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Climate, climate change

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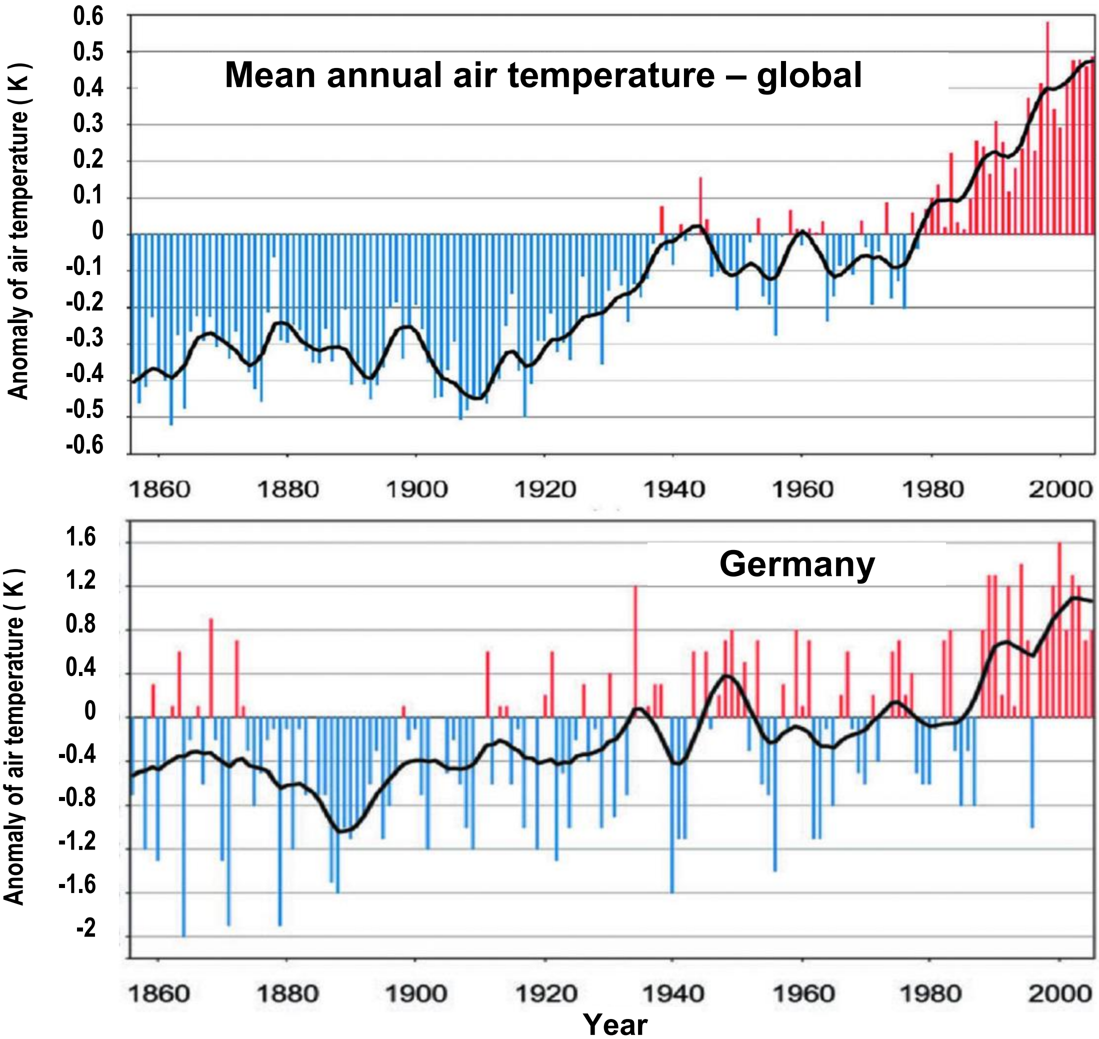
Contents

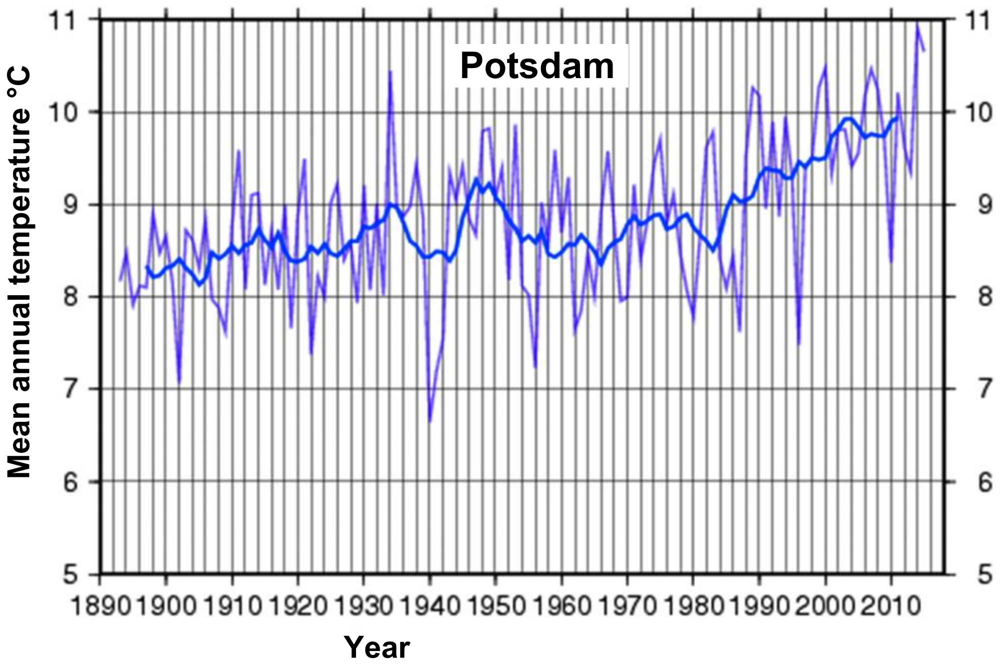
The global climate is currently changing, primarily due to anthropogenic greenhouse gases. There are many other factors which play a role in climate, starting with the sun's radiation. Climate during the past ice ages was highly variable; by contrast it has been relatively stable over the past 10,000 years. Different scenarios and climate models are used to determine how climate might develop in the future.

1 The earth's climate

The global climate determines living conditions on earth. These can vary hugely depending on geographical position and are characterised by their respective climate parameters. What humans experience as climate in their sphere of life are the daily and seasonal characteristics in the form of weather phenomena determined by the climate in their ▷ *Region*, city (▷ *City, town*) or ▷ *Landscape*. These respective mesoclimates and microclimates differ from the global, large-scale macroclimate, as shown in Figure 1 for temperature.

Figure 1: Development of the global mean annual temperature (top) and, by comparison, in Germany (middle) from 1856 to 2005. Temperature variations are shown here in relation to the reference period 1961 to 1990. Below, the trend of the local mean annual temperature for Potsdam between 1893 and 2015 is shown for comparison purposes.





Source: The authors, based on Gerstengarbe/Werner 2007: 34 (top), 39 (middle) and PIK-Klimadaten 2016 (bottom)

1.1 Climate parameters

The climate at a geographical location or at several locations within a contiguous region is described by climate parameters, which characterise the entirety of the weather phenomena in the atmosphere over an extended period. These climate parameters include, for example, *mean annual temperature, the lowest and highest recorded temperature, average daily minimum temperature of the coldest months* or *daily maximum temperature of warmest months* and the *mean daily temperature fluctuation*. Other parameters relating to rainfall, clouds, humidity, sunshine and wind speed also characterise the climate. Meteorology has traditionally viewed climate as the statistical description of weather over a sufficiently long period of months to thousands or millions of years. The typical period (standard reference period) as defined by the World Meteorological Organisation (WMO) is 30 years; the last full standard reference period was 1961 to 1990 (cf. ARL 2013). Figure 1 shows the development of the climate parameter *mean annual air temperature at the earth's surface* over a period of more than 100 years for three different spatial references: globally, regionally for Germany and locally for Potsdam (Gerstengarbe/Werner 2007). The three temperature profiles vary, but all show an increase from around 1970, an indication of the current climate change. If we want to understand these or even earlier climate changes in the earth's history, we need to look at other climate elements as well as the atmosphere.

1.2 Climate and weather

Weather can be experienced every day; we experience heat or cold and thus what temperature means. In the same way we become familiar with other short-term atmospheric conditions, such as wind, precipitation as rain, snow or hail, as well as sunshine and clouds. We also know whether a currently prevailing weather situation is typical of the region and season or more exceptional or even extreme. We usually lack experience of more spatially remote weather situations or weather situations further back in time and are reliant on observational data and the experience of others. This is particularly true of climate: even though it also refers to temperature, rainfall and sunshine duration, these parameters do not cover conditions that are experienced with the senses, but rather calculated, abstract variables, such as the mean annual temperature illustrated in the charts. This even applies to the local temperature profile, which is aggregated from many daily measurements at a location, and all the more so to aggregated results calculated regionally or globally from the measurements at many locations.

1.3 Macroclimate and climate zones

The earth's macroclimate can be divided into climate zones according to different criteria, based on large-scale circulation in the atmosphere or the links between vegetation and climate parameters, for example. Classifications based on threshold values of temperature and rainfall and which take into account the seasonal fluctuations of these parameters are widely used. The earth's climate zones determined in this way correspond to various types of ecosystem (▷ *Ecology*) with different flora and fauna as well as various types of weather event. The earth's regions vary considerably, and specific weather phenomena with different seasonal cycles can be observed within them, for example winter storms in Europe or tropical hurricanes in warmer regions. Thunderstorms, torrential rainfall events, dry and rainy seasons, monsoon and trade winds vary in strength and frequency from region to region. The earth's global climate includes all of these different weather phenomena in their geographical and seasonal variability. In the case of the current climate change, however, clear spatial and qualitative changes in the climate zones as well as the associated weather events can already be seen (cf. Gerstengarbe/Werner 2007).

1.4 Mesoclimate and microclimate of region, country and city

Below the spatial dimension of the macroclimate, the mesoclimate of a city or landscape depends on its orology (the relief of the land) and its height above sea level. It is also influenced by the nature and size of adjacent waters as well as settlement structures or patterns of use (e.g. ▷ *Agriculture* and ▷ *Forestry*). Factors influencing the climate include airstreams, radiation properties of the surfaces (also called albedo) as well as water storage capacity, humidity and evaporation/ evapotranspiration of the vegetation. The small-scale exchange of heat, energy, water and other substances between the soil, plants and ground-level air layers are part of the microclimate.

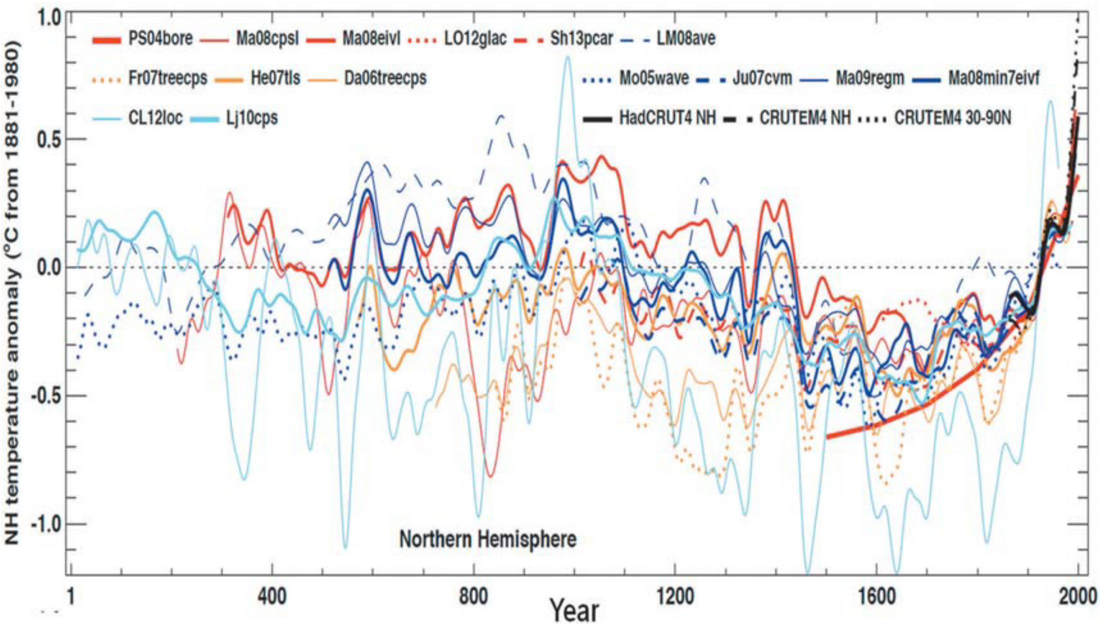
The close relationships between ecology and climate can be observed, for example, in the differences between spatially adjacent urban and rural climates. In cities, building development results in an urban climate, which is usually warmer than that of the surrounding area, because of radiation-related heating, waste heat and emissions from air pollutants as well as impeded air exchange. By contrast, temperature conditions are usually cooler in open spaces than in urban areas because of air and radiation exchange, whereas forests in particular tend to feature more moderate temperature conditions compared to the surrounding open space. The shelter of the canopy reduces insolation and terrestrial radiation on the forest floor, and it is cooler during the day and in summer and warmer at night and in winter. The tropical rain forest is one particular example of the climate function of ecosystems. Forest ecosystems store water in the ground, which evaporates predominantly in the heat of the day, with the trees emitting more organic substances into the air, which serve as condensation nucleii (cf. Pöschl/Martin/Sinha et al. 2010). Besides the cooling effect, the evaporation also helps cloud formation, thus reducing harmful heating up from the high midday insolation, and the rain poured out of the clouds returns the evaporated water. With these types of process, ecosystems perform important regulation functions in the climate system. The ever-humid regional rain forest climate is vanishing following large-scale deforestation and is being replaced with a desert climate, with the water cycle in particular being disrupted in addition to the altered radiation conditions. It is worth noting that in order to understand climate, the biosphere with its vegetation and regulatory function plays an important role as well as the atmosphere.

2 Climate as a changing system

2.1 Reconstruction of early climate changes

Climate research has made significant progress over the past two decades in developing an understanding of early climate changes and the climate system. ‘Climate proxies’ are used to reconstruct the climate of the past, before any instrument-based recording existed. Climate proxies are indirect indicators of climate, which can be found in natural archives such as tree rings, stalagmites, ice cores, corals, lake or ocean sediments, pollens or in human archives such as historical records or journals. Climate proxies usually have to be calibrated using instruments in order to obtain quantitative data of past climate conditions, such as temperatures, composition of the atmosphere, insolation, etc.Figure 2 shows temperature reconstructions from the last 2000 years in the northern hemisphere from a range of climate proxy data (Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013). The various curves describe different regional climatic conditions. The data proves that nowadays it is generally warmer than during the Medieval Warm Period. Nonetheless, there are still claims to the contrary in non-scientific publications. Historical documents contain a plethora of information on the effects of climate changes on civilisation with regard to the climate change from the Medieval Warm Period to the Little Ice Age (Glaser 2001).

Figure 2: Reconstruction of regional temperature changes in the northern hemisphere over the past 2000 years. The different coloured lines represent various regions and data sources.



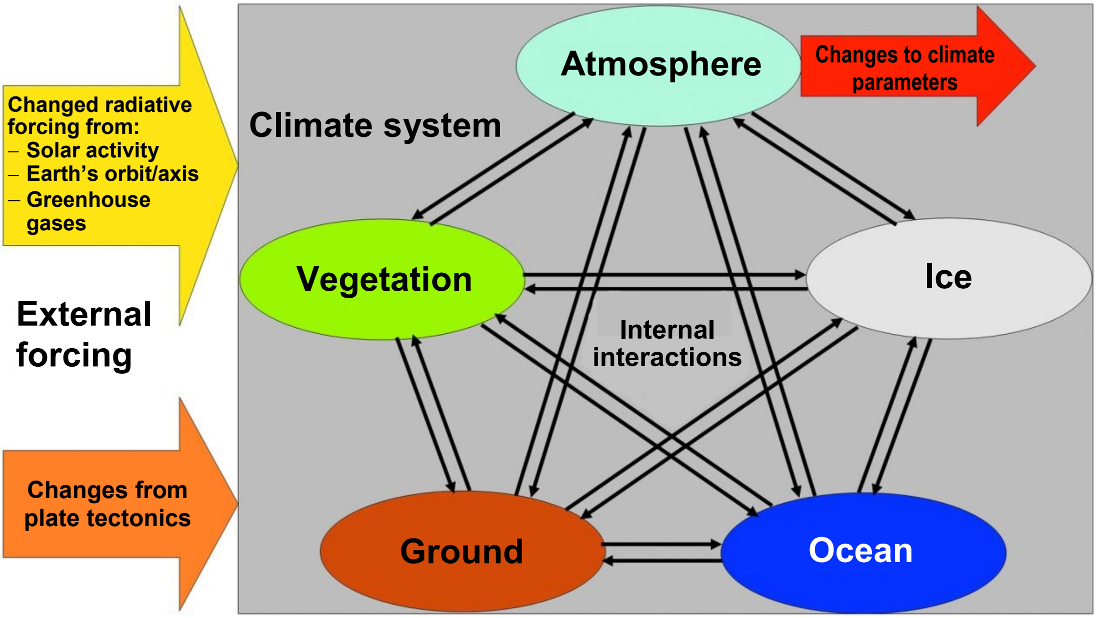
Source: Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013: 409

Climate models play a significant role in helping us understand the causes of and relationship between changes in the global or regional climate. These models contain growing knowledge about the earth's climate system.

2.2 Elements of the climate system

The global climate system, as outlined in Figure 3, includes the atmosphere with wind, weather, clouds and greenhouse gases, insolation, the hydrosphere with the oceans, the lithosphere with continents, mountains and volcanoes, the cryosphere with glaciers, sea ice cover and the vast ice masses on Greenland and in the Antarctic as well as, as already mentioned, vegetation and animal communities in the biosphere with cultivated and uncultivated ecosystems. Energy, information and substances are exchanged between the components of this complex climate system – they interact with each other. In the process, the radiation properties of the earth's surface or the composition of the earth's atmosphere and the climate above it, for example, change. Living organisms and ecosystems are therefore not just climate indicators, they are also actors in the climate system. As a result, the net radiation – and thus the influence on the climate – change depending on how much of the earth's surface is covered with ice, forest, steppe or desert or because of clouding.

Figure 3: Elements of the earth's climate system. Internal interactions between these result in non-linear responses of the climate system to external influences such as insolation or changes in the amount of greenhouse gases in the atmosphere.



Source: The author, based on Stock 2013: 19

2.3 Astronomical climate factors

The main radiative forcing is the radiation of the sun that reaches the earth. It is responsible for the climate conditions that make life on earth with flowing water possible. However, insolation changes over time. Firstly, the activity and luminosity of the sun itself varies, for example in a roughly 11-year sunspot cycle. The number of sunspots is an indicator of the sun's activity: the more sunspots and thus energy conversion, the greater the radiation of the sun. Secondly, insolation on earth changes as the earth's orbit around the sun (eccentricity), the tilt of the earth's axis (obliquity or skew) as well as its pendular movement (precession) change. These orbital parameters have different cyclical variations, known as Milanković cycles, of which the 100,000-year cycle is currently having by far the greatest influence on the climate. The changes are key to explaining the climate changes in the ice ages (Berger/Loutre 1991). Climate models play a significant role in helping us understand these relationships. Figure 4 from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) shows the reconstruction of the earth's climate data from the past 800,000 years (Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013). The changes over time of nine parameters in the lines (a) to (i) represent the earth's orbital forcing and the proxy data; the coloured areas represent simulation results with several climate models, for example the CLIMate and BiosphERe model, CLIMBER-2 (Ganopolski/Calov 2011). The models are forced by the change to the orbital parameters and the atmospheric concentration of the effective greenhouse gases. Figure 4 above shows:

a) eccentricity,

b) obliquity and

c) precession.

We even know the future changes of these astronomical parameters. Figure 4 below shows the reconstructed responses of the climate system to these changes (Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013).

d) The atmospheric concentration of CO_2 greenhouse gas from ice cores of the Antarctic (calculated e.g. by Lüthi/Le Floch/Bereiter et al. 2008)

e) The temperature of the ocean surface in the tropics (Herbert/Peterson/Lawrence et al. 2010)

f) The temperature in the Antarctic based on up to seven ice cores, calculated as part of the European Project for Ice Coring in Antarctica (EPICA) (Oerter 2006)

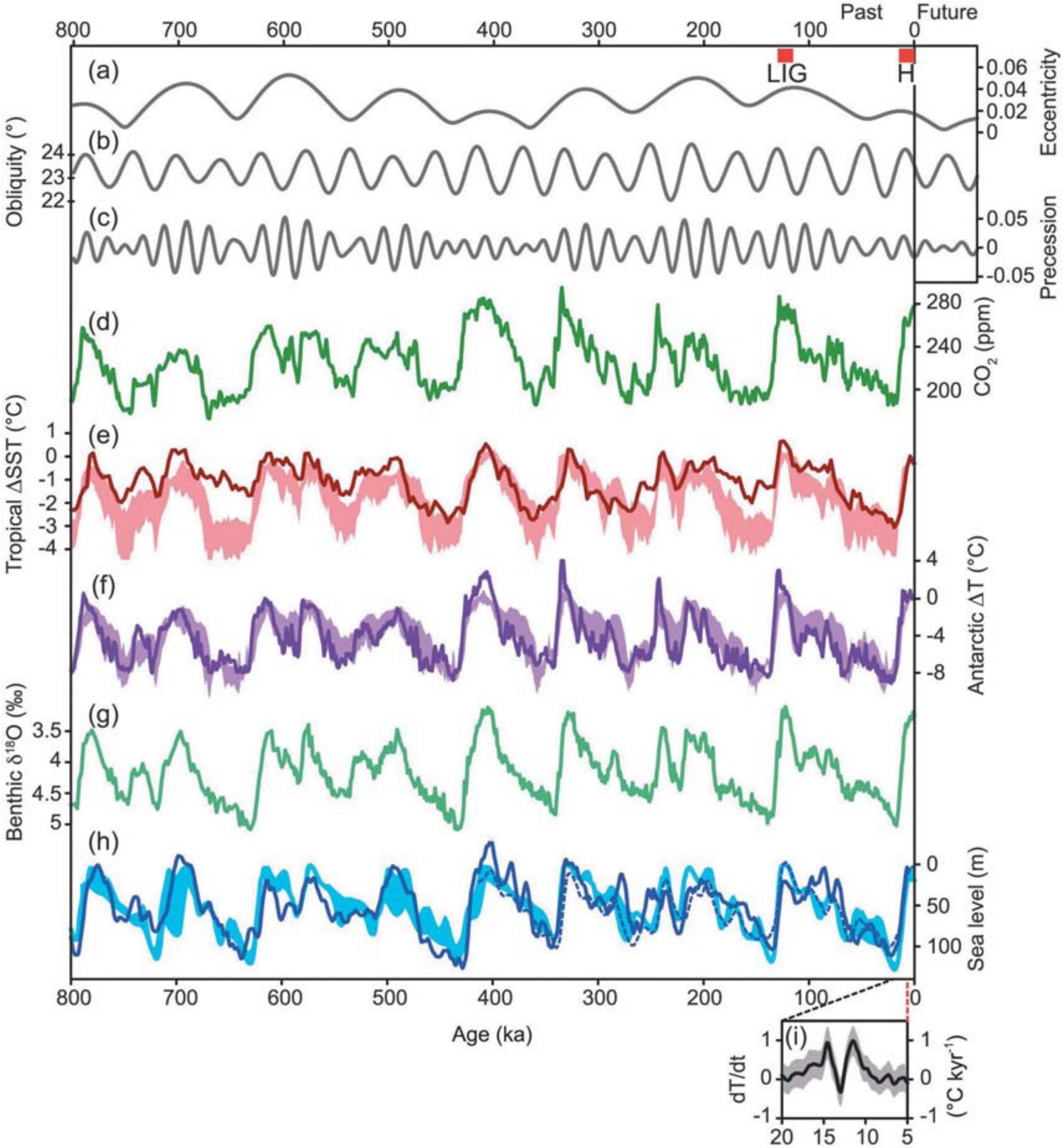
g) Reconstruction of temperatures in the deep sea from 57 sediment samples taken from across the globe using the 18O fraction in calcite shells of benthic organisms, as well as a proxy for the global volume of ice (Lisiecki/Raymo 2005)

h) Reconstruction of the sea level, dashed line: (Rohling/Braun/Grant et al. 2010); continuous line: (Elderfield/Ferretti/Greaves et al. 2012)

i) The small diagram at the bottom of Figure 4 shows the relative, sometimes rapid, temperature changes at the end of the last ice age (Shakun/Clark/He et al. 2012).

The transitions from phases of widespread glaciation to interglacial warm periods happened within a few thousand years. The process was probably triggered by the thawing of frozen surfaces, which resulted in rapid warming because of the reduced albedo, followed by slower intensification from the rise in greenhouse gases. Compared to the ups and downs of the climate in the ice ages, the past 10,000 years – the Holocene (H) – have been relatively stable, similar to the last warm interglacial period around 120,000 years ago (LIG).

Figure 4: Reconstruction of orbital parameters and the earth's climate data from the past 800,000 years

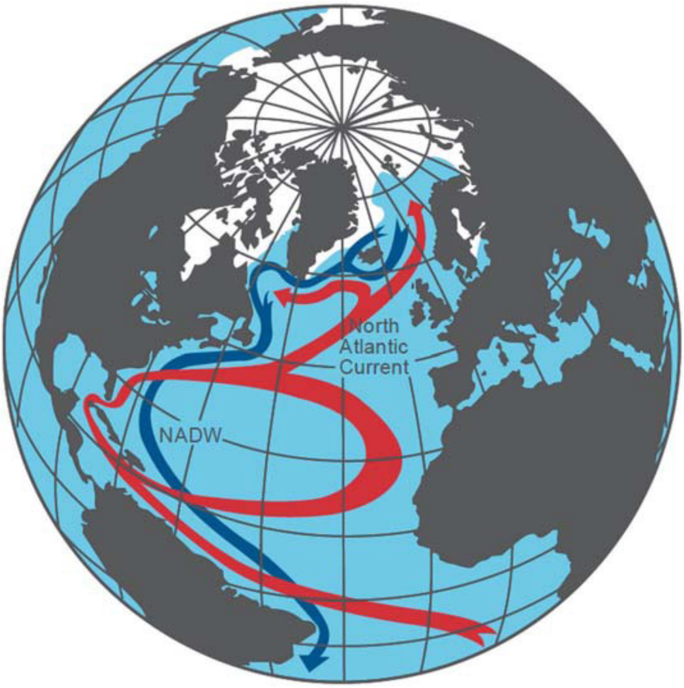


Source: Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013: 400

2.4 Geological climate factors

In terms of geology, very long-term changes, such as the shift of the continental plates and the distribution between continents and oceans, affect the climate, as do relatively short-term factors, for example volcanic eruptions or changes to the ocean currents, such as during El Niño and La Niña events in the Pacific. The vast bands of warm surface currents (red) and cold deep water currents (blue) in the oceans shown in Figure 5 as an extract for the Atlantic ensure an effective heat exchange between the hot equatorial zones and colder regions.

Figure 5: Vast bands of currents of warm surface water (red) and cold deep water (blue) in the Atlantic



Source: Rahmstorf 1997: 825

Thanks to the North Atlantic Current as an extension of the Gulf Stream, Europe enjoys a much more favourable climate, which is ideal for arable farming, compared to Alaska. The occurrence of warm and cold periods during the ice ages shown above in Figure 4 can be explained by the response of these ocean currents to variations in insolation. The current is forced by the difference in density between the salty warm water of the surface current and the low-salt, cold meltwaters around Greenland. During the ice ages, this forcing oscillated between two conditions (cf. Rahmstorf 2002). In the warm periods, the current in the North Atlantic was almost the same as it is today. Very cold periods occurred in the absence of this current, probably because of excessive melting of the ice masses.

The land-ocean distribution as well as the orology and radiation properties of the earth's surface are highly significant for the climate system, depending on whether they are covered with ice, snow, water, sand or vegetation. The time behaviour of the processes is also relevant. For example, land experiences faster temperature changes than water; snow and ice surfaces can melt faster than the subsequent release of greenhouse gases from the ground or wetlands. Volcanic activity and other geological processes are other climate factors, which also change the earth's surface or the composition of the atmosphere and thus the radiation properties.

2.5 Atmospheric climate factors

After insolation, the radiation properties of the atmosphere and earth's surface – known as *greenhouse effect* and *albedo* – represent the second main climate forcing. Approximately 30% of the radiation from the sun is reflected on clouds or bright surfaces. This is known as albedo. The natural greenhouse effect, i.e. that occurring without humans, is related to the fact that the atmosphere is virtually transparent to visible light, whereas much of the heat radiation emitted by each form of matter in the infrared range (IR) according to its temperature is absorbed. The absorption of infrared radiation in the atmosphere is effected by relatively low numbers of molecules of more than two atoms. Because of their bonding structure, the atoms in the molecule vibrate in such a way that they can absorb and emit infrared radiation from the corresponding frequencies. These are called greenhouse gases and include above all water vapour (H_2O), but also carbon dioxide (CO_2), methane (CH_4) and nitrogen oxides, as well as laughing gas (N_2O), and the fluorinated gases released by humans, chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6).

The earth's surface and the atmosphere absorb energy from insolation and the greenhouse effect, but also emit energy back into the atmosphere and eventually space through heat radiation. In the lower area of the atmosphere, the troposphere, a lapse rate forms until a balance is reached between the incident and outgoing radiation, with a higher temperature at the earth's surface and lower temperatures as altitude increases. The resulting greenhouse effect acts like increased radiative forcing from the sun, measured in W/m^2. Dust and aerosols with sulphur dioxide (SO_2) or soot, released from volcanoes, combustion or other processes, which can temporarily shield or repel the incident sunlight, e.g. from increased cloud formation, oppose greenhouse gases.

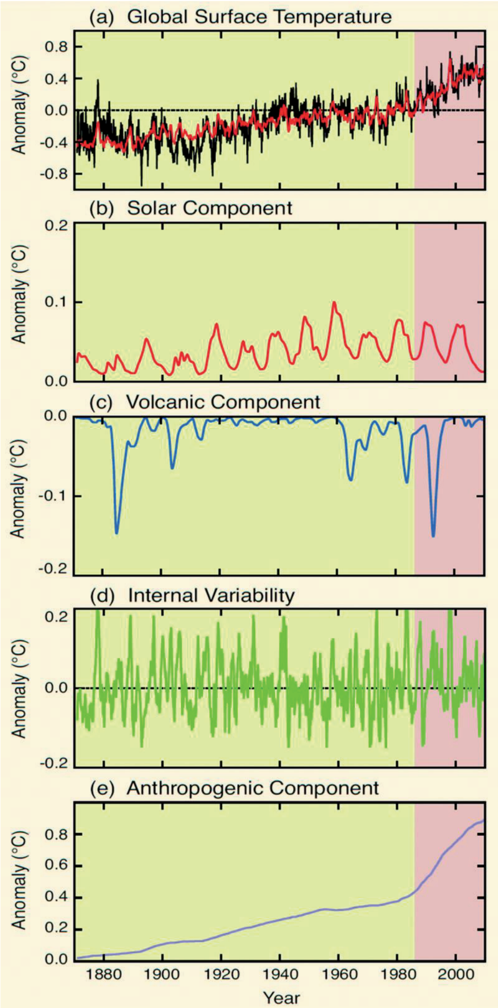
3 Current climate change

3.1 Scientific data on current climate change

In 2013 and 2014 the Intergovernmental Panel on Climate Change (IPCC) published the Fifth Assessment Report (AR5) on current climate change and its possible effects (IPCC 2013, 2014a, 2014b). The report confirmed with even greater certainty earlier findings to the effect that the climate is clearly changing at present, and that this is due to human influences, primarily the release of greenhouse gases, in particular CO_2.

Figure 6: (a) Deviation of global mean annual temperature from 1870 to 2010 relative to

the average for 1960 to 1990. (b) to (d) temperature changes caused by natural influencing factors and (e) by anthropogenic emissions



(a) Black: observed change in temperature in relation to average 1960–1990
Red: model calculation of temperature change as a result of all factors (b) to (e)

(b) Natural influence of change in solar radiation on temperature

(c) Natural influence of volcanic eruptions on temperature, e.g.
1883: Krakatoa
1991: Pinatubo

(d) Natural influence of the internal variability of the climate system on temperature, e.g. from El Nińo and La Nińa events

(e) Influence of anthropogenic emissions of greenhouse gases, dust and aerosols on temperature

Source: The authors, based on Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013: 393

Figure 6 shows the global warming of the atmosphere from 1870 to 2010 and the various contributing factors that play a role in this (Masson-Delmotte/Schulz/Abe-Ouchi et al. 2013). This is based on a range of observational data on temperature at the earth’s surface, solar activity and radiation, volcanic eruptions, ocean currents as well as data on anthropogenic emissions of greenhouse gases, dust and aerosols. Climate models can be used to calculate the relevant proportions of natural and anthropogenic influences on the climate. The study shows that, from 1985 at least, anthropogenic emissions of greenhouse gases are the main cause of the rise in temperature. Unlike during the ice ages, the sun is presently only playing a secondary role, as are other natural influences from volcanoes or the internal variability of the climate system. Between 1998 and 2013 temperature in the atmosphere rose more slowly than in previous decades.

The media wondered whether global warming had paused between 1995 and 2010. There are three factors for the temporarily lower rise: short-term internal variations in the climate system, e.g. from the input of energy in the oceans, the observed minimum in the 11-year solar cycle and a cooling effect from aerosols from several volcanic eruptions. Nonetheless, there has definitely not been a break in global warming as demonstrated by the El Niño year 2014, which was the warmest since measurements began.

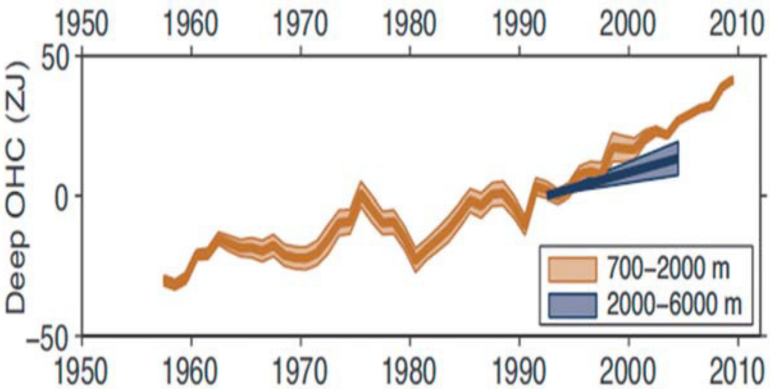
3.2 Observed consequences of climate change

Since the middle of last century and increasingly so from around 1980, a growing number of diverse changes have been observed, which are unique in terms of their form and pace compared to the changes of past centuries and even millennia. Not only is the temperature of the lower atmosphere rising, but the oceans too are becoming warmer, glaciers are thawing, permanently frozen ground is becoming warmer, ice sheets are losing mass, the sea level is continuing to rise, and ocean acidification is rising due to the absorbed carbon dioxide. New, improved and advanced measuring systems in the seas show that between 1971 and 2010 oceans absorbed and stored more than 90% of the energy added to the climate system (see Fig. 7). This shows there has been no break in global warming. The layers close to the water surface heated up the most. In the top 75 metres, the temperature rose by 0.11°C on average each decade between 1971 and 2010. Even the water in the deep sea has already warmed.

One physical consequence of the warming of the atmosphere and ocean is a larger volume of water in the form of vapour and droplets in the atmosphere. With current global warming of approximately 1°C compared to the pre-industrial level, this could mean roughly 7% more water in the water cycle. Another consequence of warming is the decline of the Arctic sea ice (IPCC 2013). This, in turn, alters the large-scale atmospheric currents such as the jet stream and the occurrence and duration of extreme weather events such as heat waves and drought periods or heavy rainfall (Petoukhov/Petri/Rahmstorf et al. 2016). Changes to precipitation vary considerably from region to region. Between 1950 and 2008 rainfall increased in humid regions of the tropics and in the middle latitudes of the northern hemisphere, whereas it decreased in the dry regions of the subtropics. Changes have been observed in many extreme weather events. For example, since the middle of the last century the number of cold days and nights has decreased and the number of warm days and nights increased. Heatwaves have occurred more frequently in Europe, Asia and Australia. Heavy rainfalls have become more intense and frequent in North America and Europe, as is also indicated by flood events. Combined climate and flow models can be used to verify whether past, well-documented flood events might have turned out differently had it not been for the already advanced climate change at that time. Many events such as the catastrophic flooding in England in autumn 2000 indicate that the risk of flooding (▷ *Flood protection*) has already increased as a result of anthropogenic climate change (Pall/Aina/Stone et al. 2011).

Figure 7: Development of heat absorption (Oceanic Heat Content – OHC) in the deep sea in

zettajoules = 1021 J



Source: IPCC 2013: 262

3.3 Computer models of the climate system

It is generally only possible to study the non-linear dynamics of complex systems and thus the correlations of causes and effects using computer models, whereby the knowledge of system components, how they interact with each other and respond to external influences is translated into mathematical and numerical relationships. As with all such models relating to observation variables, climate models are designed to represent the complex processes in the climate system as realistically as possible on the one hand and, by necessity, as simply as possible on the other. The models have two major functions: firstly they serve to examine and hone scientific knowledge by comparing simulations with observational, measured or reconstructed data, as explained above when looking at the palaeoclimate. Secondly, these types of honed computer models offer the only realistic chance of predicting possible future trends in a non-linear system. Simply extrapolating the past to the future under different parameters is too unreliable for potential forecasts, even in linear systems.

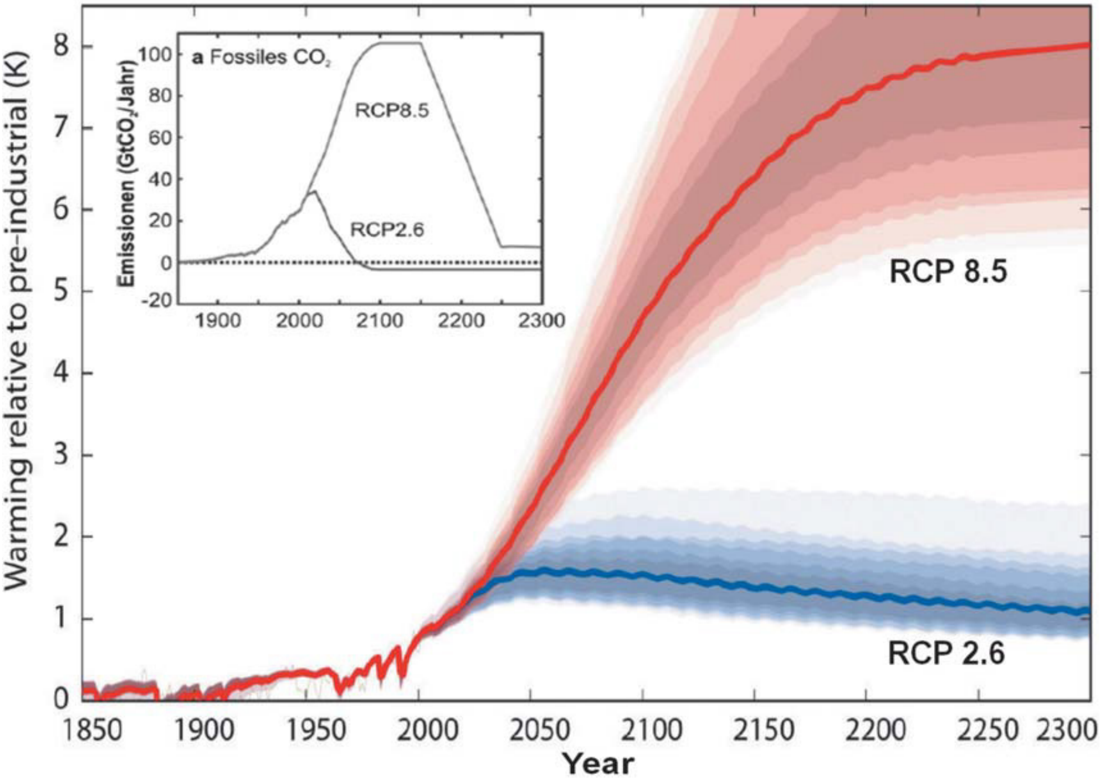
Global climate models simulate the earth's climate system and its dynamics on the basis of physical laws using mathematical equations, which are solved in a three-dimensional grid system around the globe. These equations describe the components and subsystems of the climate system with their changes and interactions. The atmosphere and ocean are the main subsystems of the climate system. Climate models that globally represent these processes are known as General Circulation Models (GCM). The current GCM models have been developed from weather models. A typical global climate model divides the atmosphere and the ocean vertically into many discrete layers, each of which is represented by a two-dimensional grid. In the model, the equations for the transport of heat, pulse, humidity (in the atmosphere) and salt content (in the ocean) are solved on this three-dimensional grid. All of the processes that occur on scales smaller than the mesh size of this grid, e.g. cloud formation, are parameterised, i.e. their properties are averaged as a function of the variables on the grid nodes above a grid cell. Global climate models are good at reproducing the average seasonal temperature conditions and their geographical distribution in the resolution available today; however, the results for precipitation and other parameters of regional importance are still very inaccurate. Global climate models are supplemented by embedded regional climate models with a higher resolution, which can be better adapted to specific regional features. Comparative calculations with various models and several calculation runs of the models with slightly different initial conditions are performed both for periods of time in the past using observational data, as well as for future climate development in order to limit uncertainties and validate the results. Information about regional climate scenarios can be found in e.g. Walkenhorst and Stock (2009) or Jacob (2012).

3.4 Climate scenarios for potential future climate trends

How the earth's climate will continue to develop in the future essentially depends on what emissions of greenhouse gases and other radiation-specific substances human civilisation will release into the atmosphere in addition to those already emitted. Special scenarios called SRES A1, B1, A2 and B2 have previously been used for this (▷ *Future scenarios*). For the 2013 Assessment Report by the Intergovernmental Panel on Climate Change (IPCC 2013), new Representative Concentration Pathways (RCP) were created that include models coupled with energy, the economy, climate and land use. These models represent all drivers of anthropogenic greenhouse gas emissions of CO_2, CH_4, NO_x, etc. and map them in consistent scenarios of future consequential radiative forcings. Four different paths are calculated: three reach an anthropogenic radiative forcing of 8.5 W/m² (very high), 6 W/m² (high) and 4.5 W/m² (medium) in 2100. In another path, the (relatively low) anthropogenic radiative forcing 2.6 W/m² is only reached in 2100 on the condition that negative emissions are taken in by approximately 2080, i.e. that CO_2 is retrieved from the atmosphere again. Based on the RCP, new projections of potential climate changes in the 21st century and beyond were calculated using climate models. Figure 8 shows the progression of the global average temperature on the surface relative to the preindustrial value between 1850 and 2300, based on observational data up to 2011, and thereafter the progression calculated for two RCP scenarios using an ensemble of different climate models (Meinshausen/Smith/Calvin et al. 2011). The areas show the spectrum of different numerical modelling, and the lines represent the resulting averaged progression of the temperatures. The corresponding CO_2 emissions are included in the smaller graph.

Scenario RCP 8.5 roughly equates to 'business as usual', i.e. continuing with the intensive land use, clearing and fossil fuel emissions as in the past. It can be assumed that the expected damage e.g. from extreme weather events could soon exceed 5% of the global per capita income (Stern 2007). This would probably also push the world economy to breaking point and would be almost impossible to contain with reasonable adjustment measures (▷ *Climate change adaptation*), as found in a study for the World Bank on how adjustment to a '4 degree world' might look (World Bank 2012). Agriculture and supplies of drinking water and food could be jeopardised in many regions of the world, even this century, as a result of increasing extreme heat and drought periods. Anything above a 2 degree warming is likely to result in an exceedingly high increase of many risks for ecosystems and settlement systems (IPCC 2014a). In the long term, many coastal regions and towns are also at risk from the rising sea level and storm floods.

Figure 8: Progression of the global average temperature on the surface relative to the preindustrial value between 1850 and 2300, based on observational data up to 2011, and from 2012 on the progression calculated for two RCP scenarios with radiative forcing varying from 2.6 to 8.5 W/m². The corresponding CO_2 emissions are included.



Source: The author, based on Meinshausen/Smith/Calvin et al. 2011: 233 and (a) 228

In the climate protection scenario RCP 2.6, on the other hand, there is a high probability of keeping global warming below a limit of 2°C. In developed countries at least there is also the possibility of containing the expected consequences for the climate with adaptation measures. The anticipated investment costs of adaptation measures, the energy transition and ▷ *Climate protection* are much lower than the cost of damage expected in scenario RCP 8.5. In addition, investment would make more economic sense than repairing damage.

3.4 Dealing with uncertainties

In answer to the question of how the climate might change in the future, reference is often made to the uncertainty of such statements, sometimes even to sow doubt regarding the necessity of taking prompt action to protect the climate. Should we not wait until there is more certainty? Many people also wonder how reliable statements can be made about how the climate may be in 100 years, when even a weather forecast several days ahead is unreliable. Climate research thus addresses different types of uncertainty in depth and looks at which types can be reduced in which way, and which cannot. The question 'How will the future evolve, and what will it look like?'

illustrates that there are uncertainties that cannot be reduced, and we will simply have to live with and work around these. This is summed up in the tongue-in-cheek quote attributed to various authors ‘It’s hard to make predictions, especially about the future’ (▷ *Forecasting*).

In weather forecasting, it has been possible to significantly reduce uncertainties with greater knowledge of meteorological processes, more extensive and more informative observational data and more accurate numerical weather models. A forecasting error rooted in an inaccurate initial value increases with every future day and is pinpointed through a range of calculation runs with slightly different initial values, with the results of different calculation runs diverging increasingly in theory from day to day. The result is a statistic of potential weather trends in a probability distribution. Statements with high probability are relatively reliable, those with lower probability tend to be more unreliable, but not inconceivable. For example, temperature forecasts are more reliable than precipitation forecasts, averages are more reliable than extreme values and area-specific information is more unreliable the smaller the reference, i.e. the more specifically the weather information can apply to a certain place, the more unreliable it is.

With climate change – unlike with weather – the source of uncertainty does not lie in an initial value, but rather in how the system responds to a change in the energy balance. One major source of uncertainty for future climate trends is the development of anthropogenic greenhouse gas emissions, which crucially depends on human behaviour. As this is not predictable, we do not talk about forecasts, but rather climate projections, which can be derived from the various scenarios with regard to possible future emissions. Stock and Walkenhorst (2012) distinguish four sources of uncertainty for the bases of climate change represented in global and regional climate models:

1) Uncertainty with regard to future greenhouse gas emissions, i.e. the future development of natural and anthropogenic variables that determine the climate (including regional factors such as the way land is used and aerosol emissions).
2) Uncertainty from inaccuracies in the global climate models, the results of which serve as the boundary conditions or input variables for regional climate models.
3) Uncertainty from inaccuracies in the regional climate models.
4) Sampling uncertainty, arising from the fact that climate always has to be estimated in the model on the basis of a limited number of model years.

As already explained for the weather, a range of model runs with various models and slightly different initial values also produces a statistic for the climate with probabilities of potential future trends. This is illustrated in the spectrum of temperature profiles in Figure 8.Again here, statements about temperature are more reliable than statements about precipitation, averages are more reliable than extreme values and area-specific information is more unreliable the smaller the local reference, i.e. the more probable a climate trend can apply to a specific place, the more reliant we are on probability data. Thus, decisions must sometimes be made with considerable uncertainty.

4 Courses of action for dealing with climate change

In accordance with this scientific knowledge on current climate change and its anthropogenic causes, decisions and actions taken today will set the course for the future that humankind can expect. In order to prevent catastrophic developments, it is deemed necessary to limit global warming to far below 2°C above the pre-industrial level, even below 1.5°C for vulnerable regions if possible.This was agreed at the UN Climate Change Conference in Paris in December 2015 with internationally binding effect (cf. UNFCC 2015). However, the actions required to achieve this target were set out with less binding effect. Advice on this can be found as far back as the IPCC 2013 report as well as in scientific studies of the Paris Agreement, e.g. in Edenhofer (2016). The agreed upper limit for curbing climate change requires the use of fossil fuels to be phased out. It is vital that over 80% of the coal supplies and most of the oil and gas supplies remain in the ground. To this end, it is not only necessary to take the relevant climate protection measures, but a fundamental societal transformation and global revolution towards ▷ *Sustainability* is required, as suggested by the German Advisory Council on Global Change (*WBGU:* 2011). The German Advisory Council on Global Change believes that this is possible with the help of a radical innovation path, which will have to include all areas of the industrial metabolism. As well as aiming to limit global warming to under 2°C, the scenario by the German Advisory Council on Global Change based on all renewable energies (sun, wind, geothermal energy, hydropower and biomass) with a quick phasing out of fossil fuels, offers the allure of a substantial stimulus for the economy at all levels. This innovation path also includes adaptation measures that are strategically coordinated with each other and with climate protection. A coordinated strategy of climate protection and adaptation to climate change has also been identified as one of the action policies of ▷ *Spatial planning (Raumordnung)* (*MKRO* [Conference of Ministers for Spatial Planning] 2013). Rahmstorf and Schellnhuber (2012) outlined this twin-track approach as follows:

it is

1) necessary to adapt to climate change to control the unavoidable, and to

2) reduce emissions to avoid the uncontrollable.

The Paris Agreement gives some hope that this path towards limiting the dangerous effects of climate change will actually be taken.

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