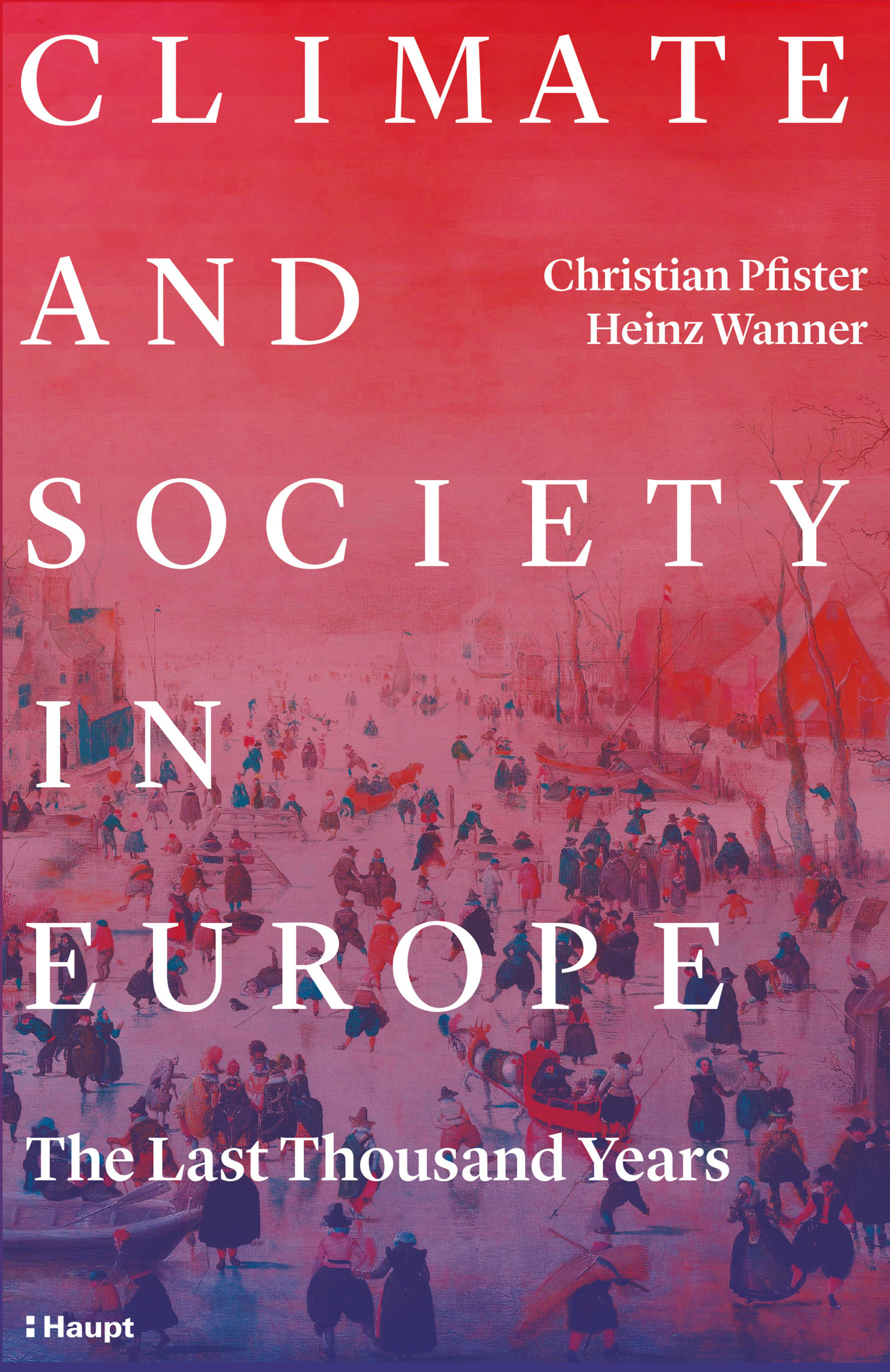

CLIMATE AND SOCIETY IN EUROPE

Christian Pfister
Heinz Wanner

The Last Thousand Years

Haupt

Climate and Society in Europe – the Last Thousand Years

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Preface

The consequences of climate change are no less threatening in the foreseeable future than those of Covid-19, which took people and the economy by surprise in 2020. Human-induced global warming is progressing rapidly. If we do not immediately undertake precautionary measures, it will result in previously unimaginable extremes in Europe too.

For the first time, a climatologist and a historian jointly present a history of climate and its effects on society over the last 1000 years. Thanks to the combination of natural and social science approaches, the book achieves significant new insights in both branches of knowledge. But believe us when we say writing this book was not an easy task. It has taken us years to reach this point, and thankfully we still enjoy each other's company. The result is a book which simultaneously meets the needs of specialists and general readers via its easy to understand language, graphics and layout. It is also complemented by illustrative stories to provide some "lighter" anecdotes.

By using examples such as the iceman Ötzi, the presentation connects the warm conditions during his lifetime 5000 years ago to the surprise thawing of his mummy in 1991. The effect of volcanic explosions on the global climate and the affected societies is explained using the Tambora volcano eruption in 1815 and detailed insights into the resulting 1817 famine in eastern Switzerland. The longer-term course of temperatures over the past millennium is shown based on models and proxy data from natural environments. Possible reasons for climate fluctuations are explained with reference to important driving factors. Reconstructions of seasonal weather and climate conditions based on documentary sources complement this perspective. The results are then used to interpret demographic, economic and cultural developments and phenomena over the last 1000 years. The final chapter points to the conditions leading to the current climate emergency and ventures a look into the future. Not without reason it is called "The return of vulnerability".

The limited size of the book did not allow us to include precipitation and major natural disasters, as initially planned. For the same reason, a detailed proof of sources was restricted to the more significant climatic events.

Numerous institutions, sponsors and personalities have supported our work. Special thanks go to the helpful staff of our host, the Oeschger Centre for Climate Change Research at the University of Bern, Switzerland, for allowing us to use its infrastructure.

We highly value a number of friends and colleagues who were willing to review chapters of our book, despite their extreme workloads.
Chapter 1: Stefan Brönnimann
Chapter 2: Stefan Brönnimann, Jörg Schibler
Chapter 3: Stefan Brönnimann, Daniel Krämer
Chapter 4: Thomas Labbé, Laurent Litzenburger
Chapter 5: Martin Grosjean, Stefan Brönnimann
Chapter 6: Stefan Brönnimann, Martin Grosjean
Chapter 7: Christian Rohr, Astrid E. Ogilvie
Chapter 8: Stefan Brönnimann

Chapter 9: Brian Campbell, Jan de Vries
Chapter 10: Martin Grosjean
Chapter 11: Thomas Stocker

The publishers Patrizia and Matthias Haupt supported us in many ways right from the start. Tamara Baumann, Carla Laub, Alex Hermann, Alfred Bretscher(†), Beat Ihly and Veronika Valler produced many brilliant figures, while Katarina Lang designed a professional and creative layout. Angela Wade took over the demanding task of creative proofreading, and Tamara Widmer tirelessly sourced books for us from libraries.

The publication of our ambitious project would not have been possible without the generous support of our sponsors, listed on page 397, and the many colleagues and friends who provided ideas, expertise, data, graphics, and their overall encouragement. We especially thank Mariano Barriendos, Ray Bradley, Rudolf Brázdil, Petr Dobrovolný, Jan Esper, Basilio Ferrante, Dominik Fleitmann, David Frank, Isabella Geissbühler, Oliver Heiri, Fortunat Joos, Johann Jungclaus, Hanspeter Holzhauser, Antoine Jover, Cornelia Kehl, Andrea Kiss, Christian Körner, Peter Lüps, Jürg Luterbacher, Kaspar Meuli, Kurt Nicolussi, Samuel Nussbaumer, Jessica Ochsenbein, Margret Möhl, Kathleen Pribyl, Christoph Raible, Christian Rohr, Manuela Roten, Marlis Röthlisberger, Christoph Schär, Gabriela Schwarz-Zanetti, Michael Sigl, Silje Sørland, Martin Stuber, Peter Stucki, Nikolaos Theocharis, Willy Tinner, Heinz Veit, Monika Wälti, Hedy Werthmüller, Ursula Widmer, and Heinz Zumbühl.

Our main objective in writing this book was to make our readers aware of the consequences of future climate change. In this regard, we dedicate it to our grandchildren Kevin, Camilia, Diego and Silvio, and Amelia and Jaro. We hope they will one day live in a world where the problems of climate change are much less severe than today!

Bern, March 2021
Christian Pfister and Heinz Wanner

Abbreviations

AC	Atmospheric circulation
AD	Anno Domini (year of Jesus Christ, same as Common Era CE)
ALIA	Austral Little Ice Age
AMOC	Atlantic Meridional Overturning Circulation
AMO	Atlantic Multideadal Oscillation
AR	Assessment Report (IPCC)
a.s.l.	above sea level
BC	Before Christ
BLIA	Boreal Little Ice Age (1300–1900 AD)
BP	Numbers the years before present
CESM	Community Earth System Model (coupled climate model)
CEuT	Central European Temperature series
CH_4	Chemical formula for methane
CMIP	Coupled Model Intercomparison Project
CO_2	Chemical formula for carbon dioxide
COP	Conference of the Parties
CORDEX	Coordinated Regional Climate Downscaling Experiment
EIKE	European Institute of Climate and Energy
ENSO	El Niño Southern Oscillation
Euro-Climhist	https://www.echdb.unibe.ch/selection/welcome/en This data platform serves as a repository for documentary sources and supplementaries from published papers.
GHD	Grape harvest date
GHG	Greenhouse gas
GSM	Grand Solar Minimum
HMP	High Medieval Period (1000–1300 AD)
HTM	Holocene Thermal Maximum
hPa	Air pressure unit of 100 Pascal (100 Newton per m^2)
IGY	International Geophysical Year
IPCC	Intergovernmental Panel on Climate Change
LIA	Little Ice Age
MCA	Medieval Climate Anomaly
MIT	Massachusetts Institute of Technology
MWP	Modern Warm Period (1900–2020)
N_2O	Chemical formula for nitrous oxide
NAO	North Atlantic Oscillation
NCAR	National Center of Atmospheric Research (Boulder, CO, USA)
O_3	Chemical formula for ozone
OC	Ocean circulation
PAGES	The project Past Global Changes
PDSI	Palmer Drought Severity Index
PET	Potential evapotranspiration
PIK	Potsdam Institute of Climate Impact Research
PMIP3	Paleoclimate Modelling Intercomparison Project, Phase III
RCM	Regional Climate Model
RWP	Recent Warm Period (1988/89–2020)
SDI	Strategic Defense Initiative

SST	Sea surface temperature
STC	Short Twentieth Century (1900–1988)
SSW	Sudden Stratospheric Warming
SVEI	Standardized Precipitation Evapotranspiration Index
TSI	Total solar irradiance
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
W	Watt (kg m^2 s^{-3})
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

1. Introduction

1.1 The switch to rapid warming – a new comparative basis in climate history

It is time for a topical history – a new history of climate and people. The climate issue is central to current public discussions. Our youth and politicians will need to deal with this issue in the longer term, because extreme events will continue to put climate on the public agenda.

We are now in a new age. Since the late 1950s, humans have become something much larger than the biological agent of past decades.[1] They became a force of nature in the geological sense[2], and as such they are also the most important driver of the climate system. Since the early 19th century, natural history has ceased to be purely natural, becoming increasingly human from this time on. Man-made global warming has emerged as one of the most pressing issues for the future of humanity and the environment. The rise in European temperatures since the late 1980s has been exceptional when compared to the last 2000 years, both in terms of its speed and spatial extent.[3] It is a hot topic in the literal sense.

Series of measured temperatures in Europe are mainly available from the mid-18th century. The series of annual temperatures in Basel, Switzerland, since 1755 (Fig. 1.1) presents a first rough insight into the Central European temperature structure of the past 265 years. It can be divided into three segments: the first period from 1755 to 1900 is the final part of the Boreal Little Ice Age (BLIA[4]; see Table 1.2). The subsequent period of slow-going anthropogenic warming (STC) ended in 1988, when temperatures moved to the higher level of the current period of rapid warming (RWP).

To put anthropogenic warming in context, we need to understand climate forcing, natural climate variability and climate extremes, as well as the history of climate science. For this purpose, the prevailing natural climate variability up to the late 1980s needs to be investigated. The current state of the climate becomes extraordinary when compared with the conditions of the past 1000 years. The comparison with the past has always played a pivotal role for the assessment of the present and the view into the future. According to Italian philosopher Benedetto Croce, historiography is an interpretation of the past in the light of the present.[5] This statement also applies to climate history. Today we are in a different climate situation than in the last century, and, for this reason, our view of past climate has fundamentally changed. It is no longer the moderate 20th century which is compared to earlier colder or warmer periods, but the new age of rapid global warming. Data from the past show how a colder world looked and suggest how a warmer world may look in the future; this is essential, not just in terms of mean values, but also in terms of extremes.

To understand how humans can – or cannot – cope with climate change, we need to examine how past climate affected people and how people responded and adapted to climatic challenges. A look into the past shows that even relatively small shifts in mean values had major impacts on human affairs. In order to fully understand events and developments in human history, we need to recognise the roles that climate and weather have – and have not – played in our past.[6]

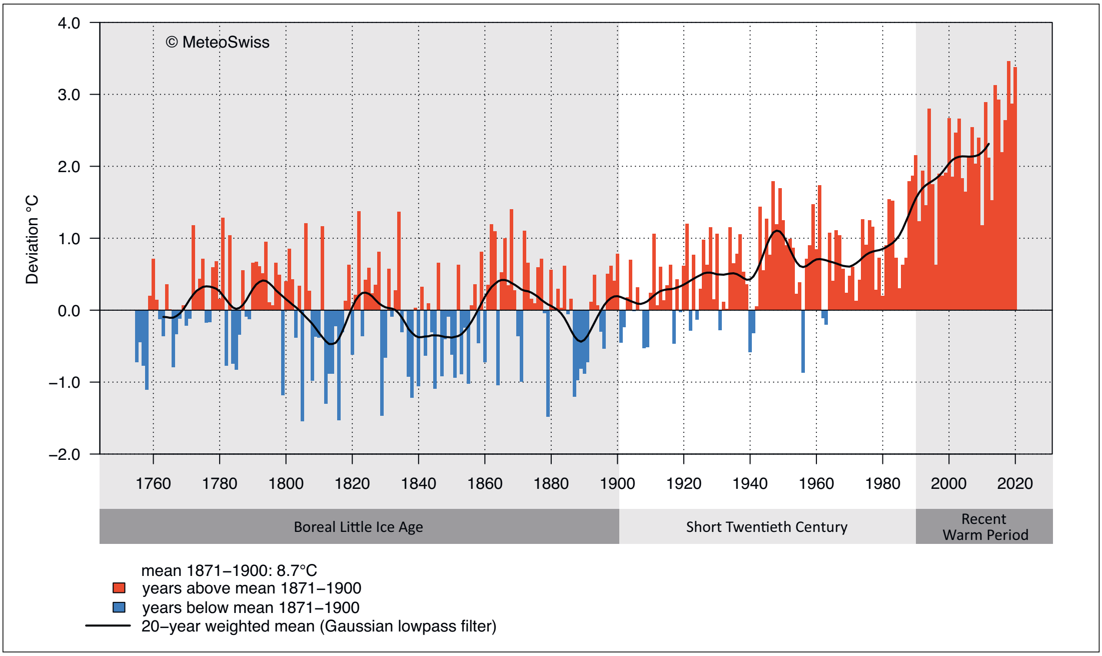


Fig. 1.1. Anomalies of annual mean temperatures in Basel/Binningen, Switzerland, from 1755 to 2020 (with respect to the 1871–1900 mean; source: Bundesamt für Meteorologie und Klimatologie MeteoSwiss). https://www.meteoswiss.admin.ch/home/climate/climate-change-in-switzerland.html; accessed 3 January 2020.

Why write a book? Scientific journals provide new, leading-edge insights, at short notice and piece by piece, but they are often difficult to understand for outsiders. Further connections can only be shown in several papers that are published in different journals or lesser-known anthologies that usually do not meet the quality criteria of the natural sciences. In this way, the big picture is lost. A sack of crumbs is not the same thing as a loaf of bread. An extended synthesis in book form can make reliable knowledge available to science and the public in the longer term.

Up until now, books on the history of climate change have been written separately by climatologists and historians, as it is difficult to reconcile the scientific cultures of the natural sciences and the humanities. This is the first work written together by a climatologist with a flair for history and a historian competent in climate history; therefore, the concept and many of the findings in this book are fundamentally new.

1.2 Two scientific cultures

Investigating climate change and its effects on people involves two different scientific cultures, namely that of the natural sciences, in particular climatology, and that of the humanities, in particular (environmental) history. The two cultures pursue different objectives; they have their own style of thinking and use disparate models of presentation. Scientists explain how natural systems work, while (environmental) historians tell stories of people who grapple with the effects of weather and climate. Scientists argue systematically and strive for the greatest possible precision and completeness, while historians seek a common thread for their narratives, starting from a few basic questions. Scientific thinking is scientifically logical, while historians build their narrative strands from rational and emotional elements, since both are part of how humans think and feel.

Another major difference between the two cultures relates to the fact that natural and historical sciences use different evidence to reconstruct climate in the period before the availability of instrumental measurements. Scientists draw on physical indicators called proxy data (Table 1.1). A distinction is made between biological proxies, such as tree rings, pollen in peat bogs, or the growth of shells, and non-biological proxies, such as ice cores from the Arctic and Antarctic, cave deposits known as speleothems, or ground sediments from the seas, lakes and rivers. These proxies are explained in Section 5.2. The storage mediums of these natural processes are called archives of nature. The analysis of any natural archive requires specific scientific skills in relation to the underlying physics, chemistry or biology of the process captured in the archive, and how it relates to past climates.

Likewise, the term archives of societies refers, in a broad sense, to mediums that contain historical sources. The historical sciences use the term "source" in a figurative sense: just as one draws water from a well, the historian draws on evidence from the past to answer historical questions. With regard to the reconstruction of weather and climate, historical sources include both documents and evidence preserved in the built environment. The term "document" comprises a broad variety of sources, such as personal manuscripts and official records, printed materials, artworks, and electronic data. Evidence in the environment includes archaeological materials, artefacts

Archives of	**Nature**		**Societies**	
Direct observations			Narrative accounts • anomalies • weather spells • daily weather • disasters	Measured values • atmospheric pressure • temperature • precipitation • runoff
Indirect (proxy) evidence	Organic • tree-rings • pollen • plant and animal remains • fossil wood	Non-organic • ice-cores • varves • sediments • speleothems • temperature of boreholes • moraines	Organic • plant phenological data • oenological data	Non-organic • ice phenological data • snowfall • snow cover • water levels
			Religious • rogations	Pictorial • paintings • drawings
			Epigraphic • flood marks	Archaeological • remains

Table 1.1. Direct and indirect evidence on past climate. For a more extensive table, see Brönnimann et al. (2018).

and indicators on buildings such as high-water marks.[7] Narrative evidence involving direct weather information and instrumental measurements is presented in Chapter 4. In addition, quantitative proxy data, such as grape and grain harvest dates, and oenological data were generated by procedures related to fiscal control and the payment of dues. This evidence is used for statistical temperature estimates akin to scientific proxy data, and is discussed in Section 5.3. Evidence from archives of societies is evaluated and interpreted by historical climatologists. The majority of them share a scientific background in physical geography with specialisations in meteorology and climatology, while historians form the minority.[8]

The term "climate history" can take two different meanings, depending on the spatiotemporal level on which it is presented. The macrohistory of climate, called palaeoclimatology, aims to deepen our understanding of the physical processes in the climate system. It is simply the history of the Earth's climate system from its beginning to the present. Climate sciences, starting from models of the physical world, focus on extending the global climate record (mostly temperatures) as far back in time as possible. These findings need to be compatible with the laws of physics and related climatological findings. Using elaborated statistics, scientists learn from the past about natural and anthropogenic forcing factors that lead to variations and changes in the climate system. Palaeoclimate research focuses mainly on the long-term, large-scale development of past climates. Regional or continent-wide series are aggregated to arrive at a hemispheric or global level. Modellers need such long global-temperature and precipitation records to validate their models, which ultimately provide evaluations of future climates in the form of longer-term averages. This issue is discussed in Section 6.4.

In contrast, historians began using the term "climate history" some 50 years ago to label a novel field of historical study. It investigates how the weather and climate changed during the recorded past and how these variations affected human history.[9] Historians are primarily concerned with understanding the role of weather and climate in the development of the *human* past. What involves people, then and now, are short-term atmospheric events taking place over weeks, days or even hours. Climatology is about the climate system and history is about people.

Microhistories of climate consist of narrative reports about individual weather periods. Characteristically, many of them also referred to the effects of weather on the living and inanimate environments, especially from the point of view of humans. The following diary excerpt about the exceptional situation in July 1540 is conclusive in this respect (Fig. 1.2). It was written by winegrower Hans Stolz, who lived in Gebweiler, Alsace, known today as Guebwiller, France. The translated English text states, "July turned torrid until the end [9 August]. A terrible water shortage plagued this country and people became hungry because mills stalled. Fruit on trees, such as pears, apples and walnuts dried out, also grapes on vines. Many cattle died of thirst."[10] Stolz's observations provide essential details permitting a realistic impression of the severity of this European megadrought (see Section 8.4.4).

However, such microhistories of weather are too fragmented to be integrated into the macrohistories of climate.[11] Unlike daily instrumental observations, they cannot be aggregated into monthly or seasonal averages.

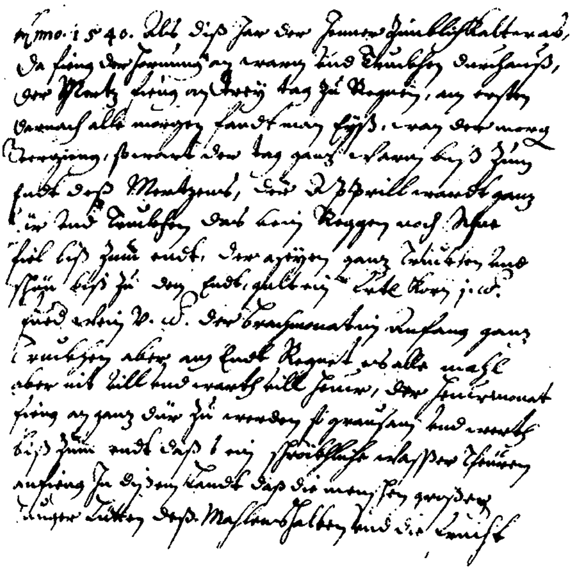


Fig. 1.2. Excerpt from the diary of Hans Stolz describing the situation in July 1540 in Guebwiller, France (Source: Stolz 1979: 373).

Long-term climate and climatic changes are statistical constructions that cannot be easily noticed by our senses. In the past, people experienced climatic change, if at all, in terms of the frequency and severity of extreme weather events or environmental challenges. American scientific historian Naomi Oreskes pointed out that there is a gap between the extent to which palaeoclimatologists provide information and the extent to which humans have responded – and still respond – to weather and climate and their effects.[12] For this reason, a two-pronged climate history is needed, encompassing both the history of the climate and the history of weather spells.

A major challenge relates to the fact that cultural aspects are important for the human interaction with weather and climate. Prominent German sociologist and historian Max Weber (1864–1920) pointed out that reality is two dimensional, consisting of material facts on the one hand and language, interpretation of reality and cultural worldviews on the other.[13] Culture – drawn from linguistic, phonetic and visual forms of expression – attributes a meaning to world affairs, including weather and climate. Besides dealing with the nature and objectivity of meteorological events reported in the documents, we should also understand why and how they were observed and recorded. This issue is discussed in Chapter 4.

The model (Fig. 1.3) draws on reflections made by German historian Rolf Peter Sieferle (1949–2016) about the relationship between nature and culture. They are adapted to the issue of atmospheric processes as a part of the material world and their representation in the sphere of human thought. The figure shows two circles representing the material and the symbolic world. Sieferle's concept of nature includes all elements of physical–material reality, as long as it is not about people. These elements include artefacts – machines, gadgets, tools, networks, and infrastructure – on which people depend for the maintenance of our vital functions. Then there is the animate and inanimate nature, i.e. the area of the environment that develops without direct human influence. Sieferle's concept of culture subsumes all elements

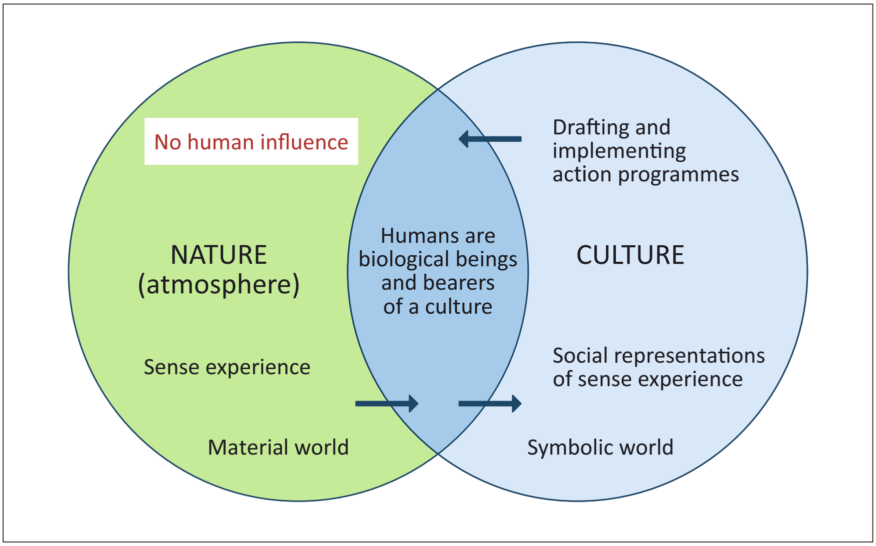


Fig. 1.3. Nature and culture – two different modes of causality. After Peter Sieferle (1997: 37–41).

belonging to symbolic reality. It includes all information stored within the human brain and other information carriers, such as books, museums, hard disks, and the Internet.

The physical human population forms an interface situated at the intersection of the two circles: people are hybrids belonging to both nature and culture. Via their bodies, they are part of the sphere of nature because they are physical beings subject to biological laws. Via their minds, they relate to the sphere of culture, because they share a symbolic system of values and beliefs. Both spheres have a different mode of causality, i.e. they use different lines of reasoning to relate effects to causes. The natural sphere of causation relates eyewitness observations or instrumental measurements to physical causes. From a scientific point of view, human activity is essentially regarded as a process of adaptation to external conditions, with the biological interactions between humans and their environment – nutrition, health and reproduction – in the foreground.

The cultural sphere of causation deals with the interpretation of weather observations and the resulting actions. Interpretations are based on cultural realities such as beliefs, traditions and values.[14] From a cultural point of view, human action flows from social communication – whoever believes that hailstorms are due to God's wrath organises processions; those who assign them to witchcraft will call for witch hunts; and those who try to avoid losses will arrange property insurance. Nature is only perceived to the extent that it is communicated. The environment outside social communication, as reconstructed by the natural sciences, is not perceived as such. Both perspectives on their own fail to recognise that humans have a dual nature: on one hand they are biological beings, on the other they are the bearers of a culture. One of the main tasks of (historical) climate research is to adequately take both aspects into account. The scientific and cultural history of climate variability are presented in Chapter 4, while societal responses to climate change are addressed in Chapters 9 and 11.

In conclusion, scientists and climate historians pursue different objectives, draw on different evidence and use different methods. In addition, their results are situated on different temporal and spatial levels. A two-pronged history combining both perspectives must give due consideration to the dual nature of humans as natural and cultural beings.

1.3 Common ground

This section demonstrates how the two hardly compatible viewpoints – the climatological and the human historical – can be reconciled to a certain extent. In order to connect the human history of climate with quantitative climate science, the first author of this book devised the "Pfister-Indices"[15] to build on preliminary work by British climatologist Hubert H. Lamb (1913–97; Fig. 1.4a). Indices are man-made proxy data summarising all available documentary evidence for temperature and precipitation from a specific month or season. They can take values ranging from -3 (for very cold or dry) to +3 (for very warm or wet). The valuation 0 is used for unspectacular seasons or months. Creating indices involves concatenating thousands of individual pieces of evidence. The procedure is explained in more detail in Section 5.4. Seasonal temperature indices for Western and Central Europe form the backbone of climate reconstruction over the last 1000 years, along with descriptions of extreme seasons (Chapters 7 and 8).

Climate history attempts to understand the role of climate and weather variations in developments in the human past. This concern distinguishes climate history from conventional history. Some historians still consider history as being limited to an account of what man does to mankind, but their numbers are dwindling. Environmental history has put this focus into perspective. It first emerged in the USA in the 1980s, then subsequently in Europe and elsewhere. The quasi-natural human environment is increasingly accepted

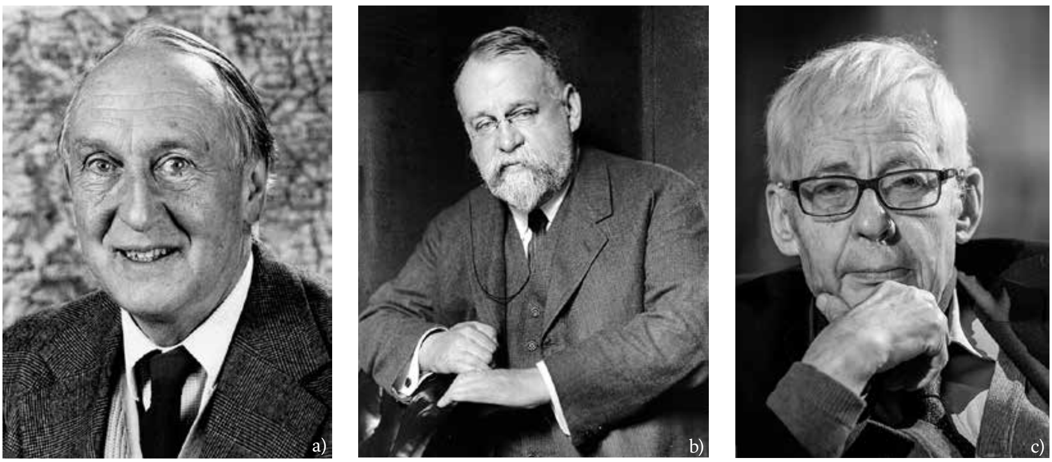


Fig. 1.4. Pioneers of palaeoclimatological research. a) Hubert H. Lamb. b) Eduard Brückner. c) Emmanuel Le Roy Ladurie (Source: Wikipedia).

as being the fourth basic category of history, on an equal level with governance, economy, and culture, as German historian Wolfram Siemann argued.[16] Environmental history is usually understood as an account of man transforming his natural surroundings. Climate history looks at the other side of the coin and asks about nature's role as an agent in history, at least prior to the early 19th century. To some extent, environmental history has paved the way for climate history, but by no means can all those who deal with this topic be associated with environmental history. Its scholars come from many disciplines, and they approach their work in different ways. Some would identify themselves as environmental historians and others as economic historians, geographers, or even climate scientists.[17]

Three pioneers have done the groundwork.[18] German geographer Eduard Brückner (1862–1927; Fig. 1.4b), son of a historian, published a monograph in 1890 titled *Climate Fluctuations since 1700 and Remarks on the Climate Fluctuations of the Diluvial Period*.[19] He not only opposed the dogma prevailing at the time, which regarded the climate of the past centuries as constant, but he also provided counterevidence in the form of early instrumental measurements, grape harvest dates and glacier fluctuations. Moreover, he addressed the social impacts of climate fluctuations, such as crop and grain price fluctuations and migratory movements. His work was forgotten until two German scientists, sociologist Nico Stehr and climatologist Hans von Storch, unearthed and partly translated it.[20]

Without knowing Brückner's German language publication, French historian Emmanuel Le Roy Ladurie (1929–; Fig. 1.4c) also used vintage data and evidence of glacier fluctuations to reconstruct pre-instrumental climates in his *History of Climate since the Year 1000*.[21] Out of consideration for his career, however, he distanced himself from the idea that seasonal and monthly weather conditions might have had an impact on human history. Four decades later, however, he admitted that he had only made such statements in order not to be discredited as a climate determinist.[22]

Hubert H. Lamb (Fig. 1.4a), with his flair for human history, evaluated a wealth of historical weather data that he discovered during his work for the British Weather Services. From these elements, he developed the notion of a Medieval Warm Period (MWP) and discovered the great significance of volcanic eruptions on weather and climate. Although he, like Brückner 80 years earlier, differentiated the significance of climate for human history[23], he was confronted with the accusation of determinism. Discussions about the social significance of climatic variations were and still are discredited by environmental determinism, which was taken to extremes by American geographer Ellsworth Huntington and his followers. This may be one reason why some historians tend to altogether ignore the potential importance of weather and climate on human development. American economic historian Jan De Vries makes the point "that the inclusion of the climate factor in the study of history must not be regarded as a search for an alternative, and deterministic explanation of the past, but as an expansion of the context in which the workings of past societies are to be understood."[24] Open climate determinism has been overcome today, but it persists in latent form, not least in scientific papers. Stehr and von Storch went so far as to claim that "a large proportion of today's climate impact research is genuine climate determinism."[25]

In order to investigate interactions between the history of human societies and the dynamics of their quasi-natural environment, we have to bear in mind that the processes in these two spheres usually follow their own path and are independent of each other. Among the most obvious examples which need to be taken into account within the human realm are population growth, economic development, the construction of large technical systems, such as transport and communication networks, globalisation, changes in institutional structures, and the rise or fall of empires. In the sphere of the natural environment, changes to which humans contribute, such as soil salinity, deforestation and drops in groundwater levels, should be distinguished from other, mostly exogenous factors, such as orbital changes, fluctuations in solar activity, large volcanic eruptions, and changes in sea surface temperature, which often take place on different temporal and spatial scales.[26]

This fact makes it particularly difficult to structure studies on climate history. Any interdisciplinary approach that combines the natural and social sciences needs to incorporate the explanatory models in each field. The sciences start from models of the physical world and then move towards models of human societies. In doing so, they come across the fact that human history studies cannot be generalised on the same level. Historians try to understand to what extent people and their economic and ecological condition were vulnerable to climatic impacts. Unlike scientists, historians "tend to eschew broad generalisations, partly because it is the detail, the differences from one case to another, which is central to historical research".[27] American historian John Brooke, from Ohio State University, also attempted to document climate development and its significance for the history of mankind, in the long term and on a global scale, by examining the influence of pandemics, such as the plague. This book provides a good overview complementing the results of this synthesis with its limitations to Europe.[28]

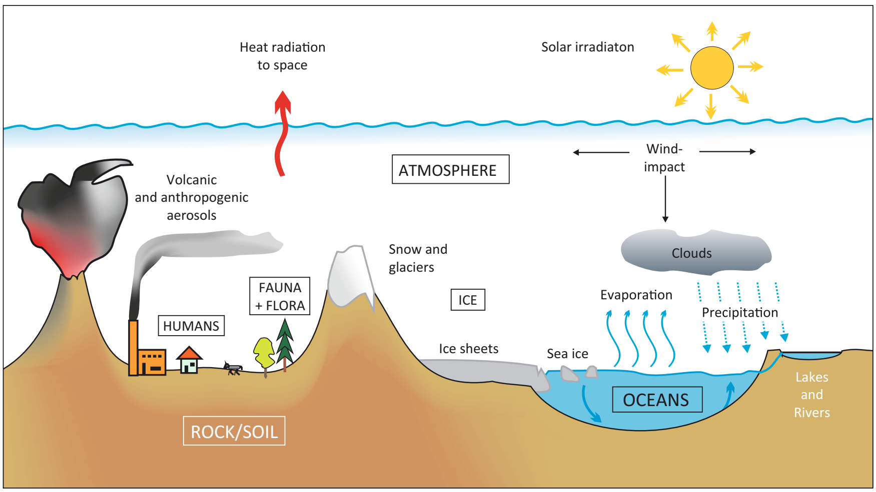


Fig. 1.5. Climate system of the Earth. The subsystems are represented in rectangles. Important processes or phenomena are also noted.

"Best data studies" are a convenient way to highlight the many aspects that interact in the study of societies, as exemplified by the "Tambora Crisis" (Chapter 3). Furthermore, to account for the plurality of drivers working over time, the focus of the analysis should be shifted away from the climate to human systems, such as the population or the economy (Chapter 9). Switching between different spatial and temporal scales presents a particular challenge, be it the change from local to global, or the connection between short-term events and longer-term variations.

As a first step, the scientific culture of climatology is discussed by presenting the basic principles that determine global climate dynamics, starting with the scheme of the climate system (Fig. 1.5). The consequences for European climate will be further presented in Chapters 6–8, 10 and 11.

1.4 The climate system

The climate system is driven by the radiative power of the Sun. Six components interact in the system, which is open to the exchange of energy into space, but almost closed in relation to mass fluxes.[29]

1. *Atmosphere:* The atmosphere is a thin, almost evenly distributed gaseous film with a small vertical extension (99% of the mass is concentrated below 30 km). This is the area where the weather takes place, with its characteristic processes like radiation, cloud formation, precipitation, airflow, heat and moisture transport, storage of natural and anthropogenic trace gases, and so on. A distinction is made between the weather-relevant layer of the troposphere (lowest 10–15 km) and the stratosphere (15–50 km), which is relevant in the event of volcanic eruptions. Volcanic and anthropogenic aerosol components as well as greenhouse gases are emitted into the atmosphere.

2. *Hydrosphere:* The hydrosphere consists almost exclusively of all water in liquid form that is distributed around the Earth. It includes the large ocean areas, covering more than two thirds of the Earth's surface, as well as the continental areas: lakes, rivers and subterranean waters. The most important processes include ocean circulation (including heat and mass transport), river runoff and evaporation of water.

3. *Cryosphere:* The cryosphere includes all types of snow and ice on the Earth's surface, such as the large ice sheets covering Antarctica and Greenland, the Arctic and Antarctic sea ice, and all continental glaciers, snow and ice fields and permafrost. It forms a long-term water reserve and reacts to radiation-balance changes. Frozen water amounts to about 2% of the world's water. In critical regions of the globe, ice melt can significantly affect the salinity of the oceans and contribute to sea-level rise.

4. *Lithosphere/land surfaces:* The lithosphere comprises solid earth (rocks and soil cover), with its complex topography that strongly influences atmospheric and oceanic movements. Like the atmosphere and the oceans, it also absorbs and re-emits radiation, stores and evaporates water and forms a

large reservoir for dust and all sorts of particles that can be transported over long distances.

5. *Biosphere:* The biosphere contains the terrestrial vegetation, the continental flora and fauna as well as the flora and fauna of the oceans. It is important for the carbon exchange between different reservoirs (e.g. CO_2 exchange with the atmosphere), influences the heat and radiation budget and alters important physical parameters like surface roughness and albedo[30], evaporation, runoff, and field capacity[31] of the soil.

6. *Anthroposphere:* In some textbooks, the anthroposphere is not included in the climate system, and humans are seen as a disruptive, external factor of the climate system. In general, humans are responsible for the emission of different substances which change the physical and biological behaviour of the other spheres of the globe, as well as for land-use changes that lead to desertification and soil degradation.

The climate system is normally characterised by variables such as temperature, air pressure, humidity, energy, density, salinity, forces, and velocities. If we want to understand or model climate processes, we must realise that the time and length scales of selected processes that take place within the different components of the climate system are very different. This makes understanding climate processes very difficult. A number of transport and exchange processes, which are important for global radiation, energy and the heat and mass budgets, are represented in Figure 1.5. In general, the amount of shortwave incoming solar radiation energy has to be balanced by the outgoing longwave (heat) radiation. Temperature differences between different regions are expressed in air-pressure differences, which are balanced out by different wind systems. Heat and motion are also important determinants of the water cycle. Clouds can form within minutes, while large continental ice sheets form over thousands of years. Important circulation, transport and exchange processes are described in more detail in Chapter 2.

"Weather" denotes the state of the atmosphere and all related processes in a specific place or small region during a short time period of one or a few days. The most basic meteorological measurements are carried out within the lowest few metres of the atmosphere. But the classical weather layer covers around 8 km in polar regions and 17 km in tropical areas. As mentioned above, it is called the troposphere and includes important phenomena such as storms, cloud formation, heavy precipitation (including snowfall), lightning strikes, and so on. At its top, the troposphere is limited by the tropopause, a transition layer that acts as a quasi-stable boundary. As the classical weather layer, the troposphere contains 90% of all air mass and almost 100% of the water vapour. Many processes are even limited to a small layer over the Earth's surface, with a vertical extent of a few hundred metres or 1 km.

"Climate" is a statistical construct involving daily, monthly and seasonal climate variables measured over a number of decades. According to the World Meteorological Organization (WMO), the standard climate period is 30 years. In the variable climate of the higher latitudes, the periods have to be even longer if highly significant statistics are required. The idea of the climate as a horizon of expectation is certainly rooted in our mind. As the saying goes, "Climate is what you expect, weather is what you get."

The English language has no term for large-scale weather phenomena that last several days ("Witterung" in German). Terms such as weather variations, recurring weather patterns, weather spells or simply weather and climate are used instead. By concentrating on the shorter weather timescale of hours to days, the atmosphere can be treated as a single-system component. That means we can ignore the influence of long-term memory effects of the other components or spheres, shown in Figure 1.5 (e.g. the ocean heat content or the sea ice). For climate studies that include longer periods, the interaction of almost all components in the figure is essential.

Formed as a pattern of interaction, Figure 1.6 shows how different forcing factors, together with internal variability, jointly affect the main components or subsystems of the climate system. The most important natural-forcing factor on centennial to millennial timescales (see upper left box, Fig. 1.6) is called orbital forcing. The movement of the Earth in space causes remarkable global or regional changes in solar radiation over cycles or periods of thousands of years (see Chapter 2 for more details). Solar activity or solar irradiance also changes as a result of cycles, namely the 11-year sunspot cycle and longer cycles of 85, 210 or 1470 years or even more. Volcanic events cause real shocks in the climate system. The high amounts of aerosols explosively ejected into the higher atmosphere reduce the Earth's surface temperature and modify the atmospheric circulation as well as the precipitation distribution. Changes in greenhouse gas or aerosol concentration lead to changes in radiation, temperature and circulation. The increasing concentration of greenhouse gases like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) is mainly responsible for global climate changes over the past 100 years.

The upper right box in Figure 1.6 shows two important phenomena induced by internal variability within the climate system, mainly due to the complex interaction between the ocean and atmosphere. The most impor-

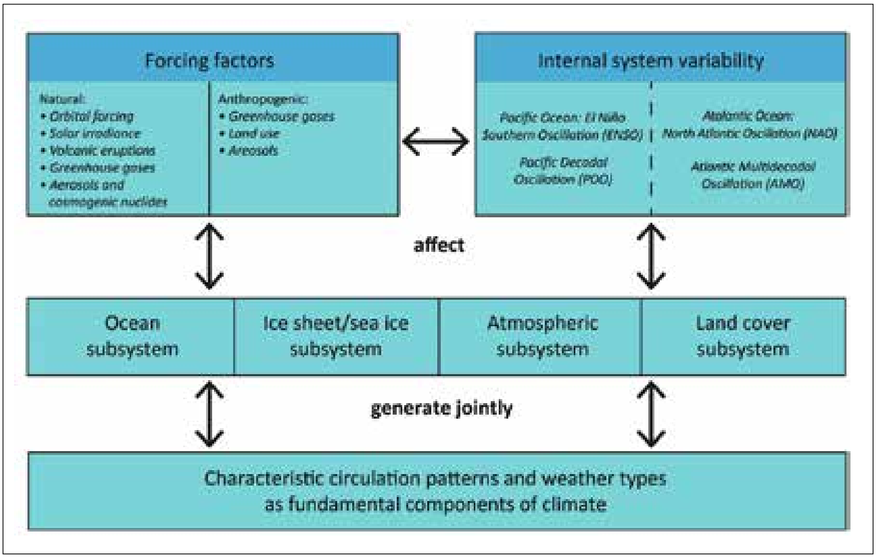


Fig. 1.6. Pattern of interaction showing the key factors and processes influencing weather and climate.

tant phenomenon is called the El Niño Southern Oscillation (ENSO). It is, more or less, a periodical west-east oriented oscillation of the air pressure and circulation in the ocean and the atmosphere of the equatorial Pacific Ocean (Fig. 1.17). The European counterpart of El Niño, called the North Atlantic Oscillation (NAO), characterises an oscillation of air pressure and sea-ice distribution in the North Atlantic area, which is most effective during the winter months (Figs. 1.17 and 1.18).

As demonstrated in Figure 1.6, forcing factors and internal system variability affect all four subsystems of the climate system. Their combination changes every day, week, month, season, year, decade, century, millennium, etc. The interaction of these subsystems generates the characteristic circulation patterns that produce average and extreme weather conditions at the local and regional scale. Therefore, climate, whether at the local, regional or global scale, is the result of all driving (forcing) factors and the internal system effects that produce the weather dynamics over a long period of time.

1.5 The global energy balance – driver of the climate system

The global energy system is driven by the Sun (Fig. 1.7). The net average incident shortwave insolation from the Sun amounts to 340 watts per square metre (W/m^2). Over a longer timescale, this energy input must be balanced by the amount of thermal energy emitted from the Earth into space. If this is not the case, the average temperature of the globe is, roughly speaking, subject to a positive or negative drift. Without an atmosphere (and therefore without any greenhouse effect) the average global temperature near the surface would be about -18°C. Organisms can only survive due to those important greenhouse gases in the Earth's atmosphere, which re-emit thermal energy back to the surface. The most important natural greenhouse gas is water vapour (H_2O). Due to the greenhouse effect, the average temperature on Earth amounts to about 15°C and not -18°C as it would be without the Earth's atmosphere. Triggered by anthropogenic activities, several greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbon (CFC), are additionally produced and affect average global temperatures.

The upper part of Figure 1.7 shows the path of the incoming shortwave radiation from the Sun during the Northern Hemisphere summer (left) and winter (right). Due to the higher position of the Sun, the tropical area receives the highest amount of energy. In addition, the solar energy is modulated by the inclination of the Earth's axis which causes polar nights during winter in both hemispheres. The lower schematic representation demonstrates that the Earth gains large amounts of energy in the tropics and loses energy in both polar regions. If this strong difference in the energy budget would not be balanced, many areas of the planet would be uninhabitable. Fortunately, this energy difference between the tropics and the polar regions is regularly balanced out by transport processes in the ocean and atmosphere.[32] Compared to the atmosphere, the equator-to-pole energy transport

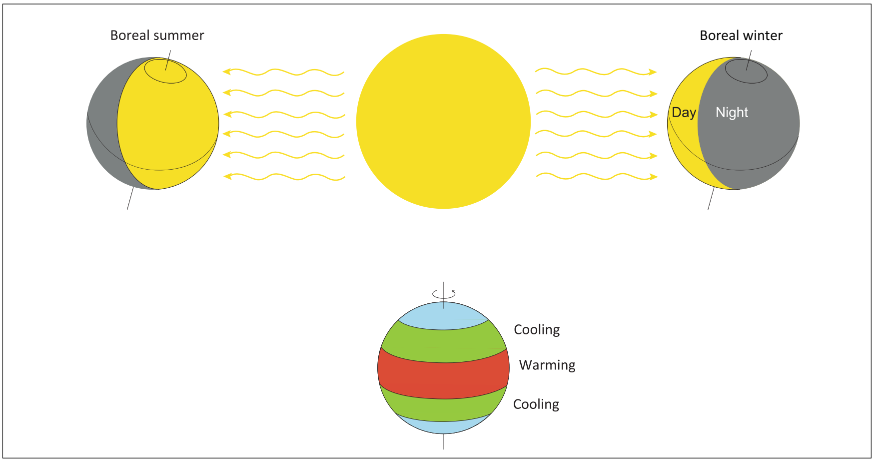


Fig. 1.7. Solar impulse of the climate system. Due to the changing angle of the incoming solar radiation, the tropics are gaining and the polar areas are losing energy (larger figures above).
Due to the obliquity of the Earth's axis this energy loss is extremely large in the corresponding winter hemisphere and leads to an enhanced energy gradient between equator and pole (smaller figure below).

through the ocean is relevant in the equatorial region, mainly also for inter-hemispheric heat transport. In the outer tropics, the exchange through the atmosphere dominates.

In addition to the heat transport, mass – in the form of air, water or water vapour, aerosols, and salt – is transported through circulation processes in the atmosphere and ocean. Europe is situated in the transition zone between warm, subtropical and cooler polar air masses. Therefore European weather and climate is highly variable (see Chapters 6–8 and 10).

1.6 What determined the Holocene energy and temperature fluctuations?

The orbit of the Earth around the Sun is pulled by the gravity of other planets. As already suggested in the previous section, the modulation of solar insolation by changes in the Earth's orbital motion sets the stage for the long-term fluctuations that occurred during the Holocene. The term Holocene denotes the actual warm period or interglacial which started about 11,700 years ago, after the end of the last glacial period. Figure 1.8 shows the three elements of Earth's orbital motion which are fundamental determinants of the insolation, the regional energy balance and the temperature of the globe. This type of forcing is also called Milanković forcing, because its physical background was first described by Serbian geophysicist Milutin Milanković (1879–1958).

The first element, called eccentricity (Fig. 1.8a), denotes the changes in the slightly elliptical path of the Earth during its annual revolution around the Sun. The Earth is actually closest to the Sun (called perihelion) around 3 January and farthest away around 5 July (called aphelion). As a result, the Earth receives about 3.5% more/less solar radiation in early January/early July. The variations in this orbital eccentricity are quasi-periodic with an average period length of about 100,000 years. The second element of orbital motion, called axial tilt (Fig. 1.8c), describes the change in the angle of the Earth's inclination between about 22.1 and 24.5°. It follows a period of about 41,000

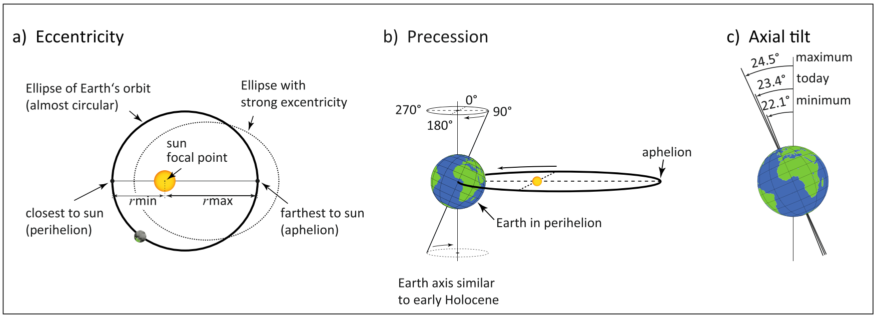
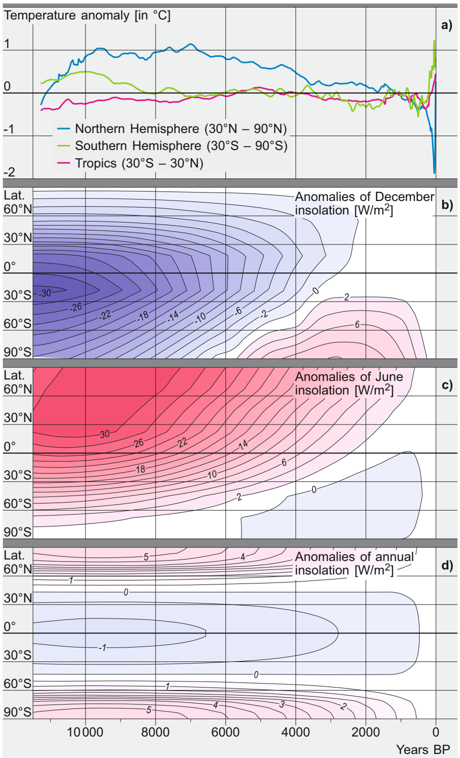


Fig. 1.8. Based on three quasi-periodic mechanisms, the position and orientation of the Earth relative to the Sun's changes causes variations of the solar insolation, called Milanković forcing. a) Change of the elliptical path of the Earth around the Sun. b) Wobbling of the Earth's axis, called precession. c) Change of the obliquity (tilt) of the Earth's axis.

years. The angle was about 24.2° at the beginning of the Holocene and stands at 23.4° today. This means that the Northern Hemisphere actually receives much less solar energy during summer. The third element of Earth's orbital motion (Fig. 1.8b) is called precession. It is characterised by a wobbling of the Earth's axis and describes a period of about 23,000 years. The influence of precession was essential in ending the Last Ice Age which began about 115,000 years ago.

The calculation of the insolation for every point on our globe has to be based on all three processes of the orbital motion. In Figure 1.9 the results are shown for the entire Holocene. The long-term average of near-surface air temperature is more or less a consequence of orbital forcing. Figure 1.9a shows three curves of Holocene temperature, reconstructed and averaged for the Northern Hemisphere, the Southern Hemisphere and the tropics. Based on various natural archives, such as ocean sediments or ice cores, the curves were reconstructed by a team led by US climate scientist Shaun Marcott. Let us first look at the mean solar insolation during boreal (Northern Hemisphere) summer (June; Fig. 1.9c). The amount of summer insolation is particularly important in the mid to high latitudes of the Northern Hemisphere, because this area is mainly covered by land masses. In the case of lower or higher solar radiation, these areas are able to amplify radiation and temperature effects, mainly through feedback from the snow and ice cover. In the case of lower (higher) temperature, the snow and ice cover increases (decreases), causing an increasing (decreasing) reflection of the incoming solar radiation and, therefore, progressively dropping (rising) temperatures. Figure 1.9c shows that during the Holocene, the insolation decreased sharply in the northern high latitudes (more than 30 W/m^2), which is an enormous amount of energy. This fact is clearly reflected in the average Northern Hemisphere temperature curve in Figure 1.9a. Therefore, a so-called Holocene Thermal Maximum (HTM) was observed between about 10,000 and 6000 years before present (BP). The precise time differed from region to region. After this maximum, the temperature decreased until the modern global warming period, reaching a temperature minimum between roughly 1300 and 1900 AD. In the literature, the cooler late Holocene period of the last

Fig. 1.9. a) Reconstructed Holocene temperature time series for three regions of the globe (°C).
b) Anomalies of the average solar insolation at the Earth's surface during December (W/m²).
c) Same as b, but for June.
d) Annual average solar insolation.



5000 years is called the Neoglacial Period.[33] Unsurprisingly most of the glaciers around the globe advanced during this period.[34]

During the austral (Southern Hemisphere) summer, represented in Figure 1.9b, the solar insolation south of the tropics increased significantly throughout the Holocene. Finally, the annual mean insolation curves in Figure 1.9d show slightly decreasing values in the northern and southern high latitudes and increasing values in the tropics. Consequently, the Holocene temperature curve of the tropics in Figure 1.9a shows a moderate temperature rise. In the Southern Hemisphere, a clear temperature maximum occurred about 10,000 years ago. Note that the changing insolation and temperature differences during the Holocene, mainly between the oceans and the continents, are a key factor in the development of monsoon systems, especially in Africa and Asia. This fact is discussed in the overview of Holocene climate in Chapter 2.

1.7 Circulation, energy and mass exchange – basic elements of climate dynamics

Figure 1.7 indicates that the energy exchange between the tropics and higher latitudes is essential for the whole biosphere of our planet. This process induces circulation processes including mass exchange. The mechanism that

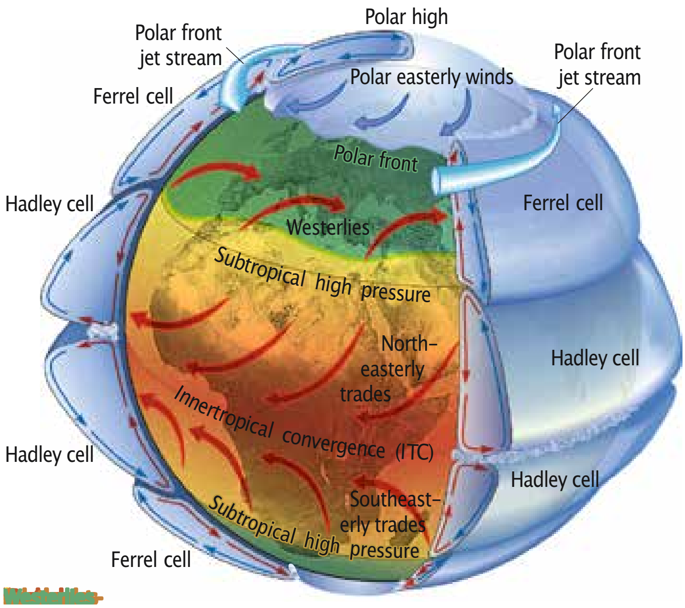


Fig. 1.10. General structure of the atmospheric exchange process called atmospheric circulation (AC).

exchanges energy and mass in the atmosphere is called atmospheric circulation (AC). In addition to the processes represented in Figure 1.7, it must be taken into account that the Earth's rotation and changes in the surface roughness between ocean and land (including mountains, rocks, forests, etc.) are responsible for the complex structure of atmospheric circulation, as shown in Figure 1.10. Over the tropical zone, two quasi-symmetric convection cells – the Hadley cells – encompass the whole globe like two ring-shaped tubes. In their lower layer, the trade winds from northeast and southeast converge over the Equator, creating an uplift of warm and moist air and inducing heavy tropical rainfall. The rising air flows back towards the poles in the upper troposphere and descends in the subtropics, generating dry anticyclones and deserts like the Sahara.

North and south of the subtropical high-pressure zones, two cells – the Ferrel cells – include dominating westerly winds. Due to the strong temperature differences between the warm tropical and cold polar air, strong westerly wind bands, called polar front jet streams, are generated in the higher troposphere. They form meanders that surround both hemispheres. In the lower atmosphere, these jets drive the mid-latitude low-pressure systems with their cold and warm fronts drifting from west to east. During European winter these mid-latitude low-pressure systems expand south to the Mediterranean area. In the continental area, the warmer winter westerlies are blocked by thermal and mechanical (roughness) effects. From December to February, cold continental air masses, driven by the cold Siberian anticyclone, periodically invade Central Europe and the Mediterranean region. During summer, the subtropical Azores High dominates in the Mediterranean area and temporarily extends to Central and Northern Europe.

Similar to the atmosphere, the ocean participates in meridional energy and mass transport between the tropics and the poles. In contrast to the AC system, the ocean circulation system (OC) has to adapt to the complex structure of the ocean basin. As Figure 1.11 shows, the energy and mass transport in the ocean is carried out in the form of the so-called "conveyor belt", which is driven by different densities as a result of variable temperatures and salinities. Warm surface currents are depicted in red, cold deep currents in blue and currents close to the ocean floor in violet. Green surfaces show areas with high salt concentrations and darker blue denotes zones with low salt concentrations. Yellow ovals mark the areas with large, sinking water masses and deep-water formations. Along the warm, equatorial zones of the globe (Indian and Pacific oceans) warm and less-dense water rises to the surface, flows around Africa and forms a bend east of Florida and the Gulf of Mexico. The sector between Florida and Greenland that transports warm and increasingly saltier water masses towards Greenland is called the Gulf Stream. Figure 1.12 shows the waves of the Gulf Stream with the transport of water masses and heat in the direction of western Scandinavia. These salty water masses cool down and, due to their high density, descend east and southwest of Greenland (Fig. 1.11; yellow ovals) and flow back towards Antarctica as deep-water currents. This circulation system between Greenland and Antarctica is called Atlantic Meridional Overturning Circulation (AMOC). It is a crucial component of long-term (centennial to multimillennial-scale) climate variability in Europe and around the world.

Understanding the exchange of energy and mass between the ocean, atmosphere, land, and vegetation, also including sea ice and continental ice sheets, is fundamental if we want to adequately understand climate variability.

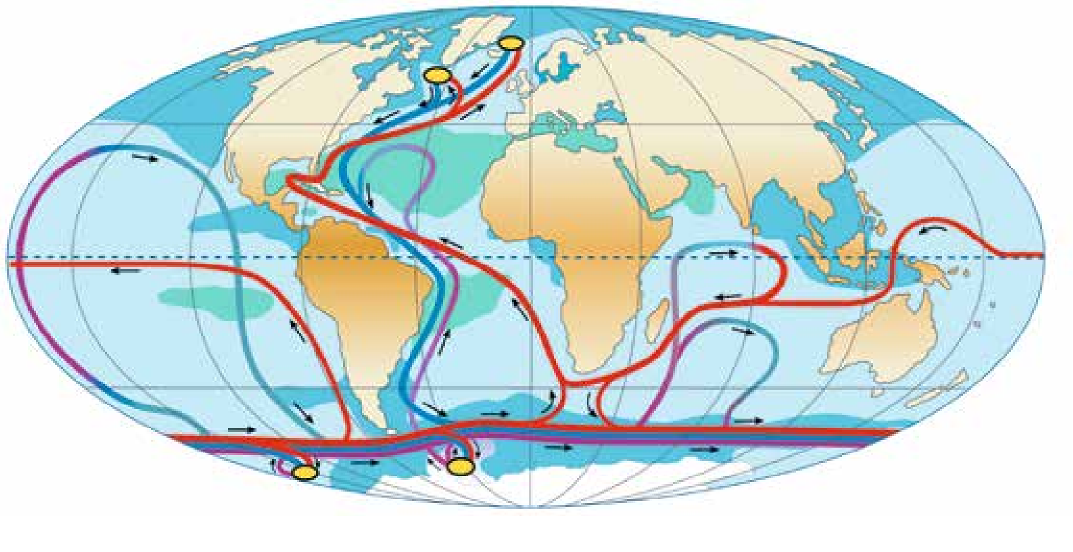


Fig. 1.11. Simplified representation of the global exchange mechanism in the ocean. Near-surface currents are depicted in red, blue marks currents in the deeper ocean, and violet shows the deepest currents near the ocean floor. Green surfaces represent areas with salt concentrations above 36‰ and darker blue surfaces mark concentrations below 34‰.

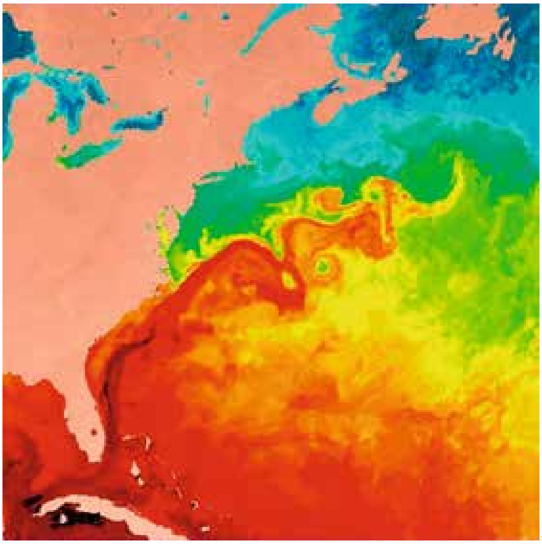


Fig. 1.12. Flow system and surface temperatures of the Gulf Stream in the central Atlantic area. Red colours mark warm water masses, blue colours show cold (Source: courtesy of Chris Kerr, NOAA/GFDL).

The exchange of heat and water vapour between the ocean and atmosphere is a key process of global climate dynamics. It is represented in a very simple drawing in Figure 1.13. Oceans mostly represent the global energy (heat) and humidity memory. They absorb the incoming shortwave radiation from the Sun, transform this energy into heat, emit this heat into the atmosphere, and evaporate water vapour. The atmospheric circulation systems stimulate and drive the ocean currents, precipitate large amounts of water, and help transport large amounts of mass and energy from the ocean areas to the continents, and vice versa. The timescale of the atmospheric processes that influence the ocean (green arrow in Fig. 1.13) is rather short. In particular, tropical hurricanes and mid-latitude storms can significantly modify ocean currents, ocean temperature and salinity. The ocean acts as a memory and is able to transmit its properties (heat, humidity) to the atmosphere, on timescales of several weeks to months or even longer (red arrow in Fig. 1.13). Together, these processes are mainly responsible for the formation of complex climate patterns with typical characteristics and effects, called modes of climate variability. These modes often oscillate with a certain periodicity and determine the continental or even hemispheric climate. As mentioned previously, the most important mode in the Pacific is the ENSO. The North Atlantic–European area is strongly affected by the NAO, which will be described in more detail later.

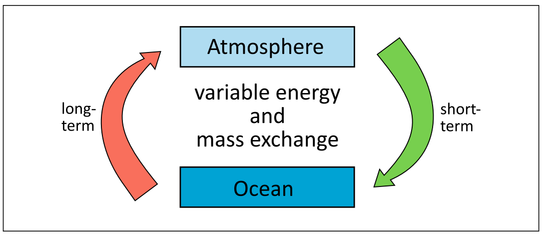
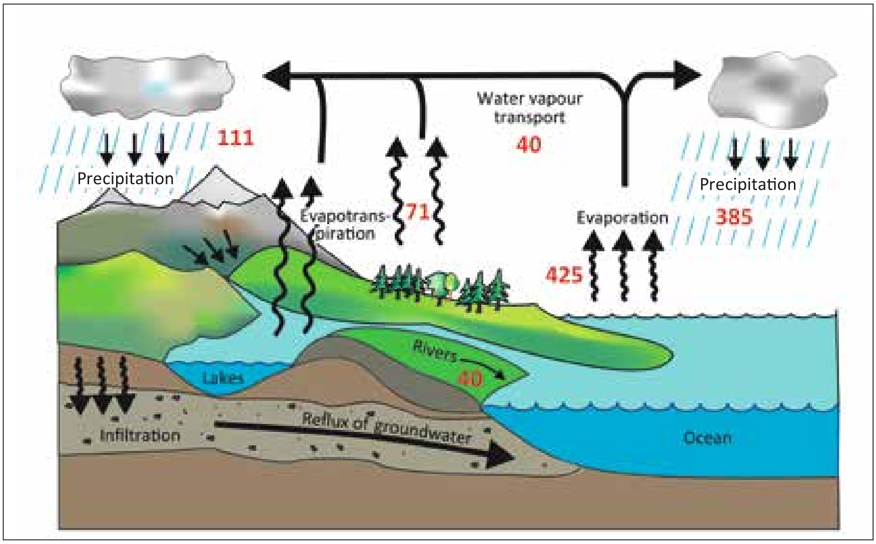


Fig. 1.13. Simple drawing of the mechanism representing the exchange process between the atmosphere and ocean.

Fig. 1.14. Schematic picture of the global water cycle. Numbers show the estimated water or water-vapour mass in 1000 km³/yr.



One of the fundamental cycles in the global climate system is the water cycle represented in Figure 1.14. It shows the exchange of water in its three states (gaseous, liquid, solid) between ocean, land and ice surfaces. Oceans cover 70% of the Earth's surface, while freshwater on the globe amounts to only 2.5%. A large part of this freshwater is stored as groundwater or ice. Large areas of the Earth, especially in the subtropics, are arid. Figure 1.14 shows the water cycle in units of 1000 cubic kilometres per year (km^3/yr). The largest component of the solar-driven water circulation system is evaporation from the ocean into the atmosphere, with 425,000 km^3/yr. A similar amount, namely 385,000 km^3/yr, falls over the ocean. The remaining 40,000 km^3/yr make up the net transport to the land surfaces in the form of water vapour or clouds. Only 71,000 km^3/yr evaporate over land surfaces, while the total precipitation amounts to 111,000 km^3/yr. Incidentally, the average precipitation for the entire globe is roughly 1 m (~ 973 mm) per year, with higher values over the ocean and less precipitation (715 mm) over land. European precipitation is fed by two main humidity sources, the North Atlantic Ocean and the Mediterranean Sea.

1.8 Forcing disturbances and internal variability generate climate change

Climate alters on different timescales, from years to millions of years. As shown in Figure 1.6, the change is the result of disturbances caused by variable forcing factors and internal variability within the complex climate system. Figures 1.8 and 1.9 show that the most important long-term forcing factor exists in the form of the three quasi-periodic mechanisms of orbital (Milanković) forcing.

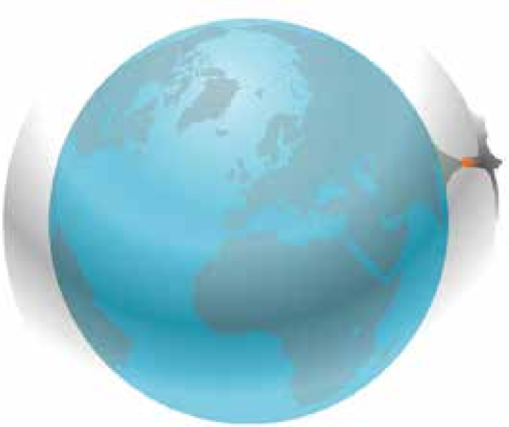


Fig. 1.15. Hypothetical distribution of the stratospheric aerosol cloud after a strong volcanic eruption in the tropics (Source: Stefan Brönnimann).

The most important short-term climate forcing is most likely caused by large volcanic eruptions.[35] Volcanic forcing is particularly efficient when large volcanic eruptions occur in tropical areas. In this case, the aerosol mass rises into the stratosphere (about 40 km above sea level), and the slowly descending aerosols are transported to both hemispheres by the stratospheric Brewer-Dobson circulation, as demonstrated in Figure 1.15. The lower tropospheric Hadley circulation (Fig. 1.10) is more or less symmetric, but the stratospheric Brewer-Dobson circulation, which is driven by atmospheric waves (vertically propagating Rossby, or planetary waves), is asymmetric in the sense that a large circulation mostly points from the tropics to the winter pole. Therefore, it is important to know the season of each volcanic eruption. During the Northern Hemisphere summer, more aerosol mass is transported within the stratosphere towards the Southern Hemisphere and vice versa, accompanied by increasing amounts of summer precipitation. It is particularly important to consider the chemical and physical characteristics of the volcanic aerosol in order to understand the effects of a particular volcanic eruption. Figure 2.8c shows the most important volcanic eruptions during the last 2000 years. More details will be discussed later in the context of the Tambora event (Chapter 3).

The irradiation of the Sun is subject to fluctuations that are more or less periodic.[36] It is well known that the number of sunspots follows a period of about 11.1 years, called the Schwabe cycle. The incoming solar radiation is higher if the number of sunspots is also high, despite the fact that the surface temperature of the dark sunspots is lower than that of their surroundings. Even if the dynamics of the solar dynamo are not fully understood, we know that the range of solar insolation between high and low solar activity varies by only a few tenths of a watt per m^2. Figure 1.16 shows a photo of the Sun and its dynamic behaviour, with brighter and darker areas. Over a period of thousands of years, the Grand Solar Minima (GSMs) are of special interest. A certain period is called a Grand Solar Minimum (GSM) if several consecutive 11.1-year-long Schwabe cycles exhibit very low irradiance values (see Fig. 6.9b). The statistical analysis of solar irradiance shows that, in addition to the Schwabe cycles, there are several longer cycles with changing solar irradiance, namely the Gleissberg cycle of about 90 years or the Suess cycle of about 210 years. An often described GSM is the Maunder Minimum, which lasted from about 1645 to 1715 AD. A curve with the solar irradiance of the last 2000 years including the lower values of the Maunder Minimum is represented in Figure 2.8d.

As already mentioned, the climate system is also subject to internal (stochastic) variability, mainly generated by non-linear interactions which, according to Figure 1.12, are mostly generated by exchange processes between the ocean and atmosphere. Two phenomena are particularly effective. Both consist of a seesaw effect in the ocean-atmosphere system (Fig. 1.17). The first and most important worldwide phenomenon, the ENSO phenomenon, encompasses a zonal-oriented seesaw in the water masses of the Pacific Ocean. The term El Niño denotes the oceanic part and Southern Oscillation is the atmospheric part of this phenomenon. El Niño is a Spanish term, created by fishermen along the coast of Peru, which means "Little Boy" or "Christ Child". It describes a warming of the waters off Peru, which occurs every two to seven years, when there is an interruption in the upwelling of cold, nutrient-rich water along the Humboldt Current, which flows north along the west coast of South America to Peru. The cause is a warm water wave (called a Kelvin wave), which is triggered in the central equatorial Pacific, spreads towards the South American coast and hinders the upwelling; therefore, the fish stocks are heavily depleted. The phenomenon was first discovered in the 1920s by British meteorologist Sir Gilbert Walker (1868–1958), who described a west-east air-pressure seesaw between the subtropical high-pressure system in the southeastern Pacific Ocean (the weather station is on Tahiti) and a low-pressure system over Indonesia (weather station in Jakarta). On the global level, the El Niño phenomenon generates a warming effect of a few tenths of a degree Celsius, which increases precipitation, especially in northwestern South America and southwestern USA, as well as dryness in Southeast Asia and Southeast Africa. The opposite state of the ocean and atmosphere, called

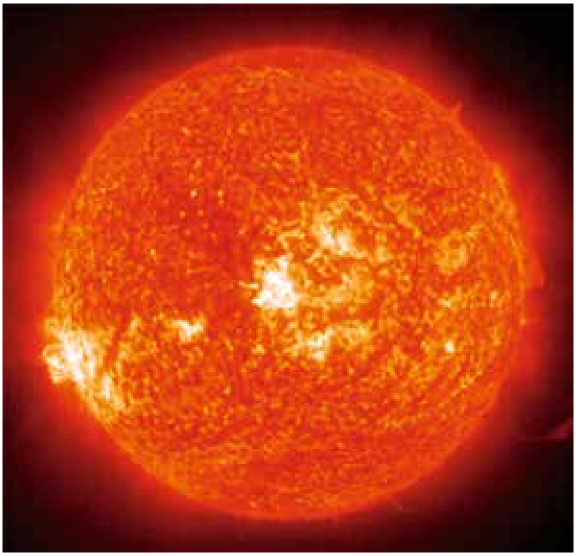


Fig. 1.16. An ultraviolet-wavelength picture of the Sun taken by the ESA/NASA Solar and Heliospheric Observatory (SOHO) on 23 October 2003 (Source: NASA).

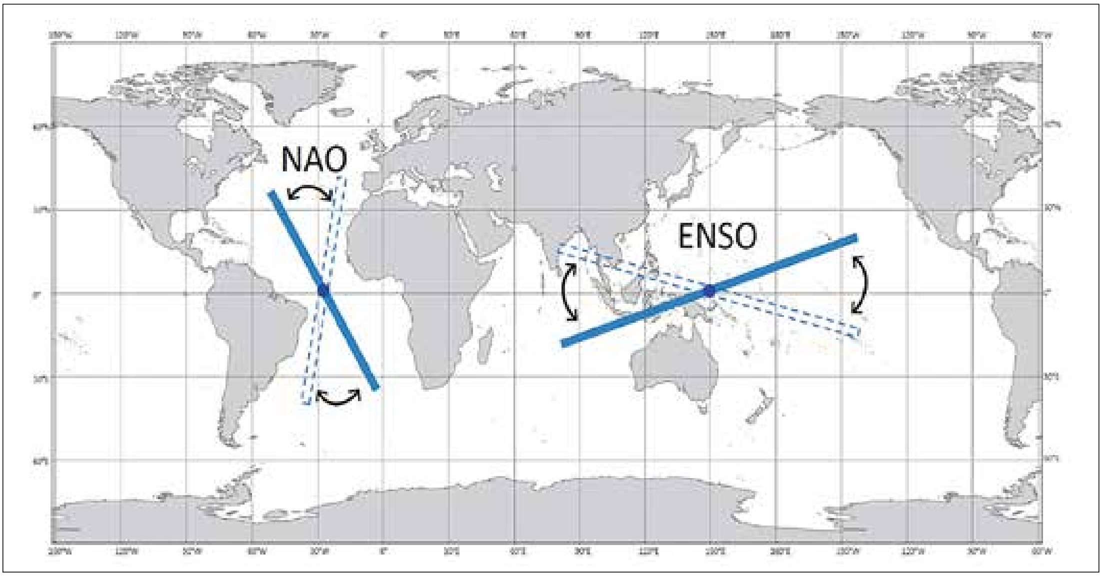


Fig. 1.17. Most-important phenomena related to internal (stochastic) variability within the climate system. NAO: North Atlantic Oscillation. ENSO: El Niño Southern Oscillation.

La Niña (meaning "Little Girl"; the younger sister of El Niño) is connected with a cold eastern Pacific area, lower temperatures mainly in the Southern Hemisphere, heavy precipitation in Australia and Southeast Asia, as well as strong dryness in southwestern USA and parts of South America. The teams of German meteorologist Klaus Fraedrich[37] and Swiss climatologist Stefan Brönnimann[38] showed that ENSO hardly influences European weather and climate. There is a weak trend towards lower winter temperatures in northwestern Europe with occasionally heavier snowfalls (see more detailed explanations in Chapter 6).

The second important phenomenon that arises from internal variability and is important for understanding European climate is the NAO. In contrast to ENSO, it is a meridional-oriented seesaw in the rather small Atlantic Ocean basin (Fig. 1.17). Similar to ENSO in the Pacific area, the NAO describes a pressure oscillation between Iceland (measured at the Stykkisholmur meteorological station) and the Azores (Ponta Delgada station) or the Iberian Peninsula (Lisbon station) that is mostly active in winter. With the help of the pressure differences, two states are differentiated as well. During his stay in Greenland, Danish missionary Hans Egede Saabye (1746–1817) discovered that the winter weather and climate in Greenland were often opposite to that in Scandinavia. It was again the important work of Walker who defined an index of the NAO, which characterises its two states represented in the form of the seesaw in Figure 1.17.

Figure 1.18 shows the climate characteristics of the positive and negative modes of the NAO seesaw phenomenon. In the case of a positive NAO index (Fig. 1.18a), air pressure is very high over the Azores and extremely low over Iceland. Simultaneously, two pools with cooler water (blue) exist east of

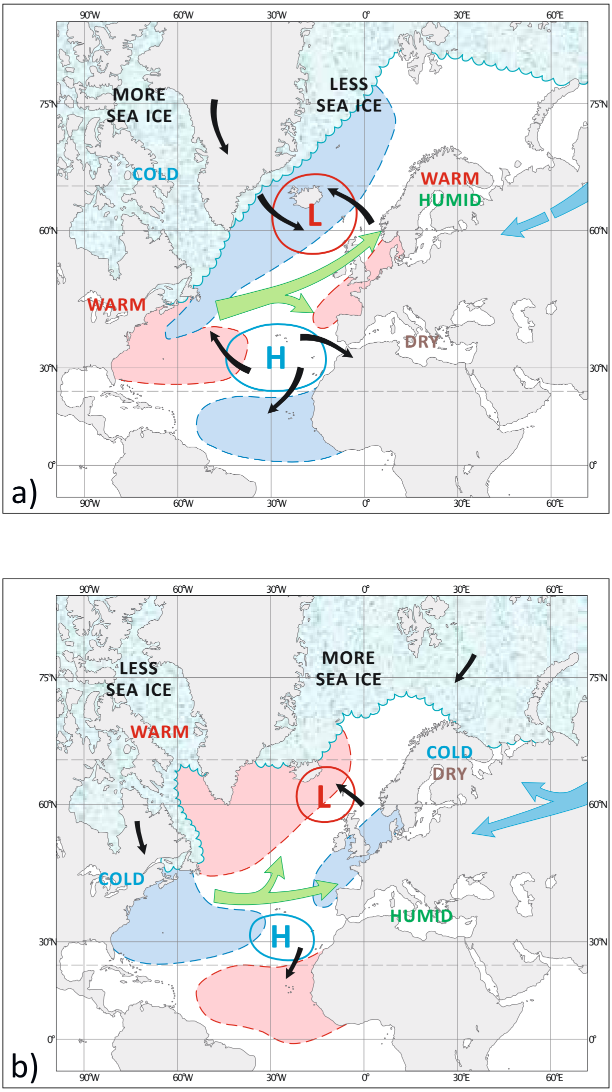


Fig. 1.18.
a) Schematic representation of the state of the European climate system in case of a positive mode of the NAO.
b) Negative mode of NAO. Blue and red colours mark areas with negative or positive sea surface anomalies. Green arrows show the direction and strength of westerly winds. Blue arrows represent the direction and strength of northeasterly winds with cold-air advection. Black arrows mark the wind direction in the lower atmosphere.
L: Icelandic Low.
H: Azores High.

Greenland and west of North Africa, and two warmer pools (red) can be distinguished east of Florida and in the eastern North Atlantic between Spain and southern Scandinavia. Due to the strong temperature and air-pressure difference between the subtropical Atlantic Ocean and its higher mid-latitude area between Iceland and Scandinavia, strong westerly winds dominate along an axis reaching from the southwest Atlantic Ocean to western Scandinavia (large green arrow). Active cyclones often drift to the European continent and, consequently, the frequency of wintertime advection of cold continental air from the northeast (small blue arrow) is low. Therefore, the weather is anomalously warm and humid in Northern Europe and dry in Southern Europe and North Africa, when low temperatures dominate over eastern Canada. West of Greenland, the sea ice extends far south and stays north between Greenland and Svalbard. In negative mode (Fig. 1.18b) the conditions are opposite, with anomalously high air pressure over Iceland and rather low pressure over the Azores. In extreme cases, the air pressure is even higher over Iceland, called NAO reversal, and the winters are extremely cold and often very dry. During this negative NAO mode, the warm-water pools are located north and south and the cold pools west and east. The westerly winds are weak and point to the Mediterranean area. The weaker westerlies (small green arrow) lead to strong outbursts of cold continental air from Siberia to Central and Northern Europe (larger blue arrow). Therefore, cold and dry weather dominates over Scandinavia, and the Mediterranean area is subject to higher humidity and precipitation. Eastern Canada and western Greenland are warm, cold conditions prevail east of Greenland, and the sea ice reaches the northern coast of Iceland and surrounds Nowaja Semlja. The NAO can have a similar weather pattern ranging from a few years to more than 10 years. Its longer time series and influence on European climate will be discussed further in Chapter 6.

1.9 The structure of the book

The book is designed as a synthesis between a natural science and a social science approach. It should help to develop a better understanding of the topic, step by step, by means of examples. The presentation is organised into 11 chapters, which are subdivided into sections. Selected inserts break the thread of scientific discussion by bringing more personal stories into play.

This introduction (Chapter 1) clarifies the perspectives of the natural sciences and humanities in dealing with the climate issue. It shows how their positions complement each other in bringing climate change and society together during the last 1000 years. Particular attention is paid to the global climate system and how it functions.

Recounting the story of the iceman Ötzi in Chapter 2 introduces the climate history of the Holocene. The last 1000 years of the Holocene represent a characteristic oscillation between cooler and warmer periods, finally entering the modern anthropogenically influenced warming. In particular, this chapter discusses why it was warm during Ötzi's lifetime and why his body, which was buried under snow for 5250 years, unexpectedly thawed in 1991; changes in the Earth's orbital parameters and rapid man-made warming play a special role here.

Large volcanic eruptions in the tropics influence both climate and human history. This topic is well illustrated in Chapter 3, using the best-case example of the Indonesian volcano Tambora; its eruption in 1815 triggered the last famine in Western and Central Europe. The effects of the eruption on the global climate system and regional climates are illustrated, but also show that the severity of the impact on human societies varied according to the quality of the social system and the integration of the transregional division of labour.

Chapter 4 reveals how, fundamentally, the perception of weather has changed over the last 1000 years. It began with the belief in natural spirits and religious miracles and ended with the observation of global weather by satellites. The Graeco-Arabic Renaissance in the 12th century opened the eyes of chroniclers to the inherent dynamics of the natural world and introduced a more realistic style of weather narratives. The invention of meteorological instruments in the 17th century and the establishment of measurement networks paved the way for the development of meteorology in the 19th century. The rise in climatology was spurred on by the ongoing research in global warming in the late 20th century.

The natural sciences and historical climatology have developed an immense variety of proxy data that allow temperature and precipitation estimations from the time before instrumental measurements began. Their possibilities and limitations are illustrated in Chapter 5. Subsequently, the concept of indices is introduced, underlying the temperature reconstructions applied in Chapters 7 and 8 and partly in 10.

Chapter 6 first describes the spatial dynamics of the current climate of Europe. Afterwards, climate development during the last 1000 years is outlined, based on data from the archives of nature. A focus is put on the main multidecadal driving factors – the Sun and volcanic eruptions – which trigger perennial variations. In addition, the role of internal variability is discussed, and the dynamics of the last 1000 years are further reconsidered, based on a simulation.

Chapters 7 and 8 present a high-resolution picture of seasonal temperatures over the millennium prior to the transition to rapid warming in 1988. Both chapters are based on Pfister-Indices related to Western and Central Europe. Both cold and hot extremes are described using the sources. The climate of the High Medieval Period (HMP), from 1000 to 1300 AD (Chapter 7), included two warm periods that were separated by a cold 12th century. The BLIA, presented in Chapter 8, involved extensive glacier advances in the late 14th, late 16th, mid-17th, late 18th, and mid-19th centuries.

Chapter 9 shifts the focus from climate to population, where statements are subject to great uncertainty. It is important to note that weather and climate, along with wars and epidemics, were just one determinant known to affect population size in agrarian societies. After all, societies had their own incentives independent of external influences. Populations were relatively resilient to crop failures. The most severe famines were related to extremes unmatched within the last centuries. The warm 13th century stands out as the major demographic and economic boom period, entailing a mushrooming of cities and cultural prosperity. The plague, introduced from East Asia to Europe in the mid-14th century, reduced the population in several waves by about 40%. After the eradication of the plague, the wider distribution of corn and potatoes and an improved efficiency in farming strategies in the 18th century led to a sustained population increase, with famines gradually declining.

Chapter 10, drawing on seasonal temperature reconstructions since the 12th century and the facts discussed in Chapter 6, presents a fresh look at the complex transition from the HMP to the BLIA, which turned out to be primarily a period of cold winters. The climatological interpretation yielded characteristic signals of medium- to long-term climate fluctuations. After a diagnostic overview of possible reasons for these features, their effects on glaciers, tree lines and human affairs are discussed.

Chapter 11 highlights the transition from slow to rapid warming in Europe around 1988–89. It highlights the pioneering work which resulted in the