or deriving predictions from scientific theories. [. . .] Though many human computers toiled alone, the most influential worked in organized groups, which were sometimes called computing offices or computing laboratories. These groups form some of the earliest examples of a phenomenon known informally as ‘big science’, the combination of labor, capital, and machinery that undertakes the large problems of scientific research (Grier 2005, p. 5).

These computing laboratories were the forerunners of today’s computational departments. Their computing planes have turned into forecasting algorithms and numerical simulations. And their machinery—mechanical desk calculators, slide rules, and tabulator machines—have become giant supercomputers. Since numerical prediction by hand reached its first peak in the late nineteenth century, the need for computation has increased heavily, so that the development of numerical methods and computing devices has become a core challenge for science. The race for better and faster computational devices and machines was and still is fueling the progress of science and engineering. Prediction, optimization, and planning are the main reasons for this need. The U.S.-American computer pioneer Vannevar Bush called this mode of knowledge production ‘instrumental analysis’. “Under instrumental analysis is to be grouped all analysis proceeding by the use of devices for supplementing pure reasoning” (Bush 1936, p. 649). Bush concluded, referring to the latest advances at the beginning of the computer age in the 1930s, that “there is a great deal more arithmetic and better arithmetic in the world than there used to be” (p. 652). This statement is extended by today’s supercomputers into the immeasurable.

In order to strengthen instrumental analysis two things were required: efficient automatic computing machines and advanced numerical methods. The computer age began when the flow of energy and the flow of symbols fused and general-purpose computing machines entered the scene. Vannevar Bush’s Differential Analyzer, a mechanical analog computer for the integration of differential equations, built between 1928 and 1932 at the Massachusetts Institute of Technology, was a forerunner of these new machines. Another was Konrad Zuse’s binary electrically driven mechanical calculator Z1, which attained limited programmability, followed by the

Z3 in 1941, the first fully operational electro-mechanical computer. Finally, in 1946 the first general-purpose electronic computer was announced: the ENIAC Electronic Numerical Integrator and Computer.[23] ENIAC consisted of 18,000 vacuum tubes, with an arithmetic design influenced by "mechanical desk calculators, electrically powered and hand operated; and electromechanical card operated IBM machines" (Burks 1980, p. 315). Computation was unbelievably fast for this time. While an experienced human computer needed 7 h to compute a single trajectory based on 750 operations of a ballistic calculation, and Bush's Differential Analyzer required 10–20 min, this time was reduced to 2.25 s by ENIAC (Goldstine and von Neumann 1946). But working with ENIAC was slowed down by the fact that each new calculation had to be hard-wired. A maze of cables had to be unplugged and re-plugged, and arrays of switches had to be set manually (Ceruzzi 1998). While computation itself was fast, setting up ENIAC took days.

ENIAC was built to solve differential equations. John von Neumann joined the ENIAC team in 1944, as he was known as one of the rare experts in solving differential equations numerically. At Los Alamos he was involved in ballistic calculations, and was well aware that to overcome the limitations of analysis fast automatic computing machines would be imperative.[24] But automatic computation needed a method for "calculating routines involving stepwise integration" of variables (Neumann von and Richtmyer 1947, p. 653). The equations had to be translated into a numerical model that could be solved step by step. Such a method is not new. The computing planes of the astronomers used a step-by-step numerical method to manually advance planets and comets forward by small distances. But now the whole computation had to be prepared in advance and then the machine set up for the entire calculation. Therefore the differential equations had to be transformed into difference equations, and the plan for step-by-step calculations had to be 'coded' and plugged in. "Coding", Goldstine and von Neumann explained in 1947, "begins with the drawing of the flow diagrams [. . . and] the coding of every operation box, alternative box and variable remote connection" (Goldstine and von Neumann 1947, p. 103). The flow diagram displays the step-by-step run

[23]"The ENIAC was an electronic calculator that inaugurated the era of digital computing in the United States. Its purpose was to calculate firing tables for the U.S. Army, a task that involved the repetitive solution of complex mathematical expressions" (Ceruzzi 1998, p. 15). ENIAC was built between 1943 and 1946 at the Moore School of Engineering at the University of Pennsylvania by J. Presper Eckert and John Mauchly. Herman Goldstine was the responsible U.S. Army coordinator and J. G. Brainerd was the project manager. In 1947 ENIAC was delivered to the Ballistic Research Laboratory of the U.S. Army in Aberdeen, Maryland.

[24]Stanislav Ulam described the situation at Los Alamos in 1943: "The blackboard was filled with very complicated equations that you could encounter in other forms in other offices. This sight scared me out of my wits: looking at these I felt that I should never be able to contribute even an epsilon to the solution of any of them. But during the following days, to my relief, I saw that the same equations remained on the blackboard. I noticed that one did not have to produce immediate solutions. [. . .] Little as I already knew about partial differential equations or integral equations, I could feel at once that there was no hope of solution by analytical work that could yield practical answers to the problems that appeared" (Ulam and von Neumann 1980, p. 95).

through the calculations, in which each operation box contains the actual calculations. But a flow diagram does not necessarily present a linear computing process. In fact, it is a complex choreography of loops and alternative loops that conceives various paths through the computation of a numerical model. And the computer

> will, in general, not scan the coded sequences of instructions linearly. It may jump occasionally forward and backward, omitting (for the time being, but probably not permanently) some parts of the sequence, and going on repeatedly through others. It may modify some parts of the sequence while obeying the instructions in another part of the sequence (p. 82).

Goldstine and von Neumann called the actual path of computing through the instructions the 'modus procedendi'. This modus procedendi unveils the behaviour of a system that is computed for each time step. In the case of ballistic calculations it works step by step through the expansion of a blast wave based on a numerical model of hyperbolic equations. In the case of atmospheric calculations, it computes the step-by-step development of a pressure, temperature or wind field. Thus, the simulation of a numerical model—coded and plugged in—enables the behaviour of a system to be predicted. When the first programming language FORTRAN Formula Translator was released in 1954, coding and manually plugging in merged into a single procedure: writing forecasting algorithms. Since then science, and in particular meteorology, has been dominated by a research style, as Frederik Nebeker pointed out in his instructive study on *Calculating the Weather*, "that results from making a forecasting algorithm one's ultimate objective" (Nebeker 1995, p. 152).

2.3 Calculating the Climate System

Vilhelm Bjerknes described a mathematical model of the general circulation of the atmosphere based on the three hydrodynamic equations of motion, the continuity equation, the equation of state for the atmosphere, and the two fundamental theorems in the mechanical theory of heat. However, to deduce an exact solution for this set of equations is not possible, and to derive a forecasting algorithm is not easy. While Bjerknes used graphical computing methods, during the 1910s Lewis F. Richardson, a British scientist, tried to achieve a computing scheme which he could calculate by hand. His scheme filled more than 200 pages of his book on *Numerical Weather Prediction*, which was published in 1922. He argued that

> whereas Prof. Bjerknes mostly employs graphs, I have thought it better to proceed by way of numerical tables. The reason for this is that a previous comparison of the two methods, in dealing with differential equations, had convinced me that the arithmetical procedure is the more exact and more powerful in coping with otherwise awkward equations (Richardson 1922, p. VIII).

In order to apply his scheme and to numerically compute it, Richardson had to divide the atmosphere horizontally into a grid, with 130 km between each grid point. This magnitude was related to the distribution of weather observation stations in Britain at that time. Although these stations were irregularly distributed, Richardson used a regular grid.[25] For the vertical resolution he defined seven layers. For this three-dimensional model of the distribution of air masses he tried to compute the development of pressure fields for 6 h. It took him 6 weeks to manually calculate his prognosis for only two of the squares of his grid for 4 am to 10 am of 20 May 1910, but he failed. He predicted a rise in air pressure of 145 mb instead of the actual 1 mb (Nebeker 1995, p. 76). Although his approach was groundbreaking for computational meteorology, his data, assumptions and idealizations were too simple due to his limited capacities for manual computation.[26] Nevertheless, in the great words of Nebeker, "Bjerknes pointed out a new road, Richardson travelled a little way down it, and his example dissuaded anyone else from going in that direction until they had electronic computers to accompany them" (Nebeker 1995, p. 82).

2.3.1 The Advent of Computational Meteorology

These electronic computers came into reach in the 1940s. John von Neumann was not only involved in the construction of some of the very first electronic computers, such as ENIAC, NORC, and the IAS computer, he also participated in the very first computer-based weather forecast. When von Neumann was working on his new IAS computer at the Institute for Advanced Study (IAS) at Princeton during the late 1940s, he chose meteorology as a test application for his computer. Von Neumann was advised by the Swedish-American meteorologist Carl-Gustav Rossby, who was the most influential figure of early numerical weather prediction—in the U.S. as well as in Europe. John von Neumann invited Jules Charney, who was working on a method that avoided the mistakes of Richardson's numerical prognosis, to lead his Meteorological Project. Charney had developed a filtering method which reduced the noise caused by energy waves with a high-phase velocity that complicated the solution of a weather model (Charney 1948). From 1948 on, Charney and his colleagues developed the very first computer model for weather forecasting, a simple barotropic model with geostrophic wind for the area of the United States

[25] Fitting the irregularly distributed measurement data into the regular grids of simulations is still a challenging practice for meteorology.

[26] "Richardson ascribed the unrealistic value of pressure tendency to errors in the observed winds which resulted in spuriously large values of calculated divergence. This is true as far as it goes. However, the problem is deeper [. . .] A subtle state of balance exists in the atmosphere between the pressure and wind fields, ensuring that the high frequency gravity waves have much smaller amplitude than the rotational part of the flow. Minor errors in observational data can result in a disruption of the balance, and cause large gravity wave oscillations in the model solution" (Lynch 1999, p. 15).

of America (Harper 2008).[27] In a barotropic model pressure is solely a function of density; fields of equal pressure (isobars) run parallel to fields of equal temperature (isotherms), and the geostrophic wind moves parallel to the fields of equal pressure (isobars). These simplifications were necessary in order to derive an effectively computable model at that time (Persson 2005b). In 1950 Charney and his colleagues used the ENIAC (the IAS computer was not yet completed) for four 24-h and two 12-h predictions of changes in the pressure of the 500 mb contour surface, corresponding to a height of about 5,500 m. The space interval was 736 km and the grid consisted of 15 $\times$ 18 space intervals (Charney et al. 1950). Even for this single level, ENIAC had to carry out more than 200,000 operations (Neumann 1945). While von Neumann later optimistically claimed that these results were as good as the results 'subjective' forecasters could achieve, others had their doubts, commenting that "500 mb geopotential is not weather" (Arakawa 2000, p. 6). Nevertheless, dynamical models gained influence in meteorology; in 1956 Norman Phillips conducted the first climate simulation based on a simple two-level model. His results, published in the seminal paper *The general circulation of the atmosphere: a numerical experiment* (Phillips 1956), reproduced global wind patterns (see Fig. 2.3), although his quasi-geostrophic and hydrostatic model lacked mountains, a contrast between land and sea, and other more 'realistic' details (Lewis 2000). However, Philips' numerical experiment showed that global circulation and cyclogenesis (the development of low-pressure areas which are responsible for weather phenomena) depended on each other. His findings helped to establish the new General Circulation Research Section at the U.S. Weather Bureau in 1955, which inaugurated numerical weather prediction (NWP) and climate modelling in the U.S. This section later became known as the Geophysical Fluid Dynamics Laboratory (GFDL).

Although computer-based NWP started in the US, it must be mentioned, as the meteorologist and historian Christine Harper pointed out in her study *Weather by Numbers*, that "this 'American Story' is full of Scandinavian characters—scientists imported to bridge the gap separating meteorological theorists and operational weather forecasts in the United States" (Harper 2008, p. 4) and leading Japanese scientists like Akio Arakawa and Syukuro Manabe. Outside the United States, too, computing and numerical modelling took off rapidly in the 1950s. Starting in the 1940s I. A. Kibel used hydrodynamic methods for weather forecasting in Russia, developing a model that was employed "for about 15 years to produce 24-h forecasts in Russia" (Wiin-Nielsen 2001, p. 33). In 1954, S. Belousov computed a one-level model on the Russian BESM and later on the Arrow computer (Blinova and Kibel 1957; Karo 1995). Also in 1954, a group of Scandinavian meteorologists associated with von Neumann's Meteorological Project carried out a barotropic forecast on the Swedish BESK computer, which was completed in 1953 (Persson 2005a).

[27]Christine Harper reconstructed the introduction of computational meteorology in the U.S. between 1919 and 1955 and the major influence of Scandinavian meteorologists in her instructive study *Weather by the Numbers* (Harper 2008). A study on *Early Operational Numerical Weather Prediction Outside the USA* is given by Andres Persson (Persson 2005a, b).

Similar efforts took place in other countries, for instance the development and integration of baroclinic models by the British meteorologists John S. Sawyer, Fred H. Bushby, and Marvis K. Hinds on the LEO computer (Sawyer and Bushby 1953; Bushby and Hinds 1954); by the French scientists Guy Dady, Robert Pône, and Jean Andreoletti on the CAB2022 computer (Dady 1955); by the German meteorologist Karl-Heinz Hinkelmann (Hinkelmann et al. 1952); and others. As early as 1948 the British Meteorological Office held a workshop together with the Imperial College on *The Possibilities of Using Electronic Computing Machines in Meteorology* (Persson 2005a, b). Akio Arakawa, a leading climate modeller, called the period between 1950 and 1960 the "epoch-making first phase":

> Through this work, the relevance of such a simple dynamical model for daily change of weather was demonstrated for the first time in history, and thus dynamic meteorologists began to be directly involved in the practical problem of forecasting. In this way, dynamic meteorology and synoptic meteorology began to merge during this phase (Arakawa 2000, p. 7).

In the 1960s, according to Arakawa, the "magnificent second phase" of numerical modelling of the atmosphere began, based on general circulation models (GCMs) with less restriction than the barotropic models. Arakawa himself made a major contribution to this second phase in 1961 by designing a primitive equation model together with Yale Mintz at the University of California at Los Angeles. Besides the models by Phillips and Arakawa-Mintz, other groups followed at GFDL (Smagorinsky 1963; Manabe et al. 1965), at Lawrence Livermore Radiation Laboratory (Leith 1964) and at the National Center for Atmospheric Research (Kasahara and Washington 1967).[28] In this second phase the modelling community grew and modelling was improved: the primitive equations of the general circulation were increasingly supplemented by new model strategies and processes influencing weather and climate. While weather forecast models are concerned only with the atmosphere, climate models in their simplest form also need to treat at least the ocean and sea-ice coverage. The reason for this is that the top few meters of the oceans hold more heat energy than the entire atmosphere. Thus, for long-time integrations the exchange of energy between atmosphere and ocean has to be taken into account as well as the ocean's circulation. Sea-ice also has a dramatic impact on the Earth's energy budget, meaning that changes in sea-ice coverage amplify climate change. The so-called ice-albedo feedback—the fact that when the climate gets warmer, sea-ice melts and the open ocean takes up more radiation from the sun or vice versa—is the main reason why greenhouse gas warming is considerably higher at polar latitudes than at tropical latitudes. Therefore, atmosphere models have to be expanded by ocean models. In 1969 Syukuro Manabe and Kirk Bryan published their results of the first coupled ocean–atmosphere model developed at GFDL, which was able to reproduce the effects of ocean currents on the atmosphere's temperature and humidity (Manabe and Bryan 1969). Later on sea-ice

[28]These early models created a family tree of GCMs (Edwards 2000). Or in other words, today's GCMs are rooted in an evolution of five decades of coding and reusing the same primitive equations of the dynamic core again and again.

models were added to the coupled ocean–atmosphere models, completing the simplest set-up suitable for climate simulations.

During this second phase a diversity of models for various objectives was coded, such as cloud-resolving models, mesoscale models, and regional models. This diversity has increasingly allowed meteorologists to investigate the whole spectrum of atmospheric phenomena. These models enabled specific in-silico experiments, for instance on the effect of doubling CO_2 concentrations (Manabe and Wetherald 1975), on the effect of tropical deforestation (Charney 1975) or the study of the paleo-climate (Gates 1976). These experiments were urgently required since measurements at the Mauna Loa Observatory showed a distinct increase in atmospheric CO_2 concentrations, and since Charney intended to focus on the question of climate sensitivity: What temperature would result from doubling CO_2 concentrations? As climate sensitivity can only be assessed by simulations, climate models have become growing 'organisms' incorporating an increasing amount of scientific knowledge. This growth heralded the third period in the 1990s, which Arakawa called the 'great-challenge third phase'. This period is characterized by coupled atmosphere-ocean models, the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), and model intercomparisons.

However, this development is still continuing. Processes between the atmosphere and the land surface have been simulated in greater detail, including heat exchange and evaporation. Today biological processes are increasingly implemented in the models as well, in order to simulate anthropogenic perturbations of the chemical composition of the atmosphere, the carbon cycle, and the climatic effects of land clearing and agriculture. As the simulation of biological processes is far more challenging than that of physical processes, models of the marine and terrestrial biosphere have been developed only recently. Climate models, which include subsystems such as air chemistry or biosphere models, are often termed 'Earth system models' (see Fig. 2.4). Perhaps years from now the 2010s will be declared the fourth phase—the age of Earth system models. Besides these enormous advances in weather and climate models and in computer resources, the dynamic core of these models and the strategy of building them has remained nearly identical same since the very early days of dynamic meteorology. But the rest has changed dramatically.

2.3.2 Model Building–Dynamic Core

General circulation models consist of two parts: the dynamic core and the subscale parametrization. Both parts must exist in a discrete version—normally using the 'grid point method' (Messinger and Arakawa 1976). As already outlined above, climate models are based on the laws of physics. They employ equations of fluid motion, of thermodynamics and of chemistry. These laws are formulated as nonlinear partial differential equations, which are too complex to be solved analytically. This means that an exact solution is not known and a numerical method has to be found to approximate the unknown, exact solution. Therefore, from a purely mathematical perspective, computer-based simulations are in principle inexact

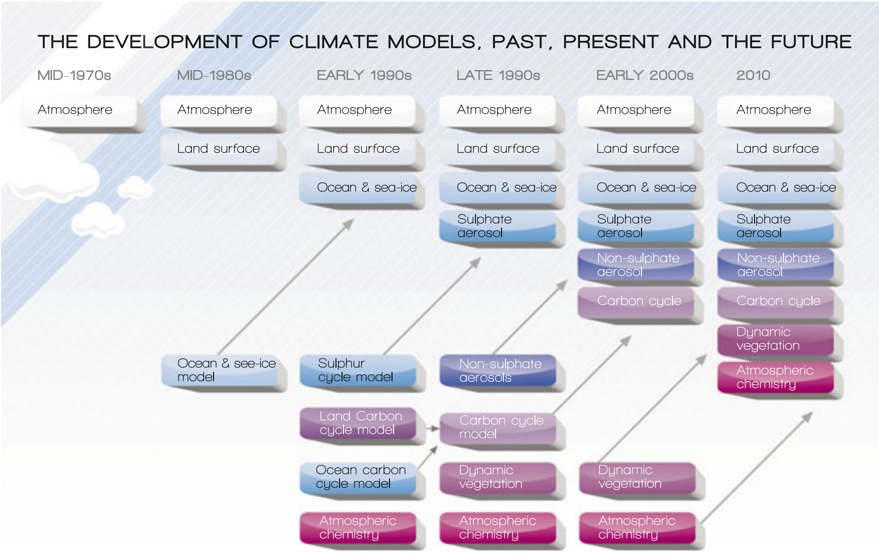

Fig. 2.4 The Development of the Earth System Model: Past, present and future. From barotropic models to general circulation models, coupled atmosphere-ocean models, and finally Earth system models
Source: Replotted by the authors from IPCC 2001, p. 48

methods, and some of the uncertainties result from this aspect.[29] However, to solve the differential equations of a general circulation model, the method of finite differences is applied. This method approximates the derivative expressions in the differential equations by differences. For instance, the differential in time of the function y, which depends on time and space, is approximated as the difference

$$\frac{\partial}{\partial t} y(t,x) \approx \frac{y(t,x) - y(t-T,x)}{T},$$

where T denotes the time interval.

To facilitate the formulation of differences, the model domain is subdivided into grid boxes, and continuous variables such as temperature, density, or humidity are converted into discretized differences (see Fig. 2.5). The discretized equations are solved for each grid point, such that the results represent grid-box averages. "Existing GCMs used for climate simulation typically have on the order of 10^4 grid columns. The average grid cell of such a model is about 200 km across"

[29]Discretization treats a continuous problem as a discrete one and therefore results in a discretization error. Numerical computation is an approximation which approximates the unknown solution using iterative methods that are stopped after a certain number of iteration steps. Therefore the computation results in a truncation error. Furthermore, numbers in computers are represented by a limited number of digits, which creates rounding errors.

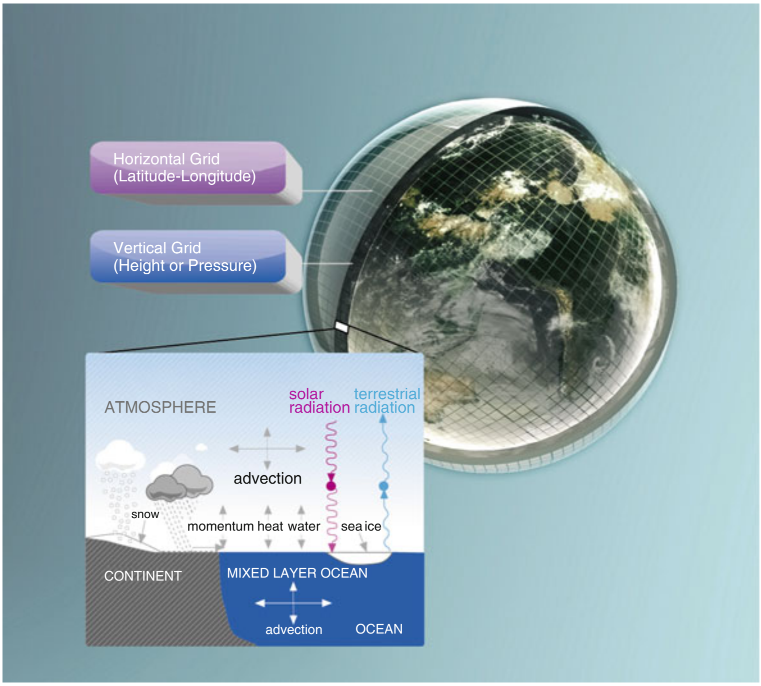

Fig. 2.5 Discretization by subdividing the atmosphere into grid cells, grid boxes, and grid columns. Subscale processes are calculated one-dimensionally within the vertical columns
Source: Replotted by the authors from NOAA, http://celebrating200years.noaa.gov/break-throughs/climate_model/modeling_ schematic.html

(Randall et al. 2003, p. 1,553). This number of grid columns has to be computed for each time interval. While Charney and his colleagues in 1950 had to start with a 15 × 18 grid for one layer at 500 mb, covering the area of North America, the increase in spatial and time resolution has driven numerical weather forecasting and climate prediction, and still does. Higher resolution enables a better 'image' of the computed atmospheric processes, and this increase in resolution is a direct result of the tremendous improvement in computing performance.[30] Today's weather models usually consist of a resolution as fine as 6 km, while climate models vary between 500 and 60 km depending on the time period they compute, which can be some decades or centuries (IPCC 2007a, p. 113).

[30]In terms of computing time, this means that Charney and his team needed 33 days to compute their prognoses, mainly because ENIAC had to be set up by physically plugging in the operations. Around 100,000 punch cards were needed to carry out the computations and to store the intermediate and final results. Nevertheless, compared to manual computing capacities, ENIAC was an unbelievably fast computer. When in the 1970s George Platzman, who had conceived the diagram of the operations on ENIAC, repeated the computation for one of the 24-h ENIAC prognoses on an IBM 5110 PC, the actual computation time took 1 hour. A current laptop would need milliseconds for this simple model (Lynch 2008).

However, no process is considered by the equations in a GCM that takes place on a scale smaller than the horizontal and temporal resolution achieved. But the scale of meteorological effects ranges between centimeters (micro turbulences) and several 1,000 km (planetary waves). Therefore, so-called ‘subscale processes’ have to be incorporated in the model, expressing the influence of unresolved processes on the global processes. Thus weather models and climate models are divided into a dynamic core (the adiabatic part) and subscale processes, so-called ‘parametrizations’, (the non-adiabatic part).

The adiabatic, or resolved part of the model numerically solves the fundamental laws of physics, the ‘primitive’ equations—primitive in the sense of primary. This is a set of nonlinear differential equations used to approximate the global general circulation of the atmosphere or the oceans. The dynamic core is still based largely on Vilhelm Bjerknes’ mathematical model of 1904, as outlined above. The hydrodynamical flow on the surface of a sphere is described by the so-called Navier–Stokes equations. Thereby the assumption is made that vertical motion is much smaller than horizontal motion, and that the fluid layer depth is small compared to the radius of the sphere. The thermal energy equation relates the temperature change to heat sources and sinks. The continuity equation describes the transport of properties as momentum, heat or other quantities, which are conserved. These differential equations have to be discretized, and the resulting algebraic difference equations are solved by numerical methods, dividing the atmosphere into a number of grid cells and several vertical layers. Each grid point is determined for each time step by the computed variables for velocity in three dimensions, temperature (heat energy), density, air pressure, and humidity (vapour, water, and ice). Thus, the flow of air masses across the grid cells, the impact of various forces on the flow, the distribution of energy, water, vapour, etc., and the density of a fluid depending on pressure, temperature, and humidity are expressed. This computable model of a ‘digital atmosphere’ is written in FORTRAN or other programming languages. The result is a set of files which the computer has to run through for each time interval in order to reveal the behaviour of the digital atmosphere over time.

2.3.3 Model Building–Subscale Parametrization

The other part of a weather or climate model is the non-adiabatic part, which calculates the effects of subscale processes on the large-scale (resolved-scale) variables depending on large-scale parameters. Typical parametrizations include radiation transport, processes on the surface, stratiform clouds, cumulus convection, subscale orographic effects, and horizontal diffusion. While the dynamic core has not changed much during the last decades,[31] tremendous research efforts have

[31]In the 1970s the computation of the dynamic core was transferred from the Gaussian grid into the spectral space for stability reasons (Bourke 1974). Currently, the dynamic core of some GCMs is being re-coded on icosahedral grids, which better model the spherical shape of Earth.

been devoted to identifying, measuring, and modelling subscale parametrizations. Parametrizations are major sources of uncertainties. The basic problem results from the fact, as Randall et al. pointed out aptly, that

> even though the basic physical equations in which we have the most confidence describe small-scale processes, in practice it is the effects of those small-scale processes that are incorporated into our models through the use of uncertain closure assumptions. It is ironic that we cannot represent the effects of the small-scale processes by making direct use of the well-known equations that govern them (Randall et al. 2003, p. 1548).

These closure assumptions are delivered by the subscale parametrizations until weather and climate models achieve a resolution of some centimeters. Another problem of parametrization is the use of diverse knowledge resources. The development of parametrizations can be divided into four different methods: Derivation of parametrizations from first principles, from laboratory studies, from focused measurement campaigns, and from models with finer resolution (Lohmann et al. 2007a).

All of these methods have in common that they are based on theory and/or measurements valid for small scales and mostly for only specific regions or situations. But in a climate model the parameterization is applied to any part of the globe, to any climate state, and to the model's coarse spatial and temporal resolution. A widely used methodology for adapting parameterizations to changing environments and scales is to adjust or 'tune' them in order to achieve a more 'realistic' match with available local data. A better method would be to use observational data at adequate scales to infer these parameters. Satellite-derived relationships, for instance, can provide clues about how specific parameterizations should work on the scales relevant for large-scale modelling. The advantage here is that statistical correlations from satellites are temporally and spatially more robust than individual measurements. Moreover, because correlations analyze relative changes, limitations to the absolute accuracy are acceptable. Relations are supposed to be valid even in a changing climate, whereas absolute values and currently measured distributions are not. However, for various processes neither measurement, laboratory study, nor simulation data are available. Modellers have to decide whether they want to include key parameters which govern these processes. If so, assumptions are the only way to incorporate them until measurement data become available. Of course, these assumptions inherit major uncertainties. Another problem is unknown processes. All of these problems introduce uncertainties into the model. Every parameterization first has to undergo tests in stand-alone versions, and then the results have to be compared to observations. After this the new parameterizations have to be implemented into the model system and the results compared with the previous version of the model and with assimilated data fields (Table 2.1).

Prominent examples of parametrization in atmosphere models are cloud parametrizations. Many processes on which clouds depend are not resolved in GCMs. Clouds play a major part in the energy balance of Earth as well as in the hydrological cycle. From the perspective of a GCM, clouds are defined by volume-averaged contents of cloud water and cloud ice, and by the total fractional area. Although the

Table 2.1

Derivation of subscale parametrization	
First principles	An analytical solution or an approximation based on some simplifications can be derived.
Laboratory studies	Utilization of data from laboratory studies because it is too difficult to measure the process in-situ. An example is the study of ice crystal formation in cirrus clouds. The advantage of laboratory studies is that they take place under controlled conditions.
Measurement campaigns	Data from focused measurement campaigns of various continental and marine sites are used to derive robust relationships between various parameters. The information is prepared in compiled data sets which represent the spatial and temporal variability of the parameterized process. It has to be mentioned that measurement data represent every influence on the investigated process, whether these influences are known or not. In this regard, this method complements the laboratory method for processes that are more complex than can be studied in a laboratory setting. The sample size in a field experiment is normally not large enough to stratify these empirical data according to all influences in question.
Models	Data and information from models with finer resolution are used to derive parameterized processes that occur on small scales. Their statistical behaviour can be described by a stochastic relationship, which is derived from model simulations with finer resolution that are able to resolve some of the processes in question. This method is questionable as it lacks an observational database.

Source: Lohmann et al. 2007a

effects of clouds on the large-scale behaviour of the atmosphere are not yet entirely known or fully understood, GCMs have included representations of some interactions between cloudiness, radiation, and the hydrological cycle since the 1960s. These representations have advanced from simple diagnostic schemes to schemes which increasingly include a sound physical basis. Cloud parametrization started with a fixed cloud approach based on information about cloud fraction and cloud optical depths compiled from observational data. Within this early approach "clouds were not allowed to influence climate except through essentially prescribed short- and long-wave radiation effects" (Fowler et al. 1996, p. 489). In the 1980s diagnostic cloud parametrizations followed. Cloud cover was diagnosed as a function of various variables, e.g., vertical velocity and relative humidity, and optical properties were prescribed as functions of cloud heights and types, while the prediction of the occurrence of clouds was based on a prescribed saturation threshold of relative humidity. In the late 1980s cloud optical properties were parameterized as functions of temperature and therefore expressed, to some extent, the feedback between cloudiness and climate. Since the 1990s GCMs have included prognostic cloud water parameterizations in order to simulate the interactions of cloud microphysics, cloud dynamics, and radiative processes (Fowler et al. 1996).

Current atmosphere models include various cloud schemes, usually one cumulus convection scheme and another for stratiform clouds. The parameterization of clouds differs in each GCM but, generally, it predicts the cloud cover, the cloud liquid water and ice water amount the concentrations of cloud droplets and number of ice crystals, the precipitation flux and the evaporation of precipitation. The following example of one specific process in ice clouds will illustrate the modelling of parametrization (Lohmann et al. 2007). The change in the ice water mixing ratio r_i is given in kg ice per kg air in time t and is written in a budget equation as follows:

$$\frac{\overline{\partial r_i}}{\partial t} = Q_{Ti} + Q_{sed} + Q_{dep} + Q_{tbi} - Q_{mli} - Q_{sbi} + Q_{frh} + Q_{frs} + Q_{frc} - Q_{agg} - Q_{saci}$$

The term on the left side of the equation denotes the change in the ice water mixing ratio r_i over time; the terms on the right denote the transport of r_i by wind, diffusion and cloud updrafts (Q_{Ti}), the sedimentation of r_i (Q_{Ti}), the sublimation of r_i if $Q_{dep} < 0$ (Q_{dep}), the generation or dissipation of r_i through turbulent fluctuations (Q_{tbi}), the melting of r_i if the temperature exceeds the freezing point (Q_{mli}), the sublimation of r_i transported into the cloud-free part of the grid cell (Q_{sbi}), the homogeneous freezing of water droplets (Q_{frh}), the stochastical and heterogeneous freezing of water droplets (Q_{frs}), the contact freezing of water droplets (Q_{frc}), the aggregation of r_i when ice crystals clump together and form snowflakes (Q_{agg}), and the accretion of r_i by snow when a precipitation particle captures an ice crystal (Q_{saci}).

Every single term on the right of the equation is parameterized. The last term, for instance, the accretion of ice water mass by falling snow (Q_{saci}), is parameterized as

$$Q_{saci} = \frac{\pi E_{si} n_{0s} a_4 q_{ci} \Gamma(3 + b4)}{4\lambda_s^{3+b4}} \left(\frac{\rho_0}{\rho}\right)^{0.5},$$

in which the collection efficiency is $E_{si} = exp(0.025(T - T_o))$, with T the ambient temperature and T_o the melting temperature. As the temperature is below 0°C—since ice crystals melt at higher temperatures—the exponent is negative and the efficiency is higher at warmer temperatures. This because at higher temperatures ice crystals are more likely to stick to snow than at lower temperatures. λ_s is the slope of the size distribution of the snow particles and n_{0s} is the intercept parameter.[32] The parametrization is based mainly on parametrizations of a finer-resolution two-dimensional model by Y.L. Lin, L. Levkov, and B.E. Potter (Lin et al. 1983; Levkov et al. 1992, Potter 1991). The intercept parameter is obtained from measurements (Gunn and Marshall 1958). The equation presented is just one

[32] Interception means that particles stick together due to small stochastical motion (Brownian motion) if the distance between an ice crystal and a snowflake is smaller than the radius of the crystal.

of several dozen that describe processes within clouds. Some of these equations date back to concepts of the 1940s as published in the relevant literature; others refer to current research. The example shows how parametrization incorporates diverse knowledge resources like measurements or parameters derived from finer-resolution models. Although all of the approaches employed are mere simplifications of reality, the growing role of parametrization increases the atmosphere model's complexity due to the large number of processes and the manifold interactions between all of these variables.

2.3.4 Simulation Runs

Following the partitioning between the dynamic core and the parametrization, an atmosphere model is initialized with atmospheric measurement data and data sets from the ocean model. It usually computes the general equations of the circulation for each grid point first, delivers results, then continues computing the effects of the subscale parameterizations and delivers results for the first time step. The data sets of the first time step are delivered to the ocean model and used to initialize the atmosphere model for computing the second time step. The spatial resolution determines the lengths of the time steps. For instance, the 110-km grid (T106) of the Fourth IPCC Assessment Report scenarios needed a ten-min time step. Thus, a simulated day consisted of 144 simulation runs, a year of 52,560 runs, and a century of more than five million runs. Each simulation run computes several hundred thousand operations. Although a coupled atmosphere-ocean model fits on any 2-MB USB drive, the computation of climate scenarios requires powerful supercomputers.

Before a coupled atmosphere-ocean model is used to compute climate scenarios it undergoes months, sometimes years, of testing and improvement. Every tiny change has to be tested on the component and the system levels. And every simulation run is followed by a test run for a higher resolution in order to check the stability of the results. When the results behave stable, it is assumed that, from a mathematical perspective, the exact but unknown solution has been approximated. Furthermore, the model must be able to represent actual climate states and patterns (see also Sect. 2.5). At a certain point the model version is frozen and released to the scientific community for simulation runs, e.g., for computing IPCC scenarios. In particular, these efforts are needed when meteorologists want to use the 'digital atmosphere' to conduct experiments. As meteorologists cannot perform controlled laboratory experiments and cannot draw on measurements alone, 'in-silico' experiments are key tools for gaining a better understanding of the system behaviour of the earth's climate, e.g., by conducting climate equilibrium simulations. If future projections are required, only in-silico experiments can give results, e.g., by conducting transient climate simulations.

Climate equilibrium simulations compare two different climate states by introducing sustained forcing, e.g., pre-industrial greenhouse gas concentrations and doubling of the CO_2 concentration. The model is computed until a new equilibrium is reached. To obtain statistically robust results, a further 30–50 years are integrated; then the statistics of these two simulations are compared. In this kind of simulation the ocean component simply takes up and releases heat but does not mimic changes in ocean circulation. By their very design, equilibrium experiments cannot reproduce the observed time evolution of climate change, but serve as useful tools to explore the effects of a specific perturbation to the climate system. These experiments are used to derive a result for climate sensitivity under certain conditions. Climate sensitivity expresses the change in global mean surface temperature per one watt per square-meter forcing.

Transient climate simulations prescribe or calculate the temporal evolution of natural and anthropogenic forcings. Such simulations are performed by complex climate models, with the ocean model simulating the dynamics of the circulation. Before an in-silico experiment can be performed, the state of the ocean is integrated to equilibrium. Thus, for initialization the ocean is forced by atmospheric variables observed as wind-stress and heat-fluxes and integrated over some 100 years (500–1,000 years).[33] Transient climate simulations attempt to reproduce observed climate change. However, what is reproduced is not the observed year-to-year meteorology, but the multi-year statistics. More recently, ensembles of simulations applying the same forcing but varying the initial conditions or some of the parameters within the uncertainty range have been performed, to obtain statistically more robust results. Because climate compounds like the deeper ocean and the cryosphere react on longer time-scales, the system will not be in equilibrium with the rate of heating of the atmosphere, but will lag behind the rate of forcings. Thus, transient climate simulations calculate a climate sensitivity slightly smaller than do equilibrium simulations.

Besides these basic experiments, the digital climate can be used for every conceivable set-up. It enables meteorologists to study the behaviour of single processes, the interplay of various processes, the behaviour of the digital atmosphere under unrealistic, past, or future conditions, and so forth. For this purpose not only GCMs, but a diversity of models of different complexity has been developed during recent decades (see Table. 2.2). This model variety is sometimes seen as a hierarchy from more conceptual (e.g., EBMs, box models) to more comprehensive (e.g., GCMs, ESMs) models (Henderson-Sellars and McGuffie 1987) or from inductive (conceptual) to quasi-deductive (comprehensive) models (Saltzman 1985, 1988; Claussen et al. 2002). As quasi-deductive models include many inductive elements hidden in the subscale parametrization, these hierarchies and classifications are not very useful. In fact, in the everyday business of climate

[33] Very recently, the actual state of the ocean has been used to start transient climate simulations. This much more realistic approach has become possible due to the new measurement network, ARGO, which since the year 2000 has continuously sounded the uppermost 2 km of the oceans by means of buoys and floats to measure the profiles of temperature, currents and salinity. These measurement data are assimilated to generate three-dimensional fields of the ocean's parameters, which then serve as an initial field for model simulations.

Table 2.2

Variety of climate models	
Box	Box models are simplified versions of complex models that reduce them to boxes and describe flows across and within the different components of the climate system. They are used for testing parametrizations and for deriving analytical formulas.
EBM	Energy Balance Models calculate the radiative fluxes and the surface temperature, assuming that all transport is diffusive.
CRM	Cloud Resolving Models consist of a fine resolution that resolves cloud-scale and mesoscale circulations.
EMIC	Earth Models of Intermediate Complexity include more processes and integrate more climate components than simple energy balance models. EMICs consist on a coarse horizontal resolution, but allow long-time integrations for paleo-climate studies or sensitivity studies.
RCM	Regional Climate Models increase the resolution of a GCM in a small, limited area of interest. The climate calculated by a GCM is used as input at the edges of the RCM. RCMs represent regional land surfaces (mountains, coastlines, changing vegetation characteristics etc.) on much smaller scales than GCMs.
GCM	General Circulation Models for the atmosphere and the ocean, as described in this section.
ESM	Earth System Models based on coupled ocean–atmosphere models, which additionally include biosphere and/or chemistry modules. ESMs simulate the behaviour of the atmosphere, the ocean, the cryosphere and the biosphere, and the interactions between these different components of the Earth system as well as the impact of human activities on climate.

Source: Henderson-Sellars and McGuffie 1987; Saltzman 1985, 1988; Claussen et al. 2002

modelling and simulation the whole spectrum of models is used. For instance, box models are used for testing parametrizations in GCMs, EMICs are used to explore the solution space of processes of GCMs, and GCMs are used to develop and evaluate parameterizations used in EMICs. However, there exist far more models for specific purposes today. For instance, in the context of climate change modelling, energy models and integrated assessment models (IAMs) play a crucial role.

2.4 International Coordination of Climate Modelling

In 1950 dynamical meteorology started with a singular weather forecasting model developed by a small group of scientists at Princeton. Only few computers were available at the time and computation, even of highly simplified models, required days to deliver any results—e.g., for a coarse resolution of a pressure field at 500 mb. Today, the situation has changed entirely. Weather and climate modelling has become a conjoint international endeavour engaging a growing community of thousands of meteorologists and hundreds of research programs worldwide. Sub-communities of model users and data users have propagated. Measurement and simulation methods have been standardized and exabytes of data are available. These developments have completely reshaped the scientific discipline of meteorology over the last decades. Since the late 1980s the Intergovernmental Panel on Climate Change (IPCC) has introduced a conjoint rhythm of model development, improvement, and evaluation which is unseen in other scientific disciplines. These conjoint efforts have improved climate modelling and put meteorology into a leading position in exploring the use of computer-based simulations for the production of scientific knowledge. However, these efforts toward coordination and standardization on an international level are the indispensable precondition to make a forecasting algorithm one's ultimate objective and to enable reliable projections into future climate trends. Over the last two decades these efforts have transformed meteorology into an 'e-science' based on a growing cyberinfrastructure of supercomputers, computing centers, coded knowledge, and advanced data analysis.

2.4.1 The International Structure of Climate Research

Because weather forecasting and climate prediction require global data, meteorology can look back on a long tradition of international measurement and research campaigns. The International Meteorological Organization (IMO) was founded way back in 1873, and the first International Polar Year took place in 1882 and 1883. Today the World Meteorological Organization (WMO) of the United Nations represents 188 member states. The WMO organizes various international climate research programs, including the World Climate Programme (WCP) and the World Climate Impact Assessment and Response Programme (WCIRP) since 1979, the Intergovernmental Panel on Climate Change (IPCC) since 1989, the Global Climate Observing System (GCOS) since 1992, the Climate Information and Prediction Services (CLIPS) since 1995, and the IPCC Data Distribution Centre (DDC) since 1998 (see Table 2.3).[34]

Some of the WMO programs are coordinated along with the United Nations Environment Programme (UNEP), the International Council of Scientific Unions (ICSU), and the United Nations Framework Convention on Climate Change (UNFCCC) in order to support Agenda21. According to the Swiss Forum for Climate and Global Change (ProClim), there are currently 110 international organizations, agencies, networks, and committees and 112 international programs (ProClim 2010, Research information service).

A characteristic feature of these organizations is that they create an interface between scientific knowledge and socio-political interests. However, meteorology has always been interlinked with society and politics. Since the nineteenth century, agricultural and military needs for weather forecasting have driven the field's development. But the emerging interest in environmental issues in the 1970s installed a new dimension of the interlinking between meteorology, in particular climate science, and politics—introducing national and international conferences,

[34]The WMO website provides an overview of milestones since 1875, when the first International Meteorological Conference was held in Brussels. URL: http://www.wmo.int/pages/about/milestones_en.html. The Swiss website ProClim offers a research information service of international environmental organizations. URL: http://www.proclim.ch

Table 2.3

Scientific and technical programs and projects of the World Meteorological Organization (WMO)

WMO World Weather Watch (WWW) Programme	
GOS	Global Observing System
GDPFS	Global Data-processing and Forecasting System
WWW/DM	Data Management and System Support Activities
OIS	WWW Operational Information Service
ERA	Emergency Response Activities
IMOP	Instruments and Methods of Observation Programme
	WMO Polar Activities
TCP	Tropical Cyclone Programme
WMO World Climate Programme (WCP)	
CCA	Climate Coordination Activities
AGM	Agricultural Meteorology Programme
WCIRP	World Climate Impact Assessment and Response Strategies
WCDMP	World Climate Data and Monitoring Programme
WCASP	World Climate Applications and Services Programme, including the Climate Information and Prediction Service Project
WMO Atmospheric Research and Environment Programme (AREP)	
GAW	Global Atmosphere Watch
WWRP	World Weather Research Programme
THORPEX	Observing System Research and Predictability Experiment
WMO Applications of Meteorology Programme (AMP)	
PWSP	Public Weather Services Programme
AeMP	Aeronautical Meteorology Programme
MMOP	Marine Meteorology and Oceanography Programme
AMDAR	Aircraft Meteorological Data Relay
AMP	Agricultural Meteorology Programme
WMO Hydrology and Water Resources Programme (HWRP)	
BSH	Basic Systems in Hydrology
HFWR	Hydrological Forecasting in Water Resources Management
CBH	Capacity-building in Hydrology and Water Resources Management
CWI	Cooperation in Water-related Issues
APFM	Associated Programme on Flood Management
WHYCOS	World Hydrological Cycle Observing System
Other major WMO programs and projects	
TCP	Technical Cooperation Programme
RP	Regional Programme
SAT	Space Programme
ETRP	Education and Training Programme
DRR	Disaster Risk Reduction Programme
ClimDevAfrica	Climate for Development in Africa
DBCP	Data Buoy Cooperation Panel
HOMS	Hydrological Operational Multipurpose System
IFM	Integrated Flood Management Helpdesk
INFOHYDRO	Hydrological Information Referral Service
SWIC	Severe Weather Information Centre
WAMIS	World AgroMeteorological Information Service
WHYCOS	World Hydrological Cycle Observing System
WIS	WMO Information System
WIGOS	WMO Integrated Observing System
WWIS	World Weather Information Service

Source: http://www.wmo.int

programs, and organizations. While the first World Climate Conference (WCC-1) in Geneva in 1979 still followed a mainly scientific approach, which led to the establishment of the World Climate Programme and the IPCC, the WCC-2 in 1990 had a more political agenda, highlighting the risk of climate change. Even as early as 1985 the Villach Conference put the emphasis on the role of an increased CO_2 concentration in the atmosphere by establishing the Advisory Group on Greenhouse Gases (AGGG). The Villach Conference, along with the first IPCC Assessment Report in 1990 and the WCC-2, created a worldwide awareness about the impact of CO_2 among scientists, policy makers, and the public. This awareness has led to the appointment of the Intergovernmental Negotiating Committee on Climate Change (INC) and to the United Nations Framework Convention on Climate Change (UNFCCC) in order to ensure stabilization of greenhouse gas concentrations in the atmosphere at a viable level.[35] In 1997 the adoption of the Kyoto Protocol introduced a measure of CO_2 equivalents (CO2-eq), based on the benchmark emission levels published in the second IPCC Assessment Report in 1990, as well as emissions trading and the clean development mechanism (CDM) (see also Chap. 5 of this volume). All of these measures and conventions refer to preindustrial conditions before 1750 of a CO_2 concentration around 280 ppm (IPCC 2007b) and try to deal with the effects of human-induced global warming.

The interlinking of climate science with politics has been widely analyzed from the perspective of policy studies (Jasanoff and Martello 2004; Grover 2008; Halfmann and Schützenmeister 2009). These studies take into account that the international organizations that drive climate science can be described as boundary organizations with dual agency, stimulating scientific knowledge and social order. Boundary organizations "facilitate collaboration between scientists and non-scientists, and they create the combined scientific and social order through the generation of boundary objects and standardized packages" (Guston 2001, p. 401). But the agency of the international organizations which drive climate science has a unique characterization because they can act only by influencing the behaviour of their members—states, national institutions, and programs. They use scientific procedures—conferences, workshops, networks, peer reviews, etc.—in order to facilitate collaboration among scientists as well as collaboration between scientists and non-scientists. These organizations have to interconnect scientific knowledge and political decisions, which entails various problems for both scientific and political autonomy (see also Sect. 2.5). They have turned meteorology into an open 'big science'.[36]

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[35]The Convention on Climate Change was negotiated at the Earth Summit in Rio de Janeiro in 1992, followed by the annual Conferences of the Parties (COP) since 1995. In November and December 2011 the COP-17/MOP-7 will take place in South Africa.

[36]The term 'big science' was coined for large programs in science which emerged in industrial nations during and after World War II: for instance, the Manhattan Project to develop the atomic bomb led by the United States, involving more than 130,000 people at 30 research sites. These military-based programs are termed as 'closed big science', while meteorology is characterized as an 'open big science', since free access to data and computer codes is provided to researchers worldwide (Halfmann and Schützenmeister 2009).

Table 2.4

World Climate Research Programme (WCRP). A program sponsored by the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU), and the UNESCO Intergovernmental Oceanographic Commission (IOC)	
CliC	The Climate and Cryosphere Project
CLIVAR	Climate Variability and Predictability (including the Seasonal Prediction Model Intercomparison Project (SMIP))
GEWEX	Global Energy and Water Cycle Experiment
SPARC	Stratospheric Processes and their Role in Climate
WGCM	Working Group on Coupled Modelling (organizing numerical experimentation for IPCC, including the Model Intercomparison Projects AMIP and CMIP)
WGNE	Working Group on Numerical Experimentation (improvement of atmospheric models)
TFRCD	Task Force on Regional Climate Downscaling (translating global climate predictions into useful regional climate information, e.g. COordinated Regional Climate Downscaling Experiment CORDEX)

Source: http://www.wmo.int

However, sociopolitical decisions are made on the basis of scientific results, and these results draw strongly on models—as only models can study climate sensitivity, the influence of various gases on radiative forcing, and future developments. Therefore, the international coordination of climate science also has to be analyzed from the perspective of modelling. International cooperation here means to ensure a comparable, transparent, and sound scientific basis for understanding climate change. Related to these requirements, the World Climate Research Programme (WCRP), launched in 1980 by ICSU, WMO, and IOC, has the mission "to develop and evaluate climate system models for understanding, assessing and predicting Earth climate change and variations" (WCRP 2009, Activities page; see Table 2.4). In 1980, the Working Group on Numerical Experimentation (WGNE) was established, followed in 1997 by the Working Group on Coupled Modelling (WGCM) and in 2008 by the Task Force on Regional Climate Downscaling (TFRCD). These groups help to improve numerical models and they organize numerical experimentation for the IPCC Assessment Reports. The WCRP working groups and task force reflect the requirements on modelling that emerged over the last decades: the coupled atmosphere-ocean models that were the standard of the third and fourth IPCC Assessment Reports, model intercomparison, the improvement of parametrization, the new domains of Earth system modelling and of downscaling, as well as a framework for the seamless prediction of weather and climate variations. All of these requirements need international collaboration and sufficient computational capability, since higher resolution and higher complexity are core prerequisites. With regard to these requirements, in May 2008 the WCRP held the World Modelling Summit "to develop a strategy to revolutionize the prediction of the climate to address global climate change, especially at regional scale" (Shukla 2009, p. 2). Four objectives were identified as main priorities of future model development: representation of all aspects of the climate system within the models, an increase in accuracy, advanced computational capabilities, and establishment of a world climate modelling program. One of the recommendations is to launch multi-national high-performance computing facilities (Shukla et al. 2010; Shapiro et al. 2010). These facilities are needed not only to increase resolution and complexity, but also to conduct new evaluation methods like ensemble tests and prognoses, for model intercomparison, and for data assimilation methods.

Model intercomparison, in particular, requires international cooperation. In 1990 the WCRP's Working Group on Coupled Modelling agreed on the Atmospheric Model Intercomparison Project (AMIP), a standard experimental protocol for global atmospheric general circulation models. In 1995 the Coupled Model Intercomparison Project (CMIP) followed, as a standard experimental protocol for coupled atmosphere-ocean general circulation models. AMIP and CMIP are both community-based infrastructures for model diagnosis, validation, intercomparison, documentation, and data access. Both projects collect output from model control runs for standardized scenarios (e.g., CMIP for constant climate forcing, 1% CO_2 increase per year until 1970 and doubling after 1970, 'realistic' scenarios, atmosphere only, etc.). The output is used to diagnose and compare the participating models, in particular those models taking part in the IPCC process. Or in other words, as it is pointed out on the CMIP homepage: "Virtually the entire international climate modeling community has participated in this project since its inception in 1995" (CMIP 2010, Overview). CMIP currently is conducting the fifth phase (CMIP5) for the fifth IPCC Assessment Report in 2014. The purpose, as outlined by the WGNE, is to provide

> a comprehensive set of diagnostics that the community agrees is useful to characterize a climate model; a concise, complete summary of a model's simulation characteristics; an indication of the suitability of a model for a variety of applications; information about the simulated state and about the processes maintaining that state; and variables that modeling groups and users would like to see from their own model and from other models. [Finally, the model intercomparison should] allow model developers to compare their developmental model with other models and with AMIP vintage models to determine where they currently stand in the development process (PCMDI 2010, Projects: AMIP).

AMIP as well as CMIP are carried out by the Programme for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory in the U.S. Besides AMIP and CMIP other model intercomparison programs have been established, for instance the Seasonal Prediction Model Intercomparison Project (SMIP), the Aqua-Planet Experiment Project (APE), and the Paleoclimate Modelling Intercomparison Project (PMIP).

Besides model intercomparison, Earth system modelling relies on collaboration. Earth system models (ESMs) are vast clusters of various models developed by various modelling communities. Usually, an atmospheric and oceanic general circulation model is coupled with other multi-layer models of vegetation, soil, snow, sea ice, land physics and hydrology, chemistry, and biogeochemistry. Examples of community-based networks and programs include the European Partnership for Research Infrastructures in Earth System Modelling (PRISM) of the European Network for Earth System Modelling (ENES), the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR) and the Earth

System Modeling Framework (ESMF) in the U.S., as well as the British Grid-ENabled Integrated Earth system modelling framework for the community (GENIE). The goal of these programs is not only to conduct and coordinate Earth system research, but also to standardize methods, formats, and data, and to develop software environments. Earth system models stimulate new developments in meteorology, like integrated assessments for evaluating Earth systems, advanced coupling technologies, and infrastructures combining modelling and data services. They require efficient strategies to deal with massive parallel platforms and other new computing architectures. For instance, the mission of ENES is "to develop an advanced software and hardware environment in Europe, under which the most advanced high resolution climate models can be developed, improved, and integrated" (ENES 2009, Welcome page). The same holds for ESMF and other programs.

2.4.2 Standardization of Methods, Formats, and Data

Imperative for international cooperation is the standardization of methods, formats, and data. As early as 1873 the need for high-quality observational data and their worldwide compatibility led to the establishment of the International Meteorological Organization (IMO), the forerunner of the WMO. At that time the aim was to define technical standards and to make the output of observation devices comparable. Since then the Commission for Instruments and Methods of Observations (CIMO) has ensured the generation of high-quality observation data by testing, calibrating, defining quality-controlled procedures, and ensuring the traceability of meteorological measurements to the International System of Units (SI) of the International Bureau of Weights and Measures (BIPM). The task of CIMO even today is to promote and facilitate the international standardization and compatibility of instruments and methods of observations, in particular for satellite data. For instance, spectra of CO_2, oxygen, and vapour are measured by downward-directed spectrometers in Earth's orbit. The increase of greenhouse gases changes the spectral distribution of outgoing infrared radiation. But the measurement data are yet not independent of the devices used or the local environments, and therefore not really comparable from one satellite to another. New benchmark strategies are under development to create absolute standards (Anderson et al. 2004). However, the growing amount of data demands further standardizations. Globally used file formats, metadata conventions, reference data sets, essential variables and indicators have been developed. Today, not only observational data but also in-silico data and their production methods (models) have to be standardized. Benchmarks are also important to improve the evaluation of models, using advanced strategies like frequentist and Bayesian statistics, optimal filtering, and linear inverse modeling (see also Chap. 4 of this volume). In fact, guaranteeing standards for the models and their results is one of the challenges for climate modelling and the integrated assessment of climate change.

The international distribution of data is built on common formats for data files like netCDF and HDF5. The Network Common Data Form (netCDF) is a widely used format for scientific data and data exchange. Measurement data as well as simulation results are stored in netCDF data files, while the Hierarchical Data Format (HDF5) is a common format for satellite data. One problem with large data sets is that they need to be completed by meta-descriptions in order to be able to clearly identify the data sources, coordinates, and other features to ensure long-term reproducibility. Without this information these data are worthless. But scientific data are not always carefully described and stored, and this applies to historical data in particular. Therefore, the CF Metadata Convention and the WMO's Gridded Binary (GRIB) format attempt to ensure that a minimum amount of metadata accompany each data set. These formats are important to create data sets that can be globally distributed and used by the entire meteorological community.

A different aspect of data standards is the assimilation of reference data sets. Reference data sets are needed to enable model intercomparison and model evaluation. They are used to initialize standardized in-silico experiments and to generate comparable and reproducible results. Various research groups worldwide have devoted their work to assimilating reference data sets, for instance the NECP/NCAR Reanalysis I and II (RA-I, RA-II) and the ERA-15 and ERA-40 data sets. The National Centers for Environmental Prediction (NECP) and the National Center for Atmospheric Research (NCAR) in the U.S. reanalyze meteorological measurement data covering the period from 1948 to 2002. The project is using state-of-the-art analysis and forecasting systems to perform data assimilation (Kalnay et al. 1996). In the same way, the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyzed the period from mid-1957 to mid-2002 in 2000 (ERA-40). ERA-40 is using data from the International Geophysical Year and provides data to the community as a GRIB file. These data files are available on the institutions' data server at no charge for research use. Reanalysis data are based on quantities analyzed within data assimilation schemes. These schemes combine measurement and modelled data because measurement data exhibit great uncertainties due to their inhomogeneous characteristics. In order to obtain data sets that meet the needs of the applications and can be used for evaluation, measurement data have to be 'improved' by combining different types with different spatial-temporal distributions and different error characteristics. Reanalysis combines information of the actual state (measurement) with physical laws, and takes into account observation error as well as model error.[37]

[37]"The data assimilation system during reanalysis is as far as possible kept unchanged. The analysis is multivariate, and a 6-h forecast, the background, provides the most accurate a priori estimate for the analysis. Each analysis represents a state of the model after iteratively adjusting the background towards observations in a way that is optimal, given estimates of the accuracy of the background and observations. The differences between background, analysis and observations are archived for each value offered to the analysis. In addition the physical processes are 'recorded' during the model integration from one analysis to the next, the time interval during which they should be closest to the truth. All the synoptic and asynoptic observations, describing the instantaneous weather, control the data assimilation and the quality of its products over the period" (ECMWF Newsletter 2004, p. 2).

Table 2.5

Essential Climate Variables (ECV) of the Global Climate Observing System (GCOS) of the WMO, the IOC, the UNEP, and the ICSU

Atmospheric	
Surface	Air temperature, precipitation, air pressure, surface radiation budget, wind speed and direction, water vapour
Upper-air	Earth radiation budget (including solar irradiance), upper-air temperature (including MSU radiances), wind speed and direction, water vapour, cloud properties.
Composition	Carbon dioxide, methane, ozone, other long-lived greenhouse gases, aerosol properties.
Oceanic	
Surface	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, current, ocean colour (for biological activity), carbon dioxide partial pressure.
Sub-surface	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton.
Terrestrial	
	River discharge, water use, ground water, lake levels, snow cover, glaciers and ice caps, permafrost and seasonally-frozen ground, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), biomass, fire disturbance, soil moisture.

Source: http://www.wmo.int

Another important field of standardization is the identification of relevant indicators in order to assess current climate developments. These indicators are based on essential climate variables (ECV), which are ascertainable for systematic observation (see Table 2.5). These indicators support the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). Therefore, in 1992, the Global Climate Observing System (GCOS) was established to coordinate the worldwide observations and information of participating systems, like the WMO Global Observing System (GOS) for atmospheric physical and dynamical properties, the WMO Global Atmosphere Watch (GAW) for chemical composition of the atmosphere, and others.[38] The tasks of GCOS are to coordinate all of these data for global climate monitoring, climate change detection and attribution, and the assessment of climate change and climate variability. It does not make observations directly, but provides a global network to ensure high quality standards for effective climate monitoring. From these essential climate variables other indicators can be retrieved, such as the Global Warming Potential (GWP) of greenhouse gases, and radiative forcing, which expresses how greenhouse gases affect the amount of energy that is absorbed by the atmosphere. Radiative forcing has increased from 1990 to 2008 by about

[38]The GOS, for instance, collects data from 1,000 land stations, 1,300 upper-air stations, 4,000 ships, about 1,200 drifting and 200 moored buoys, and 3,000 ARGOS profiling floats, as well as 3,000 commercial aircraft, five operational polar-orbiting meteorological satellites, six geostationary meteorological satellites, and several environmental research and development satellites. GAW coordinates data from 26 global stations, 410 regional stations, and 81 contributing stations to produce high-quality data on selected variables of the chemical composition of the atmosphere (WMO 2010).

26%, and CO_2 concentrations account for approximately 80% of this increase (EPA 2010).

A growing number of variables and indicators quantify aspects of climate change like the increase in the intensity of tropical storms in the Atlantic Ocean, the length of a growing season, and the frequency of heat waves, but also socio-political indicators for adaptation and mitigation strategies like cost-effectiveness indicators, performance indicators, and so forth. All of these indicators require adequate concepts of measurement, long-term data series, and knowledge about inherent uncertainties. It is not easy to conceive and measure them because questions of the appropriate timing (period covered), rating the weight of current and historical data, and considerations of cause-effect delays and feedbacks have to be taken into account (Höhne and Harnisch 2002). Finally, the participation of countries in periodically submitting inventories of these indicators has to be organized, for example by the UNFCCC, and surveys for policy makers have to be compiled from these inventories by environmental agencies, e.g., by the European Environment Agency (EEA), the US Environmental Protection Agency (EPA), and other institutions (see also Chap. 5 of this volume), as these indicators also play a crucial role in the evaluation of models and in conceiving scenarios.

2.4.3 Community-Based Cyberinfrastructure

A side-effect of the outlined development of international collaboration and standardization is the opulence of data overflowing data bases and archives. GOS alone collects data from more than 12,000 stations and dozens of satellites. A direct outcome of the International Geophysical Year 1957–1958 (IGY), which provided the very first satellite data collected by Sputnik, was the establishment of World Data Centers (WDC). Today, 52 WDCs are operating in Europe, Russia, Japan, India, China, Australia, and the United States, e.g., the WDC for Atmospheric Trace Gases in Oak Ridge, Tennessee (U.S.), the WDC for Biodiversity and Ecology in Denver, Colorado (U.S.), the World Data Center for Climate (WDCC) in Hamburg, Germany, and the WDC for Glaciology and Geocryology in Lanzhou, China (WDC 2010, List of current WDCs). Besides these, other international data centers like the WMO Information System (WIS) and the IPCC Data Distribution Centre (DDC) as well as thousands of national and local databases and archives have been launched over the last decades. All of these resources provide web-based access, allowing researchers to download data worldwide. A characteristic example is the Ice Core Gateway of the National Climatic Data Center (NCDC) in the U.S. The gateway presents a list of ice-core data sets compiled by the International Ice Core Data Cooperative, which was established in 1996 to facilitate the storage, retrieval and communication of ice-core and related glaciological data (NCDC 2010, Ice Core Gateway).

Table 2.6

Standard prefixes for SI units of the International System of Units (SI) of the International Bureau of Weights and Measures (BIPM) (short scale)

Kilo	$10^3 = 1{,}000$ (thousand)
Mega	$10^6 = 1{,}000{,}000$ (million)
Giga	$10^9 = 1{,}000{,}000{,}000$ (billion)
Tera	$10^{12} = 1{,}000{,}000{,}000{,}000$ (trillion)
Peta	$10^{15} = 1{,}000{,}000{,}000{,}000{,}000$ (quadrillion)
Exa	$10^{18} = 1{,}000{,}000{,}000{,}000{,}000{,}000$ (quintillion)
Petaflop/s	$10^{15} = 1{,}000{,}000{,}000{,}000{,}000$ (quadrillion) floating point operations per second
Petabyte	$10^{15} = 1{,}000{,}000{,}000{,}000{,}000$ (quadrillion) bytes
Terabit/s	$10^{12} = 1{,}000$ gigabits $= 1{,}000{,}000{,}000{,}000$ bits (trillion) per second

Source: http://www.bipm.org

However, exabytes of meteorological data need not only to be stored but also have to be shuffled around the globe every day. Large data sets and the distribution of vast amounts of data require an infrastructure based on supercomputers (petaflop/s), large databases (exabytes), and high-speed network connections (megabit/s) (see Table 2.6). Such a community-based infrastructure is called 'cyberinfrastructure', 'e-infrastructure', or 'high-performance computing (HPC) ecosystem', providing shared "access to unique or distributed scientific facilities (including data, instruments, [models and model output], computing and communications), regardless of their type and location in the world" (European Commission 2010, e-infrastructure). Grids interconnect heterogeneous resources. While several years ago the distribution of models and data was organized by individual institutions and informal connections between researchers, today it is organized by the services of the community-based cyberinfrastructure via grid or cloud computing. For instance, the U.S. TeraGrid interconnects eleven research institutions including the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. These institutions are connected to the TeraGrid hub in Chicago via a 10–20-gigabit-per-second (Gbps) high-speed networking connection. Some of these institutions also act as grid hubs in their states, contributing petabytes of data storage capacity or high-performance computers, data resources and tools, including more than 100 discipline-specific databases, as well as high-end experimental facilities. An important task of grids is to create gateways. Gateways are community-developed sets of tools, applications, and data, integrated via a portal. Instead of obtaining individual allocations to a computing resource by each researcher, gateways customize the resources and applications needed by a specific scientific community (TeraGrid 2010). Examples of current gateways are the TeraGrid Geographic Information Science Gateway and the Cyberinfrastructure for End-to-End Environmental Exploration (C4E4). The C4E4 gateway allows "researchers to perform end-to-end environmental exploration by combining heterogeneous data resources with advanced tools for accessing, modelling, analyzing, and visualizing data" (C4E4 2010, Gridsphere).

Another grid related to climate science, is the Earth System Grid (ESG), which integrates supercomputers with large-scale data and analysis servers at various national labs and research centers in the US. It connects eight national and four international partners, among them the Lawrence Livermore National Laboratory, the National Center for Atmospheric Research, the Geophysical Fluid Dynamics Laboratory, the British Atmospheric Data Center, and the University of Tokyo Center for Climate System Research. The ESG provides access to various models, model output, and experiments, e.g., the Community Earth System Model (CESM), via the ESG Gateway at the National Center for Atmospheric Research. In Europe, the Distributed European Infrastructure for Supercomputing Applications (DEISA) links eleven national supercomputing centers—based on the European high-speed net GÉANT (10 Gbps). The GÉANT initiative interconnects 32 European national research and education networks and links them to other networks worldwide. The aim of DEISA is to develop a robust and permanent high-performance computing (HPC) ecosystem for research in Europe (DEISA 2010). DEISA supports several scientific projects and programs like the European Network for Earth System Modelling (ENES). These grid resources are usually available at no cost for research projects managed through the peer review process.[39] It is the vision that cyberinfrastructure or e-infrastructure should build virtual laboratories and organizations for distributed communities. These virtual laboratories and organizations are supposed to enable accelerated science discovery (ASD), scientific discovery through advanced computing (SciDAC), and open scientific discovery.

While grid or cloud-computing facilitates access to resources, it embeds services, models, and data sets in an advanced computing structure. In the case of models, this entails code migration in order to make a model run on heterogeneous computer clusters. The development of massive parallel computers has already challenged scientific modelling. In the 1980s network computing became accessible and network communication allowed thousands of CPUs and memory units to be wired up together. Since that time the development of parallel computing has advanced to more complex architectures of shared and distributed memory systems, allowing massive parallel computing. Current supercomputers consist of thousands of central processing units (CPU) for massive parallel computing (Top500 Supercomputer List 2010). In order to make use of this massive parallelism, "programs with millions of lines of code must be converted or rewritten to take advantage of parallelism; yet, as practiced today, parallel programming for the client is a difficult task performed by few programmers" (Adve et al. 2008, p. 6). This bottleneck of skilled programmers has led to new scientific degree programs in scientific computing, as software has become "the new physical infrastructure of [. . .] scientific and technical research" (PITAC 1999, p. 27).

These ongoing developments—massive parallelism and computing on heterogeneous, distributed platforms—are challenging scientists, because theories and models that are not conceivable as computable from the outset will become less and

[39]Free access to data is not always practiced in science. In genetics, for instance, many data sources are commercialized. This can seriously hinder scientific progress. Fortunately, meteorology and climate science are dominated by free access to data and models as well as to computer and observation resources.

less successful as scientific practices brace for change (Drake et al. 2008). However, current practice is based on the subsequent creation of computable forms of theories and models by algorithms, and this interferes with the requirements of massively parallelized representations of these theories and models. Modelling, usually carried out by scientists, increasingly requires advanced knowledge of programming and software engineering. Either scientists have to be trained to cope with high-performance computing developments, or they need the support of software engineers. Nevertheless, scientific models are coded theory. Every change in code can cause changes in the underlying scientific concept as well as in the results. Therefore the collaboration of scientists and software engineers in the field of scientific modelling is a sensitive one. An exemplary effort to bring together climate modelling and advanced software engineering has been launched by the US-American University Corporation for Atmospheric Research (UCAR) to develop the Community Climate System Model (CCSM) respectively the Community Earth System Model (CESM)—the successors to NCAR's climate models. Work on CCSM started in 1996 and in 1999, once the importance of software engineering had been recognized, the CCSM Software Engineering Working Group was formed. The results of this collaborative approach were published in a special issue on climate modelling of the *International Journal of High Performance Computing Applications* in 2005, and involved software engineers pointing out the need for accuracy and care.

> Due to the mathematical non-linearity inherent in climate system models, it is not possible to anticipate what effect changes in one component will have on the results of other components. [. . .] Changes need to be sequenced, one at a time, so that the relative effects can be tracked and understood. This process of model development and code modification is closely linked with scientific discovery in computational science. Thus, software engineering for climate modeling must involve climate scientists at each step of the process: the specification of requirements, software design, implementation, and testing (Drake et al. 2005, p. 180).

The new paradigm of community-shared models and the community development of models requires an advanced software design. As climate models, atmosphere and ocean models are rooted in a particularly long history of coding: these models involve large bodies of legacy code, handed down from one version to the next. Most of this code is written in FORTRAN, the oldest programming language introduced in 1956. The idea of Formula Translator (FORTAN) was to give scientists "a concise, fairly natural mathematical language" (Herrick and Backus 1954, p. 112). Therefore, "Fortran's superiority had always been in the area of numerical, scientific, engineering, and technical applications" (Metcalf et al. 2004, p. 3)—especially because FORTAN programs were, and still are, noticeably faster than others. But there is another reason: FORTRAN code is easy for scientists to read and therefore supports the exchange of pieces of code, e.g., a certain parametrization, or parts of models, which is common in the climate modelling community. Although the new versions of FORTRAN, primarily the widely used f90, is capable of parallelism and grid computing, scientists increasingly are depending on advanced software design to get their coded theory to run effectively on the new computing infrastructures. The goal of advanced software design is modularity, extensibility, and performance portability—preconditions for coupling models and for using heterogeneous and distributed computing platforms. Modularity builds on component models (e.g., of the atmosphere and ocean) of a climate or Earth system model, with each component further divided into subcomponents (e.g., atmospheric dynamics and physics). It enables new capabilities and subcomponents to be adopted, and the model to be customized for specific applications by choosing between various model configurations (e.g., various physical parametrizations). Preconditions are modules and software techniques for encapsulation. Modularity enables extensibility by coupling various components, for instance those chemical and biogeochemical components actually affected by chemical coupling with the ocean and the atmosphere. Finally, performance portability has to assure that a model performs well across all platforms, based on language standards and widely used libraries like the Message Passaging Interface (MIP). As the cost per grid point of climate calculation increases heavily, performance must be improved. Therefore load balancing, a technique to distribute workload across CPUs, flexible data structures, data decompositions, and other methods must be considered by software engineers.

However, because every change to the code can have a major influence on the results, the set-up of the Software Engineering Working Group (SEWG) as part of the CCSM project in 1999 was an important step. The software engineering process includes the documentation and review of each stage of model improvement, starting with the outline of new requirements, both scientific and computational. The next step is the design of the software architecture, including interface and data structure specifications. Finally, each new implementation has to be tested on several levels (unit testing of individual subroutines and modules, integrated testing of entire models, and frequent regression tests). As the Community Climate System Model (CCSM) and the Community Earth System Model (CESM) are community models, code correctness standards are needed for each change. Furthermore, "changes reproducing more than round-off differences in the results were not permitted by a single developer. The [Change Review Broad] (CRB) required much longer simulations, broader discussions, and scientific review when new modules were introduced which changed the model climate" (Drake et al. 2005, p. 180).

This ongoing development demonstrates that developing climate models today, which was started decades ago by small groups, involves growing teams of scientists from various disciplines related to the climate as well as software engineers, computer specialists, and mathematicians. The CCSM/CESM development includes twelve working groups and more than 300 researchers from various disciplines. These researchers come from different institutions all over the country. Coordinating the community development of scientific models takes place not only in meetings and workshops, but is also based on widely used software tools and standard processes. Tools like version control systems, software repositories, and procedures for introducing new code are common. Community development will "become easier as the community moves toward componentization and shared utility infrastructures" (Drake et al. 2005, p. 180), for instance by using climate and Earth system modelling frameworks, model coupling toolkits, common component architectures, and specific libraries. Besides the modelling community, other communities have propagated during recent years. The number of model users and model output users has increased since access to models and data has been facilitated by cyberinfrastructures. The goal is to make climate simulation as easy as possible for model users. Climate and Earth system models will become operational tools like measurement and observation devices, accessible

> via a portal, which will allow a user to compose, execute and analyze the results from an Earth system simulation. After authenticating themselves with the portal, a user will have access to a library of components that can model different aspects of the Earth system (for example, ocean, atmosphere) at different resolutions. The user constructs a composite application by selecting from these components (GENIE 2010, Vision).

This plug-and-play mode uses components and couplers like bricks. In principle, anybody could conduct an Earth system experiment. But these bricks are black boxes for users outside the modeller community, entailing the risk that results could be misinterpreted due to a lack of understanding. Nevertheless, this development democratizes the use of climate and Earth system models. This, in turn, will stimulate new user groups from other fields like economics and politics to apply these models in their work.

2.4.4 The IPCC Rhythm of Model Development and CMIP

The outlined developments of community-based cyberinfrastructures and new user groups are more or less associated with the work of the Intergovernmental Panel on Climate Change (IPCC). IPCC has become a leading driver of progress in climate modelling. Set up in 1989 by WMO and UNEP, the aim of IPCC is "to provide the governments of the world with a clear scientific view of what is happening to the world's climate" (IPCC 2010, History), in the words of the UN General Assembly Resolution 43/53 of 6 December 1988. One of the major activities of IPCC is the coordination and release of the IPCC Assessment Reports, involving hundreds of scientists as Coordinating Lead Authors, Lead Authors and Review Editors. The Assessment Reports give a state-of-the-art overview of climate and climate change science. Although there has been some critique of the work and procedures of the IPCC (see also Chap. 3 of this volume), from the perspective of climate modelling the IPCC has turned out to have a beneficial influence. In particular because the rhythm of the publication periods of the IPCC Assessment Reports (FAR 1990; SAR 1995; TAR 2001, AR4 2007, AR5 2014) have introduced a unique procedure for coordinated model development: Every 5–7 years a major part of the climate modelling community contributes to these Assessment Reports by delivering scenario results. A concerted cycle of model improvement, model testing and intercomparison, and production runs precedes these deliveries (Table 2.7).

The provisional timeline for the fifth IPCC Assessment Report, scheduled to be published at the end of 2014, lists September 2013 as completion date for the

Table 2.7

Intergovernmental Panel on Climate Change (IPCC). A co-sponsored program of the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP)	
WGI	Working Group I: The Physical Science Basis
WGII	Working Group II: Impacts, Adaptation, Vulnerability
WGIII	Working Group III: Mitigation of Climate Change
TFI	Task Force on National Greenhouse Gas Inventories
TGICA	Task Group on Data and Scenario Support for Impacts and Climate Analysis
Reports	Assessment Reports (FAR 1990; SAR 1995; TAR 2001, AR5 2007, AR5 2014)
	Special Reports (e.g. Renewable Energy Sources and Climate Change Mitigation; Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation)
	Methodology Reports (e.g. IPCC Guidelines for National Greenhouse Gas Inventories)
	Development of New Scenarios (AR 1990, SR 1994, SRES 2000, currently: RCPs)
AR5	
WG I Authors	258 Coordinating Lead Authors, Lead Authors and Review Editors from 44 countries (65% new CLAs, LAs, REs; 19% female)
WG II Authors	302 Coordinating Lead Authors, Lead Authors and Review Editors
WG III Authors	271 Coordinating Lead Authors, Lead Authors and Review Editors

Source: http://www.ipcc.ch/

contribution of Working Group I (see Table. 2.8). WGI is responsible for the physical science bases and the model-based predictions. This means that all models already had to be improved and tested for performing the required experiments in 2010. Global projections in the AR5 are based on the Coupled Model Intercomparison Phase 5 (CMIP5); thus a preliminary set of CMIP5 experiments was designed and discussed in 2007, until a community-wide consensus was reached in 2008. In 2009 a list of requested model outputs was developed, and the final set of CMIP5 experiments approved by the WCRP Working Group on Coupled Modelling. In 2010 the modelling groups participating in AR5 started their production runs for CMIP5, and in February 2011 the first model output became available to the climate science community for analysis. With the First Lead Author Meeting of WGI in November 2010 work on the AR5 started. The complete process of writing and discussing of WGI's contribution to AR5 will last until the WGI Summary for Policymaker (SPM) Approval Plenary meeting in September 2013 approves the SPM line by line. During this period numerous comments have to be considered and a response to each comment has to be provided by the lead authors (Petersen 2006).

From the perspective of climate modelling, the beneficial part of this process is the model intercomparison of CMIP. In the 1980s modelling was still characterized by distinct modelling groups analyzing only their own model output. In the mid-1990s the WCRP Working Group on Coupled Models began organizing global model intercomparison of coupled atmosphere-ocean models (AOGCM) based on standard scenarios and experiments. The Program for Climate Model Diagnosis and

Table 2.8

Timetable of WG I for the fifth IPCC Assessment Report (AR5)	
CMIP5	
2007	Preliminary set of CMIP5 experiments discussed (WGCM meeting)
2008	Community-wide consensus reached on the complete, prioritized list of CMIP5 experiments
2009	List of requested model output developed
Sept. 2009	WGCM endorsed final set of CMIP5 experiments
2010	Modelling groups begin production runs and produce CMIP5 output
Feb. 2011	First model output available for analysis
31 July 2012	By this date papers must be submitted for publication to be eligible for assessment by WG1
15 March 2013	By this date papers cited by WG1 must be published or accepted with proof
WG I AR5	
8–11 Nov. 2010	First Lead Authors Meeting
18–22 July 2011	Second Lead Authors Meeting
16 Dec.–10 Feb. 2012	Expert Review of the First Order Draft
16–20 April 2012	Third Lead Authors Meeting
5 Oct.–30 Nov. 2012	Expert and Government Review of the Second Order Draft
14–19 Jan. 2013	Fourth Lead Authors Meeting
7 June–2 Aug. 2013	Final Government Distribution of the WGI AR5 SPM
13–14 Sept. 2013	Preparatory Meeting of WGI AR5 SPM/TS Writing Team & CLAs

Source: http://cmip-pcmdi.llnl.gov/cmip5/; http://www.ipcc.ch/

Intercomparison (PCMDI) collected and archived the model data and made them available to researchers outside the modelling community. Additional phases of the Coupled Model Intercomparison Project (CMIP) followed (CMIP2, CMIP2+), opening up the model output to analysis by a wider community. The planning for the third IPCC Assessment Report (TAR) put forward the wish that “not only must there be more lead time for the modeling groups to be able to marshal improved model versions and the requisite computing resources to participate, but there should also be time and capability for the model data to be analyzed by a larger group of researchers” (Meehl et al. 2007, p. 1,384). According to Gerald A. Meehl et al., CMIP3 conducted the largest international climate model experiment and multimodel analysis ever. Various experiments on climate change, climate commitment, idealized forcing and stabilization, climate sensitivity, and other topics have been performed by the AOGCMs (Table 2.9). The amount of data supplied to PCMDI from modelling groups was so extensive that conventional online data transfer became impractical and the modellers had to send in their data on disks. Seventeen modelling centers from 12 countries with 24 models participated in CMIP3, and more than 300 researchers registered for access to the multimodel dataset. Based on these data more than 200 analyses were submitted to peer-reviewed journals by spring 2004 in order to be assessed as part of AR4. The CMIP3 process inaugurated

> a new era in climate science research whereby researchers and students can obtain permission to access and analyze the AOGCM data. Such an open process has allowed hundreds of

Table 2.9

23 Coupled Atmosphere-Ocean Models (AOGCM) participating in CMIP3 and AR4	
BCC-CM1	Beijing Climate Center, China
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
CCSM3	National Center for Atmospheric Research, USA
CGCM3.1 (T47)	Canadian Centre for Climate Modelling and Analysis
CGCM3.1 (T63)	Canadian Centre for Climate Modelling and Analysis
CNRM-CM3	Météo-France
CSIRO-MK3.0	CSIRO Atmospheric Research, Australia
ECHAM5/MPI-OM	Max Planck Institute (MPI) for Meteorology, Germany
ECHO-G	Meteorological Institute of the University of Bonn (Germany), Korea Meteorological Administration (Korea), and Model and Data Group Hamburg (Germany)
FGOALS-g1.0	Chinese Academy of Sciences
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory, USA
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory, USA
GISS-AOM	Goddard Institute for Space Studies, USA
GISS-EH	Goddard Institute for Space Studies, USA
GISS-ER	Goddard Institute for Space Studies, USA
INM-CM3.0	Institute for Numerical Mathematics, Russia
IPSL-CM4	Institut Pierre Simon Laplace, France
MIROC3.2 (hires)	Center for Climate System Research, National Institute for Environmental Studies and Frontier Research Center for Global Change, Japan
MIROC3.2 (medres)	Center for Climate System Research, National Institute for Environmental Studies and Frontier Research Center for Global Change, Japan
MRI-CGCM2.3.2	Meteorological Research Institute, Japan
PCM	National Center for Atmospheric Research, USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office, UK
UKMO-HadGEM	Hadley Centre for Climate Prediction and Research/Met Office, UK

Source: CMIP3 Climate Model Documentation http://www-pcmdi.llnl.gov

> scientists from around the world, many students, and researchers from developing countries, who had never before had such an opportunity, to analyze the model data and make significant contributions (Meehl et al. 2007, p. 1393).

The CMIP3 multi-model data set also allowed new metrics to be developed for model evaluation. It gave modellers comparative insights into their own model and the others, enhancing further improvements. Therefore, CMIP5 will also be an integral part of the fifth IPCC Assessment Report, as it is a "collaborative process in which the community has agreed on the type of simulations to be performed" (IPCC 2010, p. 16). The IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections, held in January 2010 in Boulder, Colorado, developed a *Good Practice Paper on Assessing and Combining Multi Model Climate Projections* for the community (IPCC 2010). Compared to CMIP3, "since participation in the IPCC process is important for modelling centers, the number of models and model versions is likely to increase in CMIP5" (IPCC 2010, p. 16). More than 20 modelling centers are expected to participate in CMIP5, contributing more than 1,000 terabytes of data. A diversity of models is expected. Some of the models will include biogeochemical cycles, gas-phase chemistry, aerosols, etc., others will not. This introduces the problem of comparability between the models, which not only differ in various aspects from each other, but also in their individual performance. This has stimulated an ongoing debate on weighting models. CMIP3 analysis has followed a ‘one vote, one model’ policy of equal weighting to create a multi-model mean (MMM). But there might be reasons for weighting models based on some measure of performance (optimum weighting) (Weigel et al. 2010; Räisänen et al. 2010).

> Recent studies have started to address these issues by proposing ways to weight or rank models, based on process evaluation, agreement with present day observations, past climate or observed trends. While there is agreement that ‘the end of model democracy’ may be near, there is no consensus on how such a model selection or weighting process could be agreed upon (IPCC 2010, p. 16).

However, model intercomparison on a worldwide scale has not only preluded a new era in climate science involving more researchers than ever in the conjoint process of obtaining substantial and community-assessed information for the IPCC Assessment Reports. It also provides the role model of using model output, besides observational and experimental data, to gain knowledge for other disciplines. And these advances are important, as projecting the future has become the desire of mankind.

2.5 Climate Projections and the Challenge of Uncertainty

When Jule Charney and colleagues published their report *Carbon Dioxide and Climate: A Scientific Assessment* in 1979, they concluded that

> if the CO_2 concentration of the atmosphere is indeed doubled and remains so long enough for the atmosphere and the intermediate layer of the ocean to attain approximate thermal equilibrium, our best estimate is that changes in global temperature to the order of 3°C will occur and that these will be accompanied by significant changes in regional climatic patterns (Charney et al. 1979, p. 17).

Based on the numerical study of climate sensitivity carried out through experiments using models developed by Syukuro Manabe et al. and James Hansen et al., these conclusions still hold, although the authors were fully aware that “we can never be sure that some badly estimated or totally overlooked effect may not vitiate our conclusions. We can only say that we have not been able to find such effects” (p. 17). The so-called Charney report marked a turning point. It led to a series of Congressional hearings in the US during the 1980s, which turned climate change into a public policy issue. After decades of research that has made forecasting algorithms meteorology’s ultimate objective—for weather forecasting as well as for climate projections—the public now started to ask for reliable predictions (very likely projections) about climate change. Strictly speaking, however, scientific forecasting and climate projections do not have much in common. While the main purpose of scientific forecasting is to be promptly verified or falsified in order to support or to disable a hypothesis climate projections are made to be avoided, so that we never will be forced to verify them in the future. This paradox of ‘to-be-avoided projections’ leads to various problems in the interaction between science and the public, and limits the range of scientific arguments used as the bases for socio-political decisions.

2.5.1 Mankind’s Dream of Rational Forecasting

It was science itself that fed mankind’s dream of rational forecasting based on physical laws. The triumphant advance of numerical prediction, ever since Urbain Le Verrier numerically forecasted the existence of planet Neptune in 1846, motivated science to make increasing use of physical laws articulated by differential equations to extrapolate future states of a system in time and space. Such extrapolations were used to verify or falsify theories and hypotheses, for instance the hypothesis of the existence of planet Neptune. As the philosopher of science Karl Popper pointed out in his study *The Logic of Scientific Discovery*, an empirical scientist “constructs hypotheses, or systems of theories, and tests them against experience by observation and experiment” (Popper 1992, p. 2). In case of planet Neptune the astronomer Johann Galle successfully verified Le Verrier’s hypothesis by observation in a single night. He did exactly what Popper described in his book: he tested a single prediction which could be proved or disproved straightforwardly. Either planet Neptune could be observed or not, based on Le Verrier’s assumptions that disruptions in the orbit of planet Uranus could be caused by a planet which had yet to be discovered. Le Verrier had inferred the possible position of this unknown planet numerically and asked Galle to observe a certain area. If he had not been able to see the planet, Le Verrier’s hypothesis would have been assumed to be wrong, because it had been falsified by observation. But other reasons were conceivable, for instance, false calculations or insufficient telescope resolution. However, since Le Verrier’s day science has changed rapidly, attempting to extrapolate more advanced predictions for systems more complex than a single planet. The testability of such predictions has relied increasingly on sets of measurement data rather than on yes and no answers now that observation and experiment have been so extensively quantified.[40] One of the main achievements of nineteenth and twentieth-century science was to quantify observation and experiment by introducing advanced methods of detection and measurement, thus producing a growing amount of numbers. Based on these improved measurement methods and on powerful sets of equations expressing physical laws, nineteenth-century science

[40]As long as a single assertion can be inferred from a theory and clearly tested by observation or experiment in order to validate or falsify the theory, prediction is a practical tool for science to test its knowledge basis. Based on this practicability, Popper differentiated two forms of predictions: ‘conditional scientific predictions’ (if X takes place, then Y will take place) and ‘unconditional scientific prophecies’ (Y will take place). The conditional prediction is the type used in rational forecasting applied to a system that changes over time.

proudly called itself an ‘exact science’ as it became a matter of values and numbers, and of measuring and computing, respectively. An exact science is capable of accurate quantitative expression, precise predictions, and rigorous methods of testing hypotheses. Nevertheless, the downside of exact science is that quantitative methods are subject to limits on precision and complexity: every measurement device operates within a range of accuracy and collects only local information, which is why data sets never depict a complete and precise picture of the state of a system. Furthermore, every calculation based on infinitesimal entities like differential equations is approximative, and the inference of precise predictions is limited to simple systems. The adjective ‘exact’ easily leads to exaggerated expectations of science’s ability to forecast rationally.

The idea of predictability has been rooted mainly in the progress of physics, ever since Isaac Newton and others postulated the laws of motion in the seventeenth century. These laws turned physics into a mechanistic approach based on the dogma of strong determinism, as Pierre de Laplace aptly articulated in 1820:

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes. The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such an intelligence. Discoveries in mechanics and geometry, coupled with those in universal gravitation, have brought the mind within reach of comprehending in the same analytical formula the past and the future state of the system of the world. All of the mind’s efforts in the search for truth tend to approximate the intelligence we have just imagined, although it will forever remain infinitely remote from such an intelligence (de Laplace 1951, Preface).

That science, and also meteorology as the physics of the atmosphere, is rooted in this tradition, can be read from Vilhelm Bjerknes’ seminal paper of 1904, in the introduction of rational solution for weather prediction considered from the viewpoints of mechanics and physics.

> If, as any scientifically thinking man believes, the later states of the atmosphere develop from the former according to physical laws, one will agree that the necessary and sufficient conditions for a rational solution of the problem of meteorological prediction are the following: 1. One has to know with sufficient accuracy the state of the atmosphere at a certain time. 2. One has to know with sufficient accuracy the laws according to which a certain state of the atmosphere develops from another (Bjerknes 2009, p. 663).

If both are known with sufficient accuracy, “to construct the pictures of the future states of the atmosphere from the current state of the atmosphere at a starting point” (p. 668) will be possible. Every forecasting algorithm (GCM) based on Bjerknes’ mechanical and physical concept follows this approach. This imitation of an intelligence to which nothing would be uncertain, neither the future nor the past, characterizes mankind’s dream of rational forecasting. But despite his trust in determinism, Bjerknes was aware that a complete diagnosis of the current state of the atmosphere is not feasible and that—given that his outlined mathematical model properly describes the laws governing the development of the atmosphere from one state to the next—a strictly analytical integration of the governing equations is out of the question.[41] "Furthermore", he pointed out, "the major atmospheric processes are accompanied by a long list of side effects [. . .] The question is: to what extent are there side effects with considerable feedback effects on the development of atmospheric processes? The feedbacks evidently do exist" (p. 664). This enumeration of basic constraints—lack of complete diagnosis of the atmosphere, lack of an exact solution of the mathematical model, and lack of knowledge on relevant processes—harbours all possible sorts of uncertainty which challenge climate projection even today.

2.5.2 The Challenge of Uncertainty

As long as science is interested mainly in epistemological questions, trying to decode the mechanisms of relevant processes of a phenomenon, uncertainty is a tedious feature, but not a threatening one. But when science has to apply its knowledge, uncertainty becomes a provocation. In case of technical applications, a designed system can be fully engineered and adjusted to scientific theory as its level of freedom can be controlled and restricted, but in the case of nature this is impossible. Therefore, an application of climate change science has to take into account the conjuncture of complexity and uncertainty, which requires a new understanding of scientific prediction. This new understanding is currently shifting through the ongoing interaction of climate change science and policy. This understanding tries to include uncertainty and decision-making under uncertainty as integral parts of both human and scientific knowledge. On the one hand, it aims to reduce uncertainty in research on the climate system; on the other, it aims to assess known uncertainties and the possible consequences of different decisions, including inaction. This two-pronged approach to uncertainty characterizes climate change science and policy and has led to various developments. Over the course of the IPCC Assessment Reports, in particular, sources and sorts of uncertainties have been examined and a specific wording and classification has been developed. An extensive discussion of a typology of uncertainty is given by Arthur Petersen (Petersen 2006). He differentiates the location, nature, and range of uncertainty as well as the limits of recognized ignorance, methodological (un)reliability, and value diversity (see Table 2.10).

[41] "As is well known, the calculation of the movement of three points that influence each other according to a law as simple as Newton's already far exceeds the means of today's mathematical analysis. There is evidently no hope of knowing the movements of all points of the atmosphere which are influenced by much more complicated interactions" (Bjerknes 2009, p. 665).

Table 2.10

Typology of uncertainty involved in modelling and simulation	
Location of uncertainty	Uncertainty in models, input data, model implementation, and output interpretation.
Nature of uncertainty	Epistemic uncertainty (incompleteness and fallibility of knowledge), ontic uncertainty (due to the intrinsic character of a natural system), and a mix of both. e.g. unpredictability of long-term weather forecasts due to the limited knowledge of initial states as well as to the chaotic behaviour of weather based on its sensitive dependence on initial conditions.
Range of uncertainty	Statistical uncertainty (range of uncertainty expressed in statistical terms) based on two paradigms (frequentist and Bayesian statistics) and scenario uncertainty (range of uncertainty expressed in terms of plausibility often articulated as 'what, if' statements). Scenario uncertainty can transform into statistical uncertainty if more is known about relevant processes. Statistical and scenario uncertainty ranges can be expressed in terms of (in)exactness and (im)precision, or (un) reliability and (in)accuracy.
Recognized ignorance	Awareness of the limits of predictability and knowability expressed in terms of the subjective probability of a statement or its openness.
Methodological unreliability	Adequacy or inadequacy of methods used, e.g. quality of initial and boundary conditions, analysis methods, numerical algorithms, discretization, and qualitative peer review by best practice and standard references in the scientific community.
Value diversity	Value-laden choices of decisions, e.g. regarding the processing of data or concepts of modelling. The values can result from general and discipline-bound epistemic values as well as from socio-political and practical values. These values can bias the scope and robustness of the results and conclusions.

Source: Petersen 2006, pp. 49–64

It is worth mentioning that Petersen differentiates two notions of reliability: Firstly, reliability of a simulation according to its accurate results given for a specific domain. Secondly, reliability of a simulation related to its methodological quality (Petersen 2006, p. 55 et seq.). While the first notion of reliability refers to statistical and therefore quantifiable reliability, the second refers to methodological and qualitative reliability. An important aspect of the quantifiable reliability of a simulation is that it refers to the whole model (system level) and does not imply top-down reliability for each element of the model (component level). On the other hand, each component needs to be tested for certain circumstances and reliability has to built from the bottom up. From this—and the consideration of qualitative uncertainty, too—it follows that model evaluation consists of a number of tests, studies, and practices, all of which constitute the reliability of a model and its projections.

Although during the IPCC process a specific wording and classification of uncertainties have been developed, the consistency of wording within each working group did not apply across statements by the other working groups. While WGI (Physical Sciences Basis) dealt with uncertainties in climatic processes and probabilities, WGII (Impacts) focused on risks and confidence levels, and WGIII (Response Strategies)

Table 2.11

Levels of confidence and a likelihood scale by IPCC

Levels of confidence	**Degree of confidence in being correct**
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance
Likelihood scale	**Likelihood of the occurrence/outcome**
Virtually certain	>99% probability of occurrence
Very likely	>90% probability
Likely	>66% probability
About as likely as not	33–66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Exceptionally unlikely	<1% probability

Source: IPCC 2005, pp. 3–4

adopted a common approach only during the process for AR4 (see Table 2.11). One reason for this diverse approach among the working groups is rooted in their different topics and methods, another result from the scale of the working groups and difficulties in coordinating heterogeneous communities, especially when thousands of scientists of various disciplines are involved without any authoritative management. Nevertheless, sources and sorts of uncertainty are divers and range between the causality of natural systems and the intentionality of human systems, as well as between objective and subjective perspectives (Swart et al. 2009).[42] Furthermore, quantitative statements based on observation and measurement must be translated into future natural effects and their relevance for mankind. The problem thereby is that the causality to be considered is neither simple nor unidirectional, but a complex feedback cycle of human activities triggering natural causalities, which, in turn, cause effects that require human reaction (mitigation, adaptation). An ongoing spiral of action and reaction, including inaction as a form of reaction, must be assessed in terms of more or less (un)certain predictions or projections. Therefore, the growing awareness of the importance of communicating uncertainty is also reflected in a more subtle wording of the terms 'prediction', 'forecast', 'scenario', and 'projection' (see Table 2.12). While the first IPCC Assessment Report generously used the term 'prediction', since the second report this term has been used with more care, with the authors instead referring to the concept of 'projection'. Although there are no clear definitions of these terms, the notion of 'prediction' differs slightly from the notion of 'projection'.

Following Dennis Bray's and Hans von Storch's analysis of the nomenclature of climate science, one can say that

[42] Rob Swart et al. suggest a consistent vocabulary of confidence levels and probabilities across all working groups, special training for IPCC authors, a legitimate view of different approaches, and a supportive articulation of the nature and origins of uncertainties for the reader (Swart et al. 2009, p. 3 et seq.).

Table 2.12

Definitions of forecast/prediction, projection, and scenario by IPCC

Definition by IPCC	**AR4 WGI Glossary**
Climate prediction	A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, on seasonal, interannual or long-term timescales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.
Climate projection	A projection of the climate system's response to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/ concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.
Climate scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed explicitly to investigate the potential consequences of anthropogenic climate change, often serving as input for impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information, or instance about the currently observed climate. A climate change scenario is the difference between a climate scenario and the current climate.
Definition by IPCC	**AR4 WGII Glossary**
Climate prediction	A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, e. g., on seasonal, interannual or long-term timescales.
Climate projection	The calculated response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based on simulations by climate models. Climate projections are distinguished from climate predictions, in that the former critically depend on the emissions/concentration/radiative forcing scenario used, and therefore on highly uncertain assumptions of future socio-economic and technological development.
Climate (change) scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships and assumptions of radiative forcing, typically constructed for explicit use as input for climate change impact models. A 'climate change scenario' is the difference between a climate scenario and the current climate.

Source: IPCC 2007a, p. 943; IPCC 2007b, p. 872

> 'prediction' conveys a sense of certainty while 'projection' is associated more with the possibility of something happening given a certain set of plausible, but not necessarily probable, circumstances. A prediction can be used to design specific response strategies, while a projection, or more precisely a series of projections, provides a range on which to consider a range of response strategies (Bray and von Storch 2009, p. 535).

The interesting aspect here is the difference between probability and plausibility. While probability is a quantitative measure of statistical uncertainty and can be used as displayed in the likelihood scale, plausibility refers to expert judgments in terms of confidence. It is no coincidence that WGI uses the likelihood scale, while WGII applies levels of confidence in their report. Bray and von Storch point out that the simulated climate development is determined by the initial state, by external forcing, and by the internal variability of the climate system. But the initial state's impact on the simulated development of climate disappears after a few weeks of simulated time, the initial soil conditions after a few years, and that of the upper ocean after a few decades. As "the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature" (IPCC 2007a, p. 943). However, the initial state's loss in impact, compared to the long-term relevance of the highly uncertain factor of external forcing, transforms the probabilistic nature of climate prediction into the mere plausibility of climate projections after a certain period, the length of which remains unknown. Thus, a short-term prediction (decadal forecast) gradually turns into a long-term projection (scenario simulation).

> In both cases, any statement about a 'probability' hinges on an assessment of the probability of the conditioning elements, namely, the initial state of the climate system and the forcing scenario. Here, a key difference emerges—the initial state is known within given bounds, while the forcing scenario is an educated guess, without an associated probability (Bray and von Storch 2009, p. 535).[43]

These educated guesses rely on possible scenarios of future emissions and human behaviour and therefore can result only in possible or plausible outcomes of scenario simulations, not in probable ones. However, the purpose of scenarios and scenario simulations is to raise 'what if' questions, and to gain an understanding of how specific processes and forcings push the future in different directions. Therefore, scenario simulations are defined as

> images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. A set of scenarios assists in the understanding of possible future developments of complex systems (Nakicenovic and Swart 2000, p. 62).

2.5.3 Climate Scenarios and Storylines

Scenario simulations are plausible and often simplified representations of the future climate and entail their own range of uncertainty (scenario uncertainty). Nevertheless,

[43]Bray and von Storch conducted an analysis exploring "how climate scientists perceive the products of their efforts, as a *projection* or as a *prediction*" (Bray and von Storch 2009, p. 538). The interesting result of this analysis is that about two thirds of the 283 responses are cautious about their outcome, calling them projections, not predictions. However, there is still some confusion, with "approximately 29% of the respondents associating probable with projections and approximately 20% of the respondents associating possible with prediction" (Bray and von Storch 2009, p. 541).

scenario simulations are required to assess future possible pathways. In the context of the IPCC Assessment Reports, scenario development started in the late 1980s, with the SA90 scenario used in the first IPCC Assessment Report in 1990, followed in 1992 by a set of six scenarios (IS92a through f) for the second IPCC Assessment Report in 1995 (cf. Leggett et al. 1992; Pepper et al. 1992). For the third and fourth IPCC Assessment Reports in 2000 and 2007 a set of four storylines and forty scenarios was used, developed and published in 2000 by the *Special Report on Emission Scenarios* (Nakicenovic and Swart 2000; Girod et al. 2009). New scenarios, called Representative Concentration Pathways (RCP), have been developed for the fifth IPCC Assessment Report in 2014 (RCP Database 2010). Scenarios describe possible worlds of different economic, social and environmental conditions which result in different greenhouse gas futures—externally forcing the development of the climate system. The underlying assumptions of these scenarios are based on reports by major international bodies like the Organisation for Economic Co-operation and Development (OECD) and expert analyses. The major factors driving anthropogenic emissions and land-use are population growth, affluence, energy efficiency and the state of technology. However, the estimates of these factors involve great uncertainties. Therefore, long-term projections (scenario simulations) are very vague images of possible future developments.

The main driving factor is the growth of population, as it scales anthropogenic emissions and humans' impact on the climate and environment. Population growth is driven by the fertility rate, which is close to the replacement level in developed countries, but much higher in developing countries. Because the number of females of reproductive age controls fertility, there is some potential to predict short-term future population growth. Another important factor is mortality, which in many countries shows a decreasing trend due to improved hygiene and modern medicine. Population projections involve current age distributions, as well as economic and social developments. However, events such as wars, the post-World War II baby boom, AIDS and the recent rapidity of declining fertility in developing countries could not be foreseen. In quantitative terms, the world population reached 1 billion in 1804, 2 billion in 1927, 3 billion in 1960, 4 billion in 1974, and 5 billion in 1987, reaching the 6-billion level shortly before the millennium. Projections of future population assume a stabilization in the mid-twenty-first century. Projections range between 8 and almost 11 billion, with more recent estimates near the lower end. Recent estimates cannot be evaluated, but earlier estimates can be compared to the present-day population. The percentage errors of twelve UN forecasts of the world's population made between the years 1957–1998 and representative for the year 2000 range between 1.0 and 7.1% (Bongaarts and Bulatao 2000). This is an excellent agreement; however, errors are considerably larger on a regional scale and for longer time periods. Short-term projections benefit from the fact that most people alive at a given date are still alive three or four decades later. The most used estimates are those derived by the World Bank and the UN. The SRES scenarios used for the fourth IPCC Assessment Report employ published projections from the

International Institute for Applied Systems Analysis (IIASA) along with the UN's medium and long-range projections.

Another driving factor is economic wealth, as it is associated with high consumption of resources and high CO_2 emissions on the one hand, but also high technological standards, which reduce emissions per activity, on the other. Economic development is expressed in terms of Gross National Product (GNP). GNP is defined as the monetary equivalent of all products and services generated in a given economy in a given year. Although GNP is widely used, it does not reflect all aspects of human welfare and sustainability. Due to these inherent weaknesses of GNP, for the degree of economic development IPCC uses a simpler measure: per-capita income. The impact of future energy use will depend on fuel types and the implementation of efficient technologies. The global demand for energy of all forms is likely to increase significantly, even with substantial gains expected in efficiency. Population and GNP assumptions, along with structural and technological changes that affect energy efficiency and energy, drive the demand for energy services. Energy use per unit of economic activity, that is, energy intensity, reflects a whole range of structural, technological, and lifestyle factors (Nakicenovic and Swarts 2000). Future resource availability is a dynamic process, which is controlled by the total amount of hydrocarbon or uranium in the Earth's crust or of any other energy form; accessibility, the state of technology, cost and energy prices. Because estimates of all these factors are highly uncertain, IPCC develops low and high resource scenarios.

A working group led by Nebojsa Nakicenovic and Robert Swart, both editors of the SRES report, developed four different storylines, but no explicit judgments have been made as to their desirability or probability (see Table 2.13). The purpose of these storylines is to explore the uncertainties behind potential trends in global developments, as well as the key drivers that influence these. The construction of scenarios reflects political and economical activity or inactivity and takes place at the interface between science and politics. Scenarios link qualitative narratives on population growth, economic growth, and technological aspects, for instance concerning energy effects and land-use (storylines) with corresponding quantitative data and formalized mechanisms for each storyline. The output is the specification of future emissions of GHGs in quantitative terms.

The scenarios provide the information necessary to derive the emissions. To construct an emission inventory one needs to know the temporal evolution of the emission factors (how much of a chemical species is produced by a specific source per time unit), the number and geographical distribution of different emission sources or sectors, and the activity statistics. For the construction of inventories mathematical models are used. Most of the data are available on a national basis and are disaggregated to the model's grid. The SRES emissions inventories include data on the most important greenhouse gases: CO_2, methane, nitrous oxide, nitrogen oxides, carbon monoxide, non-methane volatile organic compounds, sulfur dioxide, chlorofluoro-carbons and hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. Carbon monoxide, nitrogen oxides, and organic

Table 2.13

Storylines of the Special Report on Emission Scenarios (SRES)	
A1	The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system.
A2	The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on the local and regional levels.

Source: Nakicenovic and Swart 2000, pp. 4, 5

compounds are used to calculate ozone concentrations.[44] The SRES scenarios for projected CO_2 emissions until 2100 range from 5% (scenario B1) to 90% (scenario A1FI). While B1 describes global, sustainable development, A1FI describes a global, fossil-fuel-intensive development. These scenarios lead to an estimated increase in the mean global temperature of 1.1–6.4°C by the end of this century. None of these scenarios take into account the possibility of countries implementing new, comprehensive measures or additional climate policy initiatives for reducing emissions of greenhouse gases. Therefore, the so-called 'post-SRES mitigation scenarios', developed by nine modelling teams worldwide, analyze the influence of mitigation strategies. The developed storylines were related to the four SRES storylines, taking into account the availability and dissemination of relevant knowledge on emissions and climate change, institutional, legal, and financial infrastructure to implement mitigation policies and measures, policies for generating innovation, and adequate consumer mechanisms.

[44]Emissions inventories are developed not only for future scenarios, but also for the past. Inventories for IPCC range from the year 1860 to 2100. Emissions inventories covering the past are provided, for instance, by the Global Emissions Inventory Activity (GEIA) project (GEIA 2010).

2.5.4 Model Evaluation and Intercomparison

The difference between probability and plausibility, or between short-term prediction (decadal forecasts) and long-term projection (scenario simulation) refers not only to different types of uncertainty (statistical vs. scenario uncertainty), it also refers to different practices of evaluation. While it is rather difficult to assess the output of scenario simulations (mostly 'to-be-avoided projections'), it is common scientific practice to evaluate short-term predictions. However, confidence in the plausibility and possibility of future scenarios inevitably requires confidence in short-term predictions and in the underlying model. As models are only as good as the quality of their inputs and representations of processes, evaluation methods have been developed that establish confidence in modelling the climate system as a whole as well as in its sub-processes. Models are evaluated in data test-beds, which provide a measurement-based link between the quantities of model-input and model-output. Model biases include coding errors, inadequate numerical methods, imperfect or lacking process understanding, parameter uncertainties, and simplifications. To quantify a model's performance and to measure its improvements, metrics and score ranking methods have been developed. In the framework of internationally organized model intercomparisons, evaluation has been standardized over recent decades (see also Sect. 2.4).

The literature about climate models often uses terms like 'evaluation', 'validation', and 'verification' in an exchangeable way, but this is misleading. While the term 'evaluation' refers to the investigation of the adequacy of a model for a specific purpose, the concept of 'validation' is related to aspects of mathematics and coding. The model must be consistent and logic, the methods have to be applied correctly, meaning that no coding errors, inadequate numerical methods, or similar faults are allowed. Sometimes the term 'verification' is used. This term is misleading as complex systems are impossible to verify—they cannot be proven to be true—because knowledge about complex systems is always incomplete and observational data are not sufficient (Oreskes et al. 1994). The reason for this is the nature of models based on inductive reasoning. Inductive reasoning infers generalizations from a limited number of observations. Some of these generalizations are fundamental; others are valid only within a specific range. Scientists observe nature, try to understand how some phenomena work, and formulate a model that is able to predict the behaviour of a phenomenon in the future. The model is accepted to be true as long as a phenomenon follows the set of rules laid out in the model. In principle, if there is one observation showing that the model failed to predict future behaviour, it is proven to be incorrect. However, the falsification of complex models is not feasible because the multitude of variables whose temporal evolution is predicted can never match the observations exactly. Thus, general statements about the correctness or incorrectness of a model are not possible.

Therefore the only criterion for the quality of a model is that it agrees with observations and measurements to some extent. As knowledge about the climate comes from observations and theoretical considerations, climate models are a composite of both fundamental physics and semi-empirical approaches. The quality of climate models depends directly on knowledge about and the quality of the representation of the physical processes, many of which are not explicitly resolved or are poorly constrained by observations, but play a key role in the Earth system. For confidence in model projections, a profound understanding of the processes as well as an understanding of the behaviour of the climate as a system is required. Therefore, in order to assess model's performance not only the processes treated in climate models have to be tested (component level), but also the system's behaviour (system level), through simulations of past and present climate states and by comparing the results with observational data. Evaluation on the component level is based on isolating components and testing them independent of the complete model. Evaluation should unveil model biases, e.g., coding errors, inadequate numerical methods, imperfect or lacking process understanding, parameter uncertainties, and simplifications. Moreover, climate models undergo permanent development to enhance their temporal and spatial resolution with increasing computer capacity, or to add new, hitherto neglected processes, or to improve parameterizations by using better physically-based approaches and new observational data. Whenever a simulation is repeated by a new model version, the results will be different. Although the differences may be minor, the results of a model will never match the parameter values describing the system's behaviour exactly.

Nevertheless, the performance of a model is evaluated by comparing model results with observational data on past and present climate states. Whereas in the early times of climate modelling results were compared to field measurements, or meteorological fields analyzed by mere visual inspection and qualified subjectively by statements like 'good agreement', in the mean time statistical methods have been applied to assess the degree of agreement between model and observation in a more objective way. Performance metrics have been developed to measure the skill of climate models and to establish a set of standard metrics to measure the strengths and weaknesses of a given model. Of course, the choice of specific metrics is based on subjective decisions and has some influence on the model's ranking. A common method used to analyze whether two data sets are different is Student's *t*-test, comprised of the ratio of the signal to noise in the respective variables (Mearns 1997). The method tests whether two data sets are really different, and is used to decide whether model results differ significantly from observations or whether the differences are arbitrary. The method is also applied to compare the climates of two periods, e.g., pre-industrial and present-day, and to test whether they are significantly different.

Performance metrics are used to evaluate a model on the system level and on the component level. The ability of models to reproduce both a specific climate state and climate change anomalies are evaluated by comparing model output to observation—based on comparing either gridded model output with assimilated variables, or interpolated model output with field observations and remote sensing data. Models are tested for their ability to reproduce the present-day climate (nowcast) and to simulate the evolution of different climate states forced by changes in boundary conditions, for instance greenhouse gas concentrations. Models are also tested to predict past climates (hindcast). Furthermore, hindcasts of the recent past are performed to evaluate short-term processes taking place on timescales for which sufficient observations are available (the last 50 years), e.g., extreme value statistics. Characteristic output variables calculated by extreme value statistics include the length of dry spells (days with less than 0.1 mm precipitation), the annual maximum 5-day precipitation amount, the number of frost days or tropical days (maximum temperature higher than 30°C per year), and so on. As modern society is particularly susceptible to extreme events, like, for instance, hurricane Katrina in 2005 and the heat wave in Central Europe in 2003, changes in regional extreme values of temperature and precipitation are key for any adaptation measures. There is concern that extreme events may change in frequency and intensity in a warmer climate. However, predictions of extreme values vary substantially between the models, and uncertainties are significantly higher than for average values. Long-term experience with model evaluation has shown that the quality of the model is different for different variables. For instance, calculated temperature values are more reliable than those for precipitation, and confidence in average values is higher than in extreme values. Models simulate the temperature extremes, especially the warm extremes, reasonably well, but have serious deficiencies in simulating precipitation extremes.

On the component level, parameterization schemes are tested in isolation in box-models or column-models, and compared to in-situ measurements to study the behaviour of the scheme. In a further step, the scheme is tested in the framework of the whole system, e.g., within an atmosphere model, by switching the new scheme on and off. Finally the full climate system model is integrated. A fundamental problem in evaluating small-scale features and processes is the problem of scale. In-situ measurements take a value representative of a specific time period and location. But since measurements do not usually represent the scales of model grid-boxes, to make use of measurements for evaluation purposes the data must be upscaled or the model output downscaled. Upscaling measurements requires a profound understanding of how processes act on different temporal and spatial scales and is a non-trivial problem.

Vice versa, downscaling from general circulation models to regional effects also involves fundamental problems. Climate change on a regional scale is analyzed by applying Regional Climate Models (RCMs) of higher spatial resolution, which are driven by global model output or by observed meteorology. Model skills vary with region and season. Thus, no general statements about regional climate model performance can be made. For instance, although RCMs capture the geographical variation of temperature and precipitation for Europe better than global models, they tend to simulate conditions that are too dry and warm in southeastern Europe in summer. “Most but not all RCMs also overestimate the interannual variability of summer temperatures in southern and central Europe” (IPCC 2007a, p. 873). These regional biases between model simulation and observation are difficult to assess. E.g., the seasonal mean temperature bias in the northern Europe region varies between different models from –5°C to 3°C, and that in the southern Europe and Mediterranean region varies from –5°C to 6°C. The cold bias in northern Europe tends to increase towards the northeast, reaching –7°C in the northeast of European Russia in winter. The bias varies from model to model and from season to season, and is more substantial in some regions and in some models than in others. Nevertheless, if climate change simulations, which are differences between two simulations (one representing present-day conditions, one future conditions) are analyzed, the relative bias of the difference might be smaller than the absolute bias. This could be because the model bias is about the same in the two simulations, such that it disappears when the difference is calculated. However, the assumption that model biases are independent of the state of climate is speculative, because it is not clear how the biases in the model simulating present-day climate will develop in future scenarios.

To analyze the causes of disagreement between model and observations, and to assess the effects of different model approaches, model intercomparisons have been developed over the last decades. Within the framework of the IPCC assessments the Program for Climate Model Diagnosis and Intercomparison (PCMDI) was established in 1989 at the Lawrence Livermore National Laboratory in the US. Its aim is to support the assessments and to develop tools for evaluating climate models. PCMDI activities focus on model intercomparisons and the development of test-beds.[45] PCMDI provides facilities for the storage and distribution of terascale data sets from multiple coupled ocean–atmosphere GCM simulations of the present-day climate as well as climate change simulations. Model output from a large variety of models and experiments is collected, processed and distributed by PCMDI to the international community to facilitate comparisons to data and tests for consistency. However, not only the results of the simulations but also the model codes are made publicly available. The degree of standardization and transparency of the evaluation procedure of numerical climate models is unique in science.

An example of model intercomparison is given by Thomas Reichler and Jinsun Kim (Reichler and Kim 2008). Reichler and Kim raised the question as to how well coupled models simulate today's climate. They designed a measure to estimate model skills. First they calculated multiyear annual mean climatologies (1979–1999) from gridded fields of global models and observations. The database contains 14 variables including air temperature, air pressure, sea surface temperature and seawater salinity. Next, they calculated for each model and variable a normalized error variance by squaring the differences between simulated and observed climate at every grid-point, normalizing with the observed interannual

[45] Model comparisons are also performed to test the system behaviour and to assess the ability of climate models to simulate the trends of the recent past (1860–2000) and past climate states. Model intercomparisons performed by PCMDI are the Atmospheric Model Intercomparison Project (AMIP), the Coupled Model Intercomparison Project (CMIP), the Seasonal Prediction Model Intercomparison Project (SMIP), and the Paleoclimate Modeling Intercomparison Project (PMIP). In addition, more than 40 international model intercomparisons have been arranged by different institutions to test the behaviour of sub-models or of specific aspects of climate models, and a great number of publications has emerged from these intercomparisons (see also Sect. 2.4).

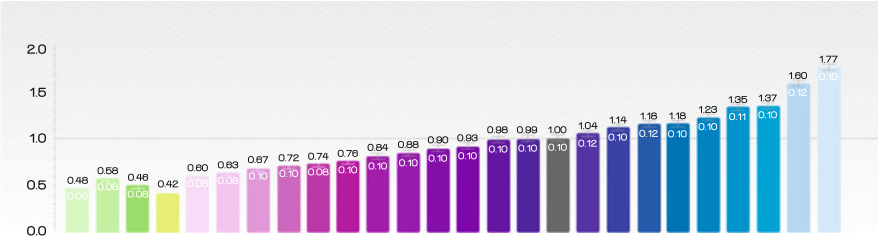

Fig. 2.6 Performance Index of 21 models Red rows denote models, the yellow row the model's median and green rows observations. Average PI is one, PIs smaller than one indicate better, PIs larger than one worse agreement
Source: Replotted by the authors from Thomas Reichler, personal communication 2006

variance on a grid-point basis, and averaging globally. A final model performance index (PI) was formed by taking the mean over all climate variables and normalizing it such that the average performing model has a PI of one. Figure 2.6 displays the performance index of the different models and a comparison to observational data not used in the comparison. Interestingly, the median model shows the best performance in all aspects.[46] The median model outperforms single models in almost all comparisons performed. This indicates that the model's errors are not biased, but well distributed around the observations. There is also no model that performs best in all aspects investigated. Interesting, for instance, is that the performance of a model to reproduce interannual variability is only weakly correlated with an index of mean climate performance (Gleckler et al. 2008). Thus a broad spectrum of climate processes and phenomena must be evaluated since the accurate simulation of one aspect of climate does not guarantee the accurate representation of other aspects. These findings suggest the use of multimodel and multiple model versions of median projections to advise policy, or the construction of a best model by weighting the various aspects of a multimodel ensemble according to their performance.

Another aspect of evaluation is model tuning. Climate models are tuned to achieve agreement with observations. The energy budget at the top of the atmosphere (TOA) controls the climate. Simulating these budgets correctly is a fundamental prerequisite for a realistic climate simulation. The budget includes the outgoing long-wave radiation and the solar radiation scattered back to space. In addition, satellite observations distinguish between clear-sky and cloudy-sky radiative budgets. Climate models are tuned to achieve agreement with the global and multiyear-averaged TOA radiative fluxes observed. Therefore the models are constrained to four parameters: the globally averaged outgoing long-wave radiation and the reflected short-wave radiation, for both clear-sky and cloudy-sky conditions. This means that parameter values are adjusted to generate good agreement with these four parameters. TOA fluxes are tuned to agree with satellite observations mainly via cloud parameters, as these are often

[46]The median is the value which separates the upper half of a sample from the lower half. Here the median is calculated for any variable at any grid-point.

poorly constrained by observations. This tuning has to be repeated whenever the model code is changed, but the same tuning parameters are then used for simulations of the past, present and future climates. To find the right parameters for model tuning requires long-term experience and skill in running climate models. However, an agreement between the model and the observations of these four global averaged energy fluxes does not guarantee a correct spatial and temporal distribution of the various variables simulated by climate models. This can only be achieved by solid physics in the model.

With regard to model tuning in particular, a discussion has erupted as to whether data from measurements should be considered more trustworthy than those from model simulations. As outlined above, models never accurately match parameter values, no matter how well they have been tuned. However, neither do observations ever match 'reality' accurately. As our perception of reality is filtered by our senses as well as by each measurement tool, our knowledge about the real world inherently must include errors and inaccuracies. Only specific aspects that can be observed and measured are covered. Various measurement platforms such as weather stations, buoys, radiosondes, satellites and rockets record data continuously. The national weather services and the World Meteorological Organization collect and distribute global weather data. But observations deliver only an image of the current situation. To learn about past climates, tree rings, ice-core data, sediments and other so-called 'proxy-data' are analyzed. However, all of these data sets and observation systems generally have deficiencies in at least one of the key requirements: accuracy, resolution, or spatial and temporal coverage (see Table 2.14).

Furthermore, most modern measurement techniques do not measure the variable of interest directly, but derive the variables indirectly using mathematical algorithms or models that interpret the measurements. This trend has increased in recent decades. For instance, the state of the atmosphere is analyzed twice daily. This is the basis of any weather forecast. Measurements are provided by balloon-driven instruments, so-called radiosondes, which measure the vertical profiles of temperature, humidity, pressure, and wind direction and velocity. Additionally, satellites measure the spectral-band intensity of radiation scattered back or emitted from the ground, from the atmosphere or from clouds. Complex mathematical algorithms interpret these reflectances and derive meteorological parameters such as surface temperature fields and wind fields. Varying a weather forecast model to optimize the state of the climate, so that it agrees best with the model results and the observations, assimilates data from satellites and radiosondes. Such assimilation techniques also include estimates of the uncertainties or inaccuracies of the model and the measurement methods. Data assimilation combines measurements with the physical principles governing numerical models. This kind of model is also called a 'data model'. Thus numerical models are evaluated by comparing the results of a 'data model' to 'model data'.

As modelling usually seeks associations—by using data as input during a model initialization, by relying on data to constrain processes in modelling, and by applying data for the evaluation of results—, these uses of measurements as references in modelling work only if the data are more accurate than the expected accuracy of the model. Unfortunately, each measurement has some uncertainty

Table 2.14

Typology of data uncertainty for cloud and aerosol measurements	
All data are samples	The spatial and temporal coverage is incomplete and there are often justified representation concerns for application to any other instance or location (e.g. local pollution or orography issues).
All data are as good as the instrumental capabilities	Space sensor examples include sensor degradation and pixel sizes that cannot resolve smaller-scale features. Or the in-situ sampling of atmospheric particles has to deal with artefacts of the measurement environment (e.g. particle break-up before sampling or water removal during analysis at warmer temperatures).
Many so-called data are model results	Models are often needed to translate a measured property into a 'useful product'. These models are based on simplifying algorithms and often need to apply a-priori assumptions to parameters and properties, which have a large impact on the resulting data. Good examples include the assumptions needed to calculate solar surface albedo and aerosol absorption in satellite measurements of aerosol traces based on perceived reflections of visible light.

Source: Stephan Kinne, personal communication 2008[47]

and advertised uncertainties are often smaller than the real ones. These real uncertainties can be so large that their use would not only fail to benefit modelling efforts, but could actually harm them. Moreover, some interactions between different variables and climate system compounds, and humans' impact on climate, although key to understanding the system's behaviour, cannot be observed, but only investigated by numerical models, like climate sensitivity. Results from this kind of model cannot be proven in principle, because observed climate changes are the result of a constellation of different forcings and the actual state of the climate.

2.6 Scientific Arguments for Socio-Political Decisions

Climate is change. It required more than 150 years of scientific work to establish this view against the traditional idea of 'klimata' as stable and static. The discovery of Ice Ages and the increasing awareness of the radiative imbalance of the

[47]This classification was provided by the climate modeller and satellite data expert Stephan Kinne in a personal communication in 2008. He emphasized that accuracy is not an abstract problem. The accuracy necessarily depends on the problem investigated. Sometimes large uncertainty is acceptable, if qualitative pattern information is needed. Nonetheless, quantifying real uncertainty is extremely important. Modelling is better served by data on the real uncertainty range than averages. Close collaborations among data-groups as well as between data-groups and modelling-groups are needed to provide more accurate products, to establish the real uncertainties and to help prevent the misuse and misinterpretation of data.

atmosphere—widely discussed as the greenhouse effect—tremendously altered the idea of climate as well as the questions posed on this emerging concept of change. If climate is change, the relationship between climate and humans has to be taken into account. As long as climate is connected to stability, neither climate change nor human influence occur as relevant thoughts. But once mankind has become aware that climate is change, these changes are interpreted as causes of the rise and fall of civilizations as unearthed by archaeologists, as reasons for economic disasters, and as sources for improving or worsening people's life environment. Climate as change inextricably interconnects the idea of climate with mankind's cultural, social, and economic interests and, not surprisingly, leads to the awareness of the human influence on climate—exerted by six billion individuals.[48] Today's debates on anthropogenic climate change are reflecting this underlying basic shift that the idea of climate has undergone. This shift comes along with two major problems.

The first problem is that this awareness of the climate-man interconnection is not based on direct perception of causal interdependencies between mankind and a natural phenomenon. It is based on a statistical outcome called climate and usually defined as the averaged weather, or more narrowly as the globally averaged surface air temperature, over a period of at least 30 years—to follow the definition of the World Meteorological Society (WMO). In other words: Climate can not be experienced and directly measured in the way we perceive weather phenomena like rain, heat, and wind. What we 'experience' is the flickering of a curve with an averaged tendency towards higher globally averaged temperatures. Thus, the relatively new branch of climate change science and policy deals with an abstract, statistical phenomenon, which has to be retranslated into local and actual events. It also has to manage the difficult business of considering the change of change—the anthropogenic change of natural climate change.

The second problem is the need for reliable statements on future developments. It is no surprise that climate change and policy draw on the idea of projecting possible future changes of climate change in order to prevent them. But to prevent change from change and to project future scenarios are challenging tasks. For both tasks climate models are imperative scientific instruments. First, because only models allow the various reasons for climate change to be differentiated through the study of alternative scenarios and complex interdependencies. Second, because only models allow past and present information on climate change to be extrapolated into the future. Neither measurement nor experiments can do so. Therefore climate models constitute the basis for establishing how climate change science and policy are related. The problem thereby is that these scenarios are accompanied by vast uncertainties, and these uncertainties complicate the decision-making needed to shape socio-economical developments.

[48] Wolfgang Lucht and Rajendra K. Pachauri refer to mankind's impact as the 'mental component of the Earth system' and an "uncontrolled coevolution of the mental, physical, and biological spheres [that] has increased over the last decades" (Lucht and Pachauri 2004, p. 343).

The question of what to do is therefore answered differently by different communities and individuals, and these answers have only partly to do with scientific arguments and simulated scenarios. As Mike Hulme showed in his study *Why We Disagree about Climate Change*, people's opinions concerning climate change depend on various 'myths of Nature', which assume nature to be 'capricious', 'tolerant', 'benign', or 'ephemeral' (Hulme 2009, p. 182 et seq.).[49] The capricious view understands climate as human-independent and fundamentally unpredictable, while the ephemeral view sees climate in a precarious and delicate state of balance. The benign view assesses climate as favourably inclined towards mankind, while the tolerant view understands climate as to some degree uncontrollable but resilient if suitably managed.[50] According to Hulme, these beliefs play an important role in peoples' attitude towards climate change, besides objective risk analysis, climate prediction, and expert judgment. The interesting aspect here is that all of these views reflect and one-sidedly over-interpret certain aspects of the behaviour of the climate system: its chaotic nature as capricious as well as ephemeral; its complex response as, hopefully, benign or at least tolerant. These beliefs dominate not only everyday philosophy on climate change, but also various scientific debates on and against climate change.

However, these opinions will not help in framing an appropriate response to climate change. One possible response is 'stability scenarios', which advertise the '2°C target'. The idea is to take efforts to limit the increase in global mean temperature to below 2°C during this century by halving CO_2 emissions by 2050 compared to 1990 (Meinshausen et al. 2009; Allen et al. 2009b; Washington et al. 2009; see also Chap. 4 of this volume and Table 2.15). Interestingly, the 2°C increase has been a robust result since the very first numerical experiments. Model-based computations deliver robust results for the low range of temperature increases, while they differ for high ranges. Therefore, it seems plausible to try to manage activities in order to have a fair chance to reach this target, although the 2°C target has been questioned by economists as infeasible, too expensive, and inappropriate (Randalls 2010), as it requires stabilization at 450 ppm CO_2-equivalent in the long term (ECF and PIK 2004; Graßl et al., 2003; Schellnhuber et al. 2006). However, the 2°C target based on robust results might be a better choice than a strategy that consists of a 'predict then act' paradigm, like the ones cost-benefit-analyses rely on in order to conceive optimal strategies. Such a paradigm could cost valuable time and money, especially since the range of 'optimal targets' varies in each study along with differences in value judgments and uncertainties about the costs of mitigation and damage (Hof et al. 2008).[51] For instance, William D. Nordhaus suggests an

[49]Mike Hulme refers here to Mary Douglas' and Aaron Wildavsky's cultures of risk (Douglas and Wildavsky 1982).

[50]Perhaps the 'tolerant view' can be compared to the UNFCCC's 'precautionary principle', which advocates that it is better to be safe than sorry and therefore advises the reduction of carbon dioxide emissions "that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Article 2).

[51]Andries F. Hof et al. studied the vast uncertainties and critical assumptions involved in cost-benefit analysis and conclude that the 'optimal targets', which range from 520 to 800 ppmv, are

Table 2.15

Information on carbon dioxide	
Pre-industrial	About 280 ppm by volume (ppmv)
2005	379 ppm, leading to a radiative forcing of +1.66 Wm^{-2} [±0.17]
2010	Approximately 390 ppmv
Doubled	560 ppmv (Basic assumption for climate sensitivity simulations, which causes a radiative forcing of 3.7 Wm^{-2} and could lead to an increase in mean global temperature of approximately 3°C [±1])[a]
2° target	Stabilization scenarios of about 450 ppmv CO_2-equivalent in the long term.
1995–2005	Growth rate of CO_2 in the atmosphere was 1.9 ppm $year^{-1}$ and CO_2 radiative forcing increased by 20%.

[a]"Without any feedbacks, a doubling of CO_2 (which amounts to a forcing of 3.7 Wm^{-2}) would result in 1°C global warming, which is easy to calculate and is undisputed. The remaining uncertainty is due entirely to feedbacks in the system, namely, the water vapor feedback, the ice-albedo feedback, the cloud feedback, and the lapse rate feedback. [. . .] Current state-of-the-art climate models span a range of 2.6–4.1°C, most clustering around 3°C" (Rahmstorf 2008, p. 38).
Sources: Rahmstorf 2008; IPCC 2007a, Chap. 2; Schellnhuber et al. 2006

economically optimal 800–850 ppm CO_2-equivalent that would result in a 3.4°C temperature increase; others suggest a 650 ppm CO_2-equivalent (Nordhaus 2007; Tol 2002). The Stern Report favours a cost-benefit analysis which advises stabilizing greenhouse gas emissions at about 450–550 ppm CO_2-equivalent (Stern 2007). "It is one of the few cost-benefit analyses on climate change that favours early emission reductions" (Hof et al. 2008, p. 412). In contrast to those 'optimal strategies',[52] practical strategies based on stability scenarios like the 2°C target could be a better practice for decision-making under uncertainty, as it offers a political anchor for mitigation policy—especially if it is translated into a 'lower than 550 ppmv' or more specifically a '450 ppmv' target.

Another possible practice is risk assessment to identify critical thresholds in natural and social systems. But identifying and predicting such thresholds is extremely difficult (Groffman et al. 2006). Even small changes, e.g., in temperature, can induce threshold changes, and these threshold changes can come suddenly and unforeseeably (Hare and Mantua 2000; Allen 2007).

> "Thresholds pose perhaps the greatest challenge currently facing climate change scientists. There is clear evidence that climate change has the potential to increase threshold changes in a wide range of ecosystems, but the basic and practical science necessary to predict and manage these changes is not well developed. [. . .] In addition, climate change interacts with other natural processes to produce threshold changes" (Fagre and Charles 2009, p. 11).

Furthermore, disturbance mechanisms that shape the environment, e.g., fires, can themselves be altered by climate change. Facing events caused by abrupt

caused by differences in value judgments and uncertainties about the cost of mitigation and damage (Hof et al. 2008).

[52]Optimal for whom? The problem is that some regions are more vulnerable to global climate change than others.

threshold changes certainly belongs to the worst-case scenarios of climate change, dramatic enough for even Hollywood screenplays. Whether abrupt events will increase beyond the 2° limit—some literature refers to an increase of more than 2° as 'dangerous'—can not be assessed, but it seems plausible that an increase of 4° will cause more changes than 2° or 1° as we fuel the 'air mass circulation engine', called climate, with more energy.

As the EMF22 International Scenarios, based on ten integrated assessment models, have recently shown, on the one hand,

> "stabilizing the global climate will require a very different world than the one we live in today"; on the other, "regardless of the target, the global costs of achieving any long term climate-related target will be higher without comprehensive action, and they may be higher not just for the initial entrants but also for those that join along the way" (Clarke et al. 2009, p. S80).

In a way climate change science and policy seems to be trapped between Scylla and Charybdis. Avoiding climate change entails approaching the danger of economic calamity, and vice versa. This is not entirely true, as recent studies have shown that the 2°C target might cost on the order of 1% of Gross Domestic Product (see also Chap. 4 of this volume). However, if mankind is unable to decide how to frame an appropriate response to climate change, nature will decide for both—environmental and economic calamities—as the economy is inextricably interconnected with the climate.

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