Frontiers in Earth Sciences

Gilles Ramstein
Amaëlle Landais
Nathaelle Bouttes
Pierre Sepulchre
Aline Govin *Editors*

Paleoclimatology

Springer

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Gilles Ramstein • Amaëlle Landais •
Nathaelle Bouttes • Pierre Sepulchre •
Aline Govin
Editors

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Editors
Gilles Ramstein
LSCE/IPSL, CEA-CNRS-UVSQ
Université Paris-Saclay
Gif-sur-Yvette, Ariège, France

Amaëlle Landais
LSCE/IPSL, CEA-CNRS-UVSQ
Université Paris-Saclay
Gif-sur-Yvette, Ariège, France

Nathaelle Bouttes
LSCE/IPSL, CEA-CNRS-UVSQ
Université Paris-Saclay
Gif-sur-Yvette, Ariège, France

Pierre Sepulchre
LSCE/IPSL, CEA-CNRS-UVSQ
Université Paris-Saclay
Gif-sur-Yvette, Ariège, France

Aline Govin
LSCE/IPSL, CEA-CNRS-UVSQ
Université Paris-Saclay
Gif-sur-Yvette, Ariège, France

ISSN 1863-4621 ISSN 1863-463X (electronic)
Frontiers in Earth Sciences
ISBN 978-3-030-24981-6 ISBN 978-3-030-24982-3 (eBook)
https://doi.org/10.1007/978-3-030-24982-3

Translated from the original French by Mary Minnock

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

A brief history of paleoclimates

Climate is undeniably a topical issue of utmost importance. It has been the focus of attention for several decades now, during which the study of ancient climates (paleoclimatology) has progressed and gained a solid reputation. Currently, this work has become fundamental to our understanding of how the climate system functions and to validate the models used to establish future projections. Thanks to the study of past climates, a database documenting a much greater diversity of climate changes than during recent centuries, has been created. This diversity makes it possible to test climate models in situations that are vastly different from those we have known over the last 150 years and, in some cases, for climates that are closer to those that await us in the future if we apply the conclusions of the Intergovernmental Panel for Climate Change.

The Earth's climate changes have always changed over time and will continue to change in the future. While we are all aware of the weather phenomena that condition our daily lives, few of us are aware of what climate really is. Climatology is the science that explores the great variability in meteorological conditions over time and space, throughout history. This word comes from the Greek word *klima* meaning inclination, in this case referring to that of the rays of the Sun. Since the dawn of our civilization, therefore, we have linked the variations in climate and in the energy received from the Sun in a relationship of cause and effect. For a long time, the term 'climate' was reserved to describe the characteristics of air temperature and precipitation particular to different parts of the globe. This description was based on meteorological measurements and their averages conducted over a few decades. It is only recently understood that climate also varies over much longer time scales and therefore concerns more than just the atmosphere. At present, specialists studying climate and its variations analyze all of the fluid and solid envelopes of the Earth. Along with the atmosphere, we associate the hydrosphere and the cryosphere which, together, represent the systems where water exists in solid (snow, glaciers, and ice sheets) and liquid form (rivers, lakes, and seas), the continents where plate tectonics and volcanic activity occur, and finally at the surface, the whole living world (biosphere) that influences nature, the properties of soil cover, and the biogeochemical cycles.

Climatology has evolved from being a descriptive discipline to become a multidisciplinary science involving five complex systems and their various interactions. It is therefore not surprising that the resulting climate studies vary on scales ranging from the season to millions of years. Although it is only in the last few decades that this science has exploded, the first discovery and study of climate change beyond the annual and decadal scales date back to the eighteenth century. It was at this time that the presence of erratic boulders in the mountainous landscape became associated for the first time with the massive extension of glaciers. In 1744, the Grenoble geographer Pierre Martel (1706–1767) reported that the inhabitants of the Chamonix Valley in the Alps attributed the dispersion of *roches moutonnées* to the glaciers themselves, which would have extended much further in the past. This was a revolutionary idea, because until then, most scientists still referred to the myth of the Biblical Flood to explain landscape structures. This was the case of Horace Benedicte de Chaussure (1740–1799) from Geneva, the French paleontologist, Georges Cuvier (1769–1832) and the Scottish geologist, Charles Lyell (1797–1875), who continued to assume that these boulders were carried by the strength of strongly flowing waters. However, the location and nature of these boulders and other moraines led some scientists to admit that ice transport would provide a better explanation for the various observations. The Scottish naturalist, James Hutton (1726–1797), was the first to subscribe to this idea. Others followed his lead and detected the imprint of climatic changes in the fluctuations of the extent of the glaciers. These pioneers were the Swiss engineer, Ignace Venetz (1788–1859); the German forestry engineer, Albrecht Reinhart Benhardi (1797–1849); the Swiss geologist, Jean de Charpentier (1786–1855); and the German botanist, Karl Friedrich Schimper (1803–1867), who introduced the notion of ice ages. But it was the Danish-Norwegian geologist, Jens Esmark (1763–1839), who, in pursuing his analysis of glacier transport, proposed in 1824, for the first time, the notion that climate changes could be the cause and that these could have been instigated by variations of Earth's orbit.

It was the work of these pioneers that led the Swiss geologist, Louis Agassiz (1801–1873) to make the address to the Swiss Society of Natural Sciences of Neufchatel in 1837 entitled 'Upon glaciers, moraines and erratic blocks'. It was also at the beginning of the nineteenth century that the Frenchman Joseph Adhémar (1797–1862), not content with studying the polar ice caps, attempted to explain in his book, *Révolutions de la Mer, Déluges Périodiques* (1842), the pattern of ice ages stemming from the precession of the equinoxes. The astronomical theory of the paleoclimates was born and would be continued, thanks to the development of celestial mechanics, by the Frenchmen, Jean le Rond d'Alembert (1717–1783), Jean-Baptiste Joseph Delambre (1749–1822), Pierre-Simon Laplace (1749–1827), Louis Benjamin Francoeur (1773–1849), and Urban Le Verrier (1811–1877). In parallel, other advances were made with the first calculations of the long-term variations in the energy received from the Sun, variations due to the astronomical characteristics of the eccentricity of the Earth's orbit, the precession of the equinoxes, and the obliquity of the ecliptic. This was demonstrated by the work of John Frederick William Herschel (1792–1871), L.W. Meech (1821–1912), and Chr. Wiener (1826–1896), supported by the work of the mathematicians André-Marie Legendre (1751–1833) and Simon-Denis Poisson (1781–1840).

This sets the stage for James Croll (1821–1890) to develop a theory of ice ages based on the combined effect of the three astronomical parameters, a theory according to which winter in the northern hemisphere played a determining role. This theory was much appreciated by the naturalist, Charles Robert Darwin (1809–1882), and was taken up by the Scottish geologist brothers, Archibald (1835–1924) and James (1839–1914) Geikie, who introduced the notion of the interglacial. It is also the basis for the classification of alpine glaciations by Albrecht Penck (1858–1945) and Edward Brückner (1862–1927) and American glaciations by Thomas Chowder Chamberlin (1843–1928). However, geologists became increasingly dissatisfied with Croll's theory and many critics of it emerged. Many refuted the astronomical theory and preferred explanations that related to the Earth alone. The Scottish geologist, Charles Lyell (1797–1875), claimed that the geographical distribution of land and seas explained the alternation of hot and cold climates, while others turned to variations in the concentration of certain gases in the atmosphere. Hence, the French physicist, Joseph Fourier (1786–1830), expounded on the first notion of the theory of the greenhouse effect. He was followed by the Irish chemist, John Tyndall (1820–1893), to whom we owe the first experiments on the absorption of infrared radiation and the hypothesis of the fundamental role played by water vapor in the greenhouse effect. Later, the Italian, Luigi de Marchi (1857–1937) and the Swedish chemist, Svante Arrhenius (1859–1927) proposed, along with other scientists of their time, that the ice ages were caused by decreases in atmospheric carbon dioxide concentration. In 1895, Arrhenius suggested, in an article published by the Stockholm Physics Society, that a 40% reduction or increase in CO2 concentration in the atmosphere could lead to feedback processes that would explain glacial advances or retreats.

A revival of the astronomical theory became, however, possible with advances in the calculation of astronomical elements by the American astronomer John Nelson Stockwell (1822–1920) and the Serbian astronomer Vojislava Protich Miskovitch (1892–1976) and of solar irradiation (1904) by the German mathematician, Ludwig Pilgrim (1879–1935). It was Joseph John Murphy (1827–1894), however, who, as early as 1869, proposed that cool summers of the northern hemisphere had instigated the ice ages. This original idea was taken up in 1921 by the German paleoclimatologist Rudolf Spitaler (1859–1946), but was popularized by the Serbian geophysicist engineer, Milutin Milankovich (1879–1958), mainly through his books *Mathematical Theory of Thermal Phenomena Produced by Solar Radiation* (1920) and *Kanon der Erdbestrahlung und seine Anwendung auf des Eizeitenproblem* (1941). Milankovitch was a contemporary of the German geophysicist Alfred Wegener (1880–1930) with whom he became acquainted through the Russsian-born climatologist Wladimir Köppen (1846–1940), Wegener's father-in-law (Thiede, 2017). The modern era of astronomical theory was born, even if there remained much criticism related to the lack of reliable paleoclimatic data and of a reliable timescale, both by geologists and meteorologists. It was not until the 1950s and 1960s that new techniques made it possible to date, measure, and interpret the climate records contained in marine sediments, in ice and on land. In 1955, the American, Cesare Emiliani (1922–1995), proposed a stratigraphy, which still applies today, based on the succession of minima and maxima of the oxygen-18 / oxygen-16 isotopic ratio measured in the foraminiferal shells found in sediments taken from the deep ocean. The interpretation of this isotopic ratio in terms of salinity was made by Jean-Claude Duplessy (1970), and in terms of temperature and volume of ice (1973) by Nicholas Shackleton (1937–2006) and Niels Opdyke (1933–2019). Mathematical tools made it possible to establish transfer functions to quantitatively interpret information collected in the oceans in 1974 by the American paleoceanographers John Imbrie (1925–2016) and Nilva Kipp (1925–1989),) and in tree rings (Harold Fritts, 1968). Efforts by the CLIMAP group (1976) resulted in the first seasonal climate chart of the Last Glacial Maximum and the pivotal article by James Hays, John Imbrie, and Nicholas Shackleton (1976). The arrival of big computers allowed the first climate simulations to be conducted using general circulation models (Fred Nelson Alyea, 1972), and further astronomical calculations led to the establishment of a high-precision time scale reference, as well as the determination of the daily and seasonal irradiation essential for climate modeling (André Berger, 1973 and Berger and Loutre, 1991).These calculations of the astronomical parameters were based on the 1974 and 1988 developments of the orbital elements by the French astronomers Pierre Bretagnon (1942–2002) and Jacques Laskar, respectively. These are valid over a few million years. The Laskar solution was extended over a few tens of millions of years by Laskar et al. (2011) and over the whole Mesozoic with the American paleobiologist Paul Olsen and colleagues (2019).

This evolution and the recent advances in paleoclimatology show the difficulties involved in tackling the study of the climate system. Overcoming these difficulties requires high-quality books to improve understanding and to update the range of disciplines involved. It is with this perspective in mind that this book was written. Written originally in French, it unquestionably fills a gap in the field of graduate and postgraduate third-level education that goes far beyond its description. It provides an overview of the state of knowledge on a number of key topics by outlining the information necessary to understand and appreciate the complexity of the disciplines discussed, making it a reference book on the subject. The first of the two volumes is devoted to the methods used to reconstruct ancient climates, the second to the behavior of the climate system in the past. Many of the thirty-one chapters are written by researchers from the *Laboratoire des Sciences du Climat et de l'Environnement* and associated research laboratories each focusing on his or her area of expertise, which ensures a reliable document founded on solid experience.

Understanding the evolving climate of the Earth and its many variations is not just an academic challenge. It is also fundamental in order to better understand the future climate and its possible impacts on the society of tomorrow. Jean-Claude Duplessy and Gilles Ramstein have achieved this huge feat by bringing together fifty or so of the most highly reputed researchers in the field.

The book they have written is a whole, providing both the necessary bases on the reconstruction techniques of ancient climates, their chronological framework, and the functioning of the climate system in the past based on observations and models. This book will allow all those who want to know more, to explore this science, which, although difficult, is hugely exciting. It will also give them the essential information to establish an objective idea of the climate and its past and future variations.

You may find most of the references and pioneering studies mentioned in this preface in BERGER A. 2012. A brief history of the astronomical theories of paleoclimates. In: "Climate change at the eve of the second decade of the century. Inferences from paleoclimates and regional aspects". Proceedings of Milankovitch 130th Anniversary Symposium, A. Berger, F. Mesinger, D. Sijacki (eds). 107–129. Springer-Verlag/Wien.DOI 10.1007/978-3-7091-0973-1.

André Berger
Emeritus Professor at the Catholic University of Louvain
Louvain la Neuve, Belgium

Introduction

For a long time, geology books devoted only a few lines to the history of past climates of our planet, mostly to establish the deposition framework for the sediments that geologists found on the continents, the only area of enquiry available to them. Scientists soon realized that the copious coal deposits of England, Belgium, Northern France, Germany, and Poland resulted from the fossilization of abundant vegetation facilitated by a warm and humid equatorial climate that reigned over Western Europe, some 350 million years ago (an illustrated insert in Chap. 2 volume I provides a diagram of continental drift since 540 Ma). Fifty million years later, the sediments of these same regions, red sandstone, poor in fossils and associated with evaporites testify to the replacement of forests by desert areas, dotted with occasional highly saline lakes, similar to what we currently find in Saharan Africa. Humidity gave way to intense aridity and we had no idea why. It was not until the discovery of plate tectonics that we realized that Europe had slowly drifted toward the tropics. This transformation of the face of the Earth due to tectonics is illustrated through 16 maps in Chap. 2 volume I.

The discovery of glaciations was a revelation for the geologists of the nineteenth century. A major polemic broke out at the Swiss Society of Natural Sciences in Neuchâtel when, in 1837, its president Louis Agassiz presented his explanation, incredible at the time, for the presence of gigantic boulders that dot the Jura mountains. He daringly claimed that these erratic boulders were not the remnants of the Biblical Flood, but rather enormous rocks transported over long distances by gigantic glaciers which used to cover the high latitudes of our hemisphere.

The controversy died down quickly, when European and American geologists discovered traces of glaciers all over the Northern Hemisphere, just as Agassiz imagined. In Europe, as in North America, mapping of the terminal moraines left behind by glaciers when they melted showed proof of the presence of gigantic ice caps in a past that seemed distant. especially since there was no idea how to date them.

As the idea of the Biblical Flood fell out of favor, a new theory, based on astronomical phenomena, soon appeared. Scientists like Joseph Adhémar and James Croll realized that there were small, quasi-periodic variations over time in the movement of the Earth around the Sun and suggested that associated mechanisms could periodically cause glacial advances and retreats. Finally, it was Milutin Milankovitch, a professor in Belgrade, who would lay the foundations for a complete mathematical theory of glaciations, the legitimacy of which was proven when paleoceanographers found the frequencies of orbital parameters reflected in the isotopic analysis of marine cores. We now know that the last one of these glacial periods culminated only 20,000 years ago and was preceded by many others.

The great contribution by Milankovitch was to plant a new idea within the scientific community: Ancient climates are not only of immense curiosity to geologists; they obey the same physical laws as those governing the current climate.

This intellectual revolution has had far-reaching consequences and has profoundly altered the approach to the study of ancient climates making paleoclimatology a science with many links to geology, geochemistry, oceanography, glaciology as well as the approach to the physical and dynamic dimensions of the climate. The first part of this book describes the physical, chemical, and biological phenomena that govern the functioning of the climate system and shows how it is possible to reconstruct the variations in the past at all timescales.

This is the work of paleoclimatologists. As soon as the means became available to them in the second half of the twentieth century, they undertook to track down all traces of climate change so as to establish a planetary vision. This led them to develop new methods of sampling continental sediments, marine sediments in the context of major oceanographic campaigns, and ice cores by carrying out large-scale drilling campaigns of mountain glaciers and the ice sheets of Greenland and of Antarctica. The level of resources that needs to be mobilized is such that the drilling campaigns of polar ice and of marine sediments from all the world's oceans could only be carried out in an international cooperative framework which makes it possible to coordinate the efforts of the various teams.

This scientific investment has produced an abundant harvest of samples containing records of past climates. On the continents, lake sediments; peat bogs; concretions in caves; and fossil tree rings have provided many indicators of environmental conditions, especially of the behavior of vegetation and the atmosphere. In the ocean, samples have been taken from all of the large basins and cores are able to trace the history of the last tens of millions of years. Finally, the large drillings in the ice sheets have provided information not only on polar temperatures, but also on the composition of the atmosphere (dust and the concentrations of greenhouse gases, such as carbon dioxide and methane).

Unfortunately, nature has no paleothermometer or paleopluviometer, and therefore, there is no direct indicator of the changes in temperature or precipitation: Everything has had to be built from scratch, not only to reconstruct the climates, but also to date them. Extracting a reconstruction of the evolution of the climate from these samples has necessitated considerable developments using the most innovative methods from the fields of geochemistry, biology, and physics. Firstly, it was essential to establish a timeframe to know which period was covered by each sample. Many methods were developed, and they are the subject of the second part of this book. Radioactive decay, which is governed by strict physical laws, plays a vital role. It has made it possible to obtain timescales converted into calendar years, and it has provided clarification on stratigraphic geology. Other more stratigraphic approaches have been implemented: identification of characteristic events that need to be dated elsewhere; counting of annual layers; or modeling of ice flow. It has thus been possible to establish a chronological framework, and paleoclimatologists are now trying to make it common to all data via an on-going effort to make multiple correlations between the various recordings. Few climatologists rely on one indicator. The confidence that they have in reconstructing a climate change at a given time is obtained by intersecting reconstructions from independent indicators but also by confronting them with results from models. Methods of reconstructing the evolution of the different components of the climate system from geological indicators then had to be developed. These are extremely varied, and their description constitutes the main and third part of volume I. Many use the latest developments in paleomagnetism, geochemistry, and statistical methods to empirically link the distribution of fossil plants and animals with environmental parameters, primarily air and water temperature. Reconstructions achieved in this way have now reached a level of reliability such that, for certain periods, not only qualitative variations (in terms of hot/cold, dry/wet) can be obtained, but even quantitative ones with the associated uncertainties also quantified. This is the level of climate reconstruction necessary to allow comparison with climate models.

The use of climate models also gained momentum during the second half of the twentieth century. First established to simulate atmospheric circulation, they have progressed by integrating more and more efficiently the physics, processes, and parameterization of the radiative budget and the hydrological cycle, in particular, by incorporating satellite data. However, the atmosphere only represents the rapid component of the climate system.

The late 1990s dramatically demonstrated the need to link atmospheric models to global patterns of the ocean and vegetation to reconstruct climate change. Indeed, teams from the GISS in the USA and from Météo-France bolstered by their atmospheric models that had succeeded in reconstructing the current climate, independently tried to use the disruption of the radiative budget calculated by Milankovitch to simulate the last entry into glaciation 115,000 years ago. In both cases, it was a total fiasco. The changes induced by the variation of the orbital parameters in these models were far too small to generate perennial snow. The components and feedbacks related to the ocean and terrestrial vegetation needed to be included. Developing a model that couples all three of these components is what modelers have been striving to achieve over the last 20 years, and these are the models that now contribute to the international IPCC effort.

Today, the so-called Earth system models that incorporate aspects from the atmosphere–ocean–terrestrial and marine biosphere, chemistry, and ice caps are used to explore the climate of the future and the climates of the past. Spatially, they are increasingly precise, they involve a very large number of processes and are run on the largest computers in the world. But, the flip side of this complexity is that they can only explore a limited number of trajectories because of the considerable computing time they require. Also, from the beginning, climate modelers armed themselves with a whole range of models. From behemoths like the ‘general circulation models’ to conceptual models, with models of intermediate complexity in-between. From this toolbox, depending on the questions raised by the paleoclimatic data, they choose the most appropriate tool or they develop it if it does not exist. With the simplest models, they can explore the possible parameter variations and, by comparing them with the data, try to establish the most plausible scenario. All of these modeling strategies are described in detail in volume II, which constitutes the last and fourth part of this book.

This investigative approach at each step of the research work, dating, reconstruction, modeling, and the back and forth between these stages allows us to develop and refine the scenarios to understand the evolution of the past climates of the Earth. We are certain that this approach also allows us, by improving our understanding of the phenomena that govern the climate of our planet and through continuous improvement of the models, to better predict future climate change. This comparison between models and data, which makes it possible to validate numerical simulations of the more or less distant past, is an essential step toward the development of climate projections for the centuries to come, which will, in any case, involve an unprecedented transition.

Acknowledgement

This book would never have been possible without the very efficient help of Guigone Camus and Sarah Amram. We are grateful to Mary Minnock for the translation of each chapter. We also thank the LSCE for its financial support and Nabil Khelifi for his support from the origin to the end. Last but not least, thank you to all our colleagues—more than 50—who patiently contributed to this book.

Preface

Before taking this journey together into the Earth's paleoclimates, it is important to know what we will be facing. This exploration will bring us into the heart of the 'Earth system': a tangle of interwoven components with very different characteristics and response times, a system in constant interaction.

The first volume is dedicated (Chaps. 1 and 2) to an introduction to climate of the Earth. Chapters 3–9 focus on different time measurement and datation technics. The most important part of this first volume deals with the reconstructions of different climatic parameters from the three major reservoirs (ocean, continent, cryosphere, Chaps. 10–21). The second volume is devoted to modeling the Earth system to better understand and simulate its evolution (Chaps. 1–9). Last but not least, the final chapter (Chap. 10) describes the future climate of the Earth projection from next century to millennia.

The first part of this book (Chaps. 1 and 2) will equip the reader with a 'climate kit' before delving into the study of paleoclimates. This quick overview shows the great diversity in the systems involved. From the microphysics of the clouds that can be seen evolving over our heads by the minute to the huge ice caps that take nearly 100,000 years to reach their peak, the spatiotemporal differences are dizzying (Chap. 1). Yet, it is the same 'Earth system' that, throughout the ages, undergoes various disturbances that we will address. Chapter 2 takes us on a journey through the geological history of our planet. The distribution of continents, oceans, and reliefs changes how energy and heat are transported at the Earth's surface by the ocean and the atmosphere.

The study of paleoclimates requires an understanding of two indispensable concepts in order to describe the past climates of the Earth.

The first is the concept of time. Measuring time is fundamental to our research, and an understanding of the diversity of temporalities particular to paleoclimatic records is essential. The second part (Chaps. 3 to 9) of this book is devoted to the question of the measurement of time. Different techniques may be implemented depending on the timescales considered in Chap. 3. Thus, although carbon-14 (Chap. 4) provides us with reliable measurements going back to 30,000–40,000 years ago, other radioactive disequilibria (Chaps. 5 and 6) need to be used to access longer timescales. But it is not only the radioactivity-based methods that inform us of the age of sediments; the use of magnetism (Chap. 7) is also a valuable way of placing events occurring on the geological timescale into the context of climate. On shorter timescales, the use of tree rings is also a valuable method (Chap. 8). Ice core dating techniques will also be outlined (Chap. 9). This gamut of different methods shows how researchers have succeeded in developing 'paleo-chronometers' which are essential to locate climate archives within a temporal context, but also to establish the connections of cause and effect between the different components of the Earth system during periods of climatic changes.

The second concept is that of climate reconstruction. Indeed, in the same way that there is no single chronometer that allows us to go back in time, there is not one paleothermometer, pluviometer, or anemometer. Just as it was necessary to invent paleo-chronometers based on physical or biological grounds in order to attribute an age and an estimate of its uncertainty to archives, the relevant climatic indicators had to be invented to quantify the variations in temperature, hydrological cycle, and deepwater current. The third part of this book (Chaps. 10

–21) is devoted to the slow and complex work of reconstruction by applying this whole range of indicators. Thus, we can reconstruct the climate of the major components of the climate system: the atmosphere, the ocean, the cryosphere, and the biosphere. But we can also take advantage of the specificities of temperate or tropical lakes, of caves and their concretions (speleothems), of tree rings and even, more recently, of harvesting dates (Chap. 17). How can paleo-winds or, to put it in more scientific jargon, the variations in atmospheric dynamics be reconstructed? Based on the isotopic composition of precipitation (Chap. 10) or of the loess (Chap. 13), not only can the evolution of the surface and deep ocean be reconstructed, but also the geometry and dynamics of large water masses (Chap. 21). For land surfaces, palynology and dendroclimatology enable us to retrace the evolution of vegetation and climate, respectively (Chaps. 12 and 16). Finally, the cores taken from the ice caps of both hemispheres make it possible to reconstruct the polar climate (Chap. 11).

In addition to these two main concepts, we also need to understand how fluctuations in the hydrology of the tropics have caused variations in lakes (Chaps. 18 and 19) and glaciers (Chap. 20); these factors also tell a part of the climate story. Other markers, such as speleothems (Chap. 14) or lake ostracods (Chap. 15) reveal changes in climate in more temperate areas.

Thus, a description of the global climate emerges from the local or regional climate reconstructions. Through coupling these reconstructions with dating, our knowledge of climate evolution progresses constantly. Nevertheless, this image is both fragmentary, because of the strong geographic and temporal disparity of our knowledge, and unclear, because of the uncertainties in the reconstructions that the paleoclimatologist tries to reduce. There is still a long way to go in terms of developing new indicators and improving those widely used in order to complete and refine this description.

The second volume of this book (Chaps. 22–30) focuses on the major processes and mechanisms explaining the evolution of past climate from geological to historical timescales, whereas last Chap. 31 examines future climate projections. First of all, we address, in the very long term, the interactions between tectonics and climate over the timescale of tens to hundreds of millions of years (Chap. 22). Then, we deal with the biogeochemical cycles that govern the concentrations of greenhouse gases in the atmosphere over the last million years (Chap. 23). And finally, we consider the interactions with ice caps (Chap. 24).

We will continue our journey simulating the climate evolution through time from the formation of the Earth (4.6 billion years ago) up to the future climates at scales from a few tens of thousands to a hundred of years. On this journey, it becomes obvious that the dominant processes, those that drive climate change, vary according to timescales: solar power, which increases by about 7% every billion years places its stamp on very long-term evolution, whereas at the scale of tens of millions of years, it is tectonics that sculpt the face of the Earth, from the high mountain ranges to the bathymetry of the ocean floor. Finally, 'the underlying rhythm of Milankovitch,' with a much faster tempo of a few tens of thousands of years can produce, if the circumstances permit, the glacial–interglacial cycles described in the preceding parts. On top of this interconnection of timescales, a broad range of processes and components of the climate system is superimposed. Through these chapters, we would like to highlight the need to model a complex system where different constituents interact at different timescales (Chap. 25). With the development of these models, the scope of investigation is vast. Indeed, ranging from recent Holocene climates (Chap. 30) to geological climates (Chaps. 26 and 27), how they evolve is underpinned by very different processes: from plate tectonics (Chap. 22) to orbital parameters (Chap. 28). The complexity of the system can also be seen in the abrupt reorganizations of the ocean–atmosphere system (Chap. 29). The capacity acquired in recent decades to replicate past climate changes using a hierarchy of models, and to compare these results with different types of data, has demonstrated the relevance of this approach coupling model simulations with data acquisition.

Nevertheless, the field of investigation of the Earth's past climates remains an important area of research with many questions being raised about the causes of climate reorganizations throughout the Earth's history. Even though several chapters clearly show recent breakthroughs in our understanding of past climate changes, and the sensitivity of our models to climate data has undeniably increased the extent to which we can rely on their outputs, we can legitimately question what they contribute to future climate. Chapter 10 addresses these issues. Will the ice caps, which have existed on Earth for only a short time relative to geological time, withstand human disturbance? And can this disturbance, apart from its own duration, have an impact on the rhythm of glacial–interglacial cycles?

At the end of these two volumes, you will have obtained the relevant perspective to project into the Earth's climates of the future. Indeed, by absorbing the most up-to-date knowledge of paleoclimatology in this book, you will be provided with the necessary objectivity to critically assess present and future climate changes. It will also give you the scientific bases to allow you to exercise your critical judgment on the environmental and climatic issues that will be fundamental in the years to come. Indeed, in the context of the Anthropocene, a period where man's influence has grown to become the major factor in climate change, the accumulated knowledge of the climate history of our planet gathered here is precious.

Gif-sur-Yvette, France

Gilles Ramstein
Amaëlle Landais
Nathaelle Bouttes
Pierre Sepulchre
Aline Govin

Contents

About the Editors

Gilles Ramstein is a director of research at Laboratoire des Sciences du Climat et de l'Environnement (LSCE, France). His initial degree is in physics and since 1992 he has specialized in climate modeling.

He has been responsible for many French and European research projects on the Pleistocene, Cenozoic, and Precambrian eras. He has also been the advisor of many Ph.D. students who have explored and expanded the frontiers of paleoclimate modeling.

As a climate modeler, he studies very different climate contexts from 'Snowball Earth' episodes (717–635 Ma) to more recent, and occasionally future, climate situations.

The main research topics he focuses on are

• **Geological time from the Precambrian to the Cenozoic**:

– Investigation of relationships between tectonics, the carbon cycle, and the climate with an emphasis on the impact on the climate and the atmospheric CO_2 cycle of major tectonic events such as plate movements, shrinkage of epicontinental seas, mountain range uplift, and the opening/closing of seaways.

– Leading international collaborations on projects on monsoon evolutions and the dispersal of human ancestors during the Neogene periods.

• **From the Pleistocene to future climate**: In this framework, his major interests are interactions between orbital forcing factors, CO_2 and climate. More specifically, his focus is on the response of the cryosphere, an important component of the climate system during these periods, with an emphasis on the development of the Greenland ice sheet at the Pliocene/Pleistocene boundary and abrupt climate changes driven by ice sheet variations.

He has also published several books and co-edited the French version of 'Paleoclimatologie' (CNRS Edition) and contributed to an online masters program devoted to educating journalists on climate change (Understanding the interactions between climate, environment and society ACCES).

Amaëlle Landais is a research director at Laboratoire des Sciences du Climat et de l'Environnement (LSCE, France). Her initial degree is in physics and chemistry and, since her Ph.D. in 2001, she has specialized in the study of ice cores.

She has been responsible for several French and European research projects on ice cores working on data acquisition both in the laboratory and in the field, interacting extensively with modelers. She has been the supervisor of ten Ph.D. students and is deeply committed to supporting and training students in laboratory work.

Her main research interests are the reconstruction of climate variability over the Quaternary and the links between climate and biogeochemical cycles. To improve our understanding of these areas, she develops geochemical tracers in ice cores (mainly isotopes), performs process studies using laboratory and field experiments, and analyzes shallow and deep ice cores from polar regions (Greenland and Antarctica). Through numerous collaborations and improvement of ice core dating methods, she tries to establish connections with other paleoclimatic archives of the Quaternary.

Nathaelle Bouttes is a research scientist at the Laboratoire des sciences du climat et de l'environnement (LSCE/IPSL). Following the completion of her Ph.D. in 2010 on the glacial carbon cycle, she went to the University of Reading (UK) for a five-year postdoc on recent and future sea-level changes. She then spent a year at Bordeaux (France) with a Marie–Curie Fellowship on interglacials carbon cycle before joining the LSCE in 2016. Since then, she has specialized in understanding glacial–interglacial carbon cycle changes using numerical models and model–data comparison.

She is mostly using and developing coupled carbon-climate models to understand past changes of the carbon cycle, in particular the evolution of the atmospheric CO_2. She has been focusing on the period covered by ice core records, i.e., the last 800,000 years. She uses model–data comparison by directly simulating proxy data such as $\delta^{13}C$ to evaluate possible mechanisms for the orbital and millennial changes. She has been involved in several projects covering this topic as well as teaching and supervising Ph.D. students.

Pierre Sepulchre is a CNRS research scientist at the Laboratoire des sciences du climat et de l'environnement (LSCE/IPSL). He completed a Ph.D. on the Miocene climate of Africa in 2007, then went to UC Santa Cruz (USA) for a two-year postdoctoral position working on the links between the uplift of the Andes and atmospheric and oceanic dynamics. His lifelong research project at CNRS is to evaluate the links between tectonics, climate, and evolution at the geological timescales, focusing on the last 100 million years. Through the supervision of Ph.D. students and his collaboration with geologists and evolutionary biologists, he also worked at evaluating paleoaltimetry methods with the use of an isotope-enabled atmospheric general circulation model, as well as linking continental surface deformation, climate, and biodiversity in Africa and Indonesia. In recent years, he led the implementation and validation of a fast version of the IPSL Earth system model that allows running long climate integrations dedicated to paleoclimate studies.

Aline Govin is, since 2015, a research associate at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif sur Yvette, France). She studied Earth Sciences at the Ecole Normale Supérieure of Paris (France) and obtained in 2008 a Ph.D. thesis in paleoclimatology jointly issued by the University of Versailles Saint Quentin en Yvelines (France) and the University of Bergen (Norway). Before joining the LSCE, she worked for five years as a postdoctoral fellow at the Center for Marine Environmental Sciences (MARUM, University of Bremen) in Germany.

Her research activities focus on the reconstruction of paleoclimatic and paleoceanographic changes by applying various types of geochemical and sedimentological tracers on marine sediment cores. She has mostly worked on the Earth's climatic changes of the last 150,000 years and is an expert of the last interglacial climate, which is an excellent case study to investigate the response of the Earth's climate to past warming conditions that could be encountered in the coming decades. Her research interests include the past variability of the deep North Atlantic circulation, the responses, and drivers of tropical monsoon systems (e.g., South American Monsoon), the development and calibration of paleo-tracers, the development of robust chronologies across archives, and the quantification of related uncertainties, as well as the comparison of paleo-reconstructions to climate model simulations of past climates.

She has authored around 30 scientific publications and has been involved in many French, German, and other international (e.g., Brazilian) projects.

The Climate System: Its Functioning and History

1

Sylvie Joussaume and Jean-Claude Duplessy

Climate plays an important role for mankind. It determines the conditions in which societies can develop as well as the resources available to them such as water and biological inputs (agriculture, forests, livestock). However, climate is a complex system. It is the result of interactions not only between the atmosphere, the oceans, landmasses and ice but also the biosphere: the living world. It varies depending on the timescale, and different mechanisms may come into play at different scales. The aim of this book is to show how a multi-disciplinary scientific community can now reconstruct, with increasing accuracy, the major features of past climates and discover how they are regulated by the geological evolution, geochemistry, physics and biology of our living planet, Earth.

Human living conditions are dependent on climate, but human beings, in turn, influence the climate system. They change the atmospheric concentration of greenhouse gases and aerosols, as well as the vegetation through deforestation and agriculture. For this reason, it is of major importance to society to understand how climate works and how man may be altering its course. This is a complex scientific problem because of the large number of feedbacks likely to occur and the study of past climates contributes to a better understanding of them by analyzing major climate changes provoked by natural causes.

Climate Change

Definition of Climate

Climate is defined by the statistics of the physical characteristics of the atmosphere. It differs from meteorology by focusing on statistics over several decades, by calculating the average state of the atmosphere and its variability from this average. In practice, climate is defined by the average conditions over a thirty-year period. Although this working definition makes sense while the weather is relatively stable, it becomes more difficult to apply during a period of rapid change. This was the case in the twentieth century during which two phases of rapid increase in the average temperature of our planet were detected by weather stations in the WMO network, one from 1910 to 1940 and the other from 1975 onwards (Fig. 1.1d). The period 1961–1990 is often taken as a reference.

Climate Changes in the Past

Climate is essentially variable, regardless of the time scales under consideration. Over past two millennia, historical chronicles and earliest instrumental measurements dating back to the seventeenth century have shown the existence of a very cold period in Europe from the sixteenth to the nineteenth century (the Little Ice Age), preceded by the Medieval Warm Period and another warm period during Roman times.

Geological data also show large upheavals in climate. Of course, this is over much longer periods than thirty years, but geologists strive to define a stratigraphic framework and precise geochronology to put these events into context within the history of our planet (Fig. 1.1). For example, about seven hundred and fifty million years ago, the Earth went through an intense glaciation phase; glaciers flowed down to sea level on every continent, even in low latitudes, to such an extent that our planet could be described as a snowball. Conversely, during the Mesozoic Era (25–65 million years), the conditions were hot, even at high latitudes. During the Cenozoic Era (from 65 million years), the glaciers grew slowly, first on the Antarctic continent and then on Greenland. For the past three million years or so, the Earth has experienced a succession of ice ages, marked by glaciers advancing over land at high and middle latitudes of

S. Joussaume (✉) · J.-C. Duplessy
Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
e-mail: sylvie.joussaume@lsce.ipsl.fr

G. Ramstein et al. (eds.), *Paleoclimatology*, Frontiers in Earth Sciences,
https://doi.org/10.1007/978-3-030-24982-3_1

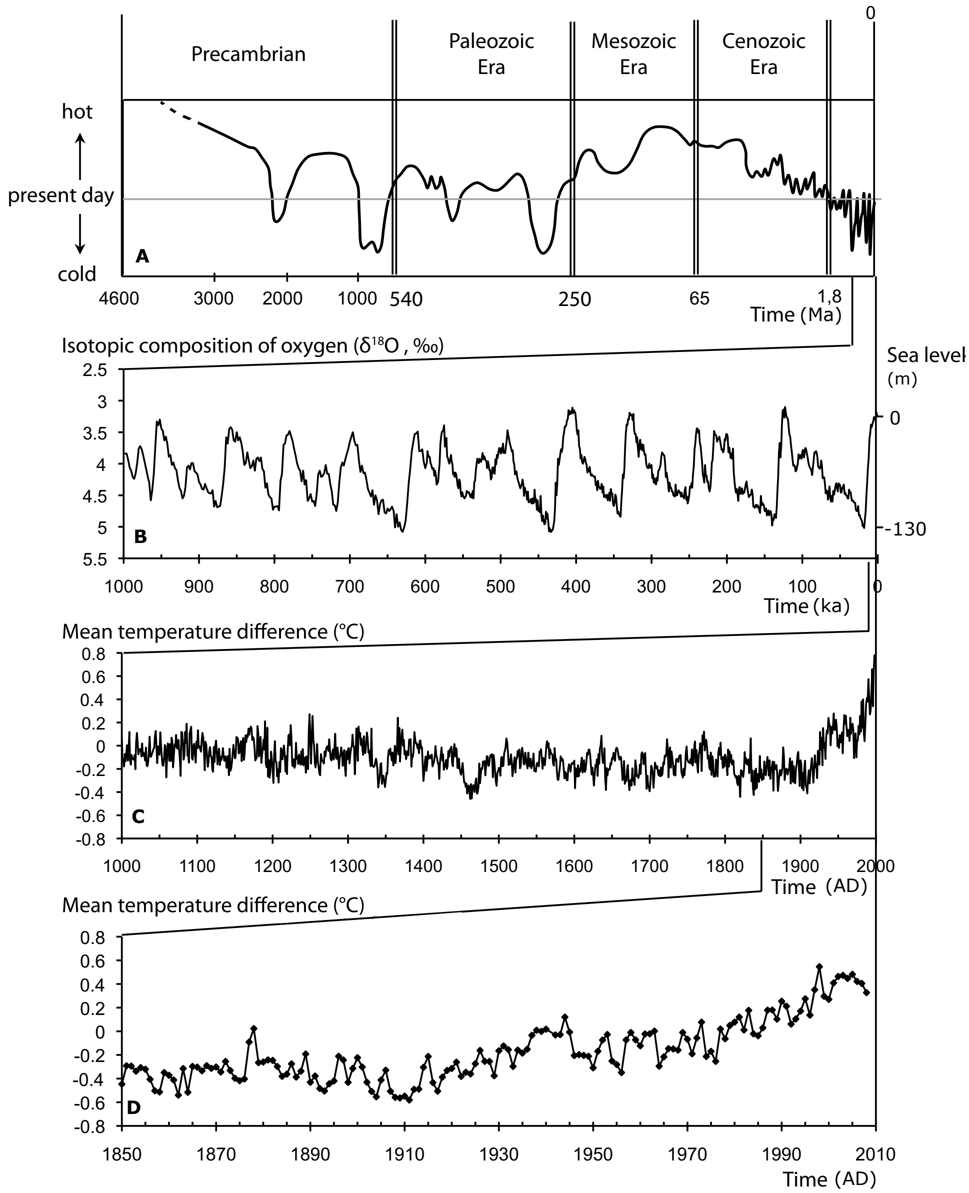

Fig. 1.1 **a** Variations in the climate of Earth over the past 4 billion years, estimated from geological data. **b** Changes in mean climate estimated from variations in the volume of glaciers and ice sheets present on the surface of continents for the last million years. **c** Variations in the average air temperature in the northern hemisphere from the year 1000 reconstructed from paleoclimate data, including historical data and the study of tree rings. **d** Variations in the average surface air temperature calculated from the global meteorological network data for the period 1860–2010. Note that the number of stations has varied during this period and was sparse throughout the late nineteenth century

the northern hemisphere, separated by interglacial periods when the ice caps receded and remained confined to the Antarctic and Greenland.

We have been in an interglacial period, called the Holocene, for the past 11,000 years. The various aspects of the evolution of climate will be expanded upon later in this book.

The last million years is the best understood geological period, because climate can be reconstructed from detailed information provided by polar ice and marine and continental sediments. Over this period, a succession of oscillations between glacial and interglacial periods marks intervals which are the result of small changes in the Earth's orbit around the Sun. The glacial periods last almost ten times longer than the interglacial periods but they are interspersed with rapid warmings which follow the outbreaks of cold in the North Atlantic and neighboring landmasses. All these major climate shifts do not occur as a result of chance and it is the work of climatologists and paleoclimatologists to understand them by analyzing climate mechanisms and the causes of their variability.

Climate Mechanisms

The Sun is the major driver of climate. Received solar energy plays a key role in establishing climate conditions on the surface of our planet. But these depend critically on the composition of the atmosphere and energy exchanges between the surface of the planet and the atmosphere that surrounds it. The Earth radiation balance compares, for each point on the Earth's surface, the energy received from the Sun and that which is emitted back into space. Significant geographical differences drive wind and ocean currents which redistribute energy, influenced by the shape of the ocean basins and the relief of the land.

The Radiation Balance of the Earth

The Greenhouse Effect

A disk with a surface area of 1 m^2, located equidistant between the Earth and the Sun and intercepting solar radiation at a perpendicular angle, would receive an energy flow of 1368 W at the top of the Atmosphere (TOA). However, the Earth is a sphere whose surface area is four times greater than that of a disk with the same diameter. This is why, on average and over the course of a year, the solar flux intercepted by a unit area is four times lower. It corresponds to a power of 340 W/m^2 TOA with a known accuracy of roughly 1 W/m^2 (Fig. 1.2). Yet all this energy is not accessible to the Earth/atmosphere. A portion, about 36%, returns back to space after being reflected by the clouds, the suspended aerosols in the air, the Earth's surface and by the air molecules themselves. So, the real amount of energy absorbed amounts to 161 W/m^2. It is offset by an infrared flux emitted by the Earth and its atmosphere to space. In fact, the Earth behaves as a 'black body': it emits energy whose intensity is proportional to the fourth power of its absolute temperature (287 K), in accordance with Stefan's law. This radiation is almost entirely concentrated in the infrared range between 4 and 100 µm (microns), with a maximum intensity centered around 12 µm. Solar radiation also behaves like a 'black body' but at temperatures of around 6000 K, and covers a range of wavelengths from ultraviolet to near infrared, from 0.2 to 4 µm, and has a maximum intensity in the visible wavelengths of around 0.6 µm.

In the absence of any greenhouse effect, i.e. if the atmosphere were perfectly transparent to infrared radiation emitted by the Earth, the temperature in equilibrium with an average absorbed flow of 161 W/m^2, would be only −19 °C. In reality, water vapor, liquid water in clouds, carbon dioxide and other trace elements present in the air absorb a large portion of infrared radiation emitted by the surface, limiting the loss of energy towards space. Acting as 'black bodies', all these constituents re-emit infrared energy in all directions including towards the ground. This additional contribution means that the average surface temperature of the Earth is 14 °C, not −19 °C. This greenhouse effect is a natural phenomenon due in large part to the presence of water vapor, which contributes about 55% of the total greenhouse effect, to other greenhouse gases (carbon dioxide, methane, nitrous oxide) which account for 28%, with the remainder caused by clouds. Throughout the geological history of the Earth, the composition of the atmosphere has changed significantly and changes in the greenhouse effect have greatly contributed to past climate variations (see

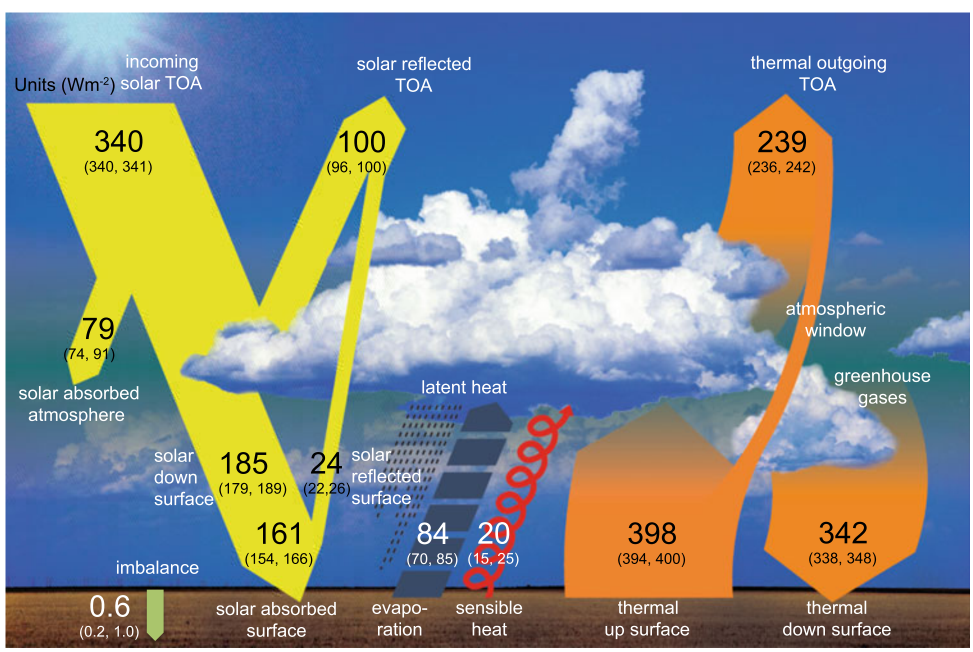

Fig. 1.2 Radiation balance of the Earth. The solar radiation incident at ground level is fully offset by infrared radiation emitted towards space (*Source* IPCC 2013)

Chap. 2, Volume 1 as well was Chaps. 22, 26 and 27, Volume 2). Since the beginning of the industrial era (about 1850), human activities have significantly increased the concentration of greenhouse gases already naturally present in the air and have introduced new ones, such as chlorofluorocarbons (CFCs) which are active agents of the greenhouse effect.

The Water Cycle

As solar radiation passes through the different layers of the atmosphere, part of it is absorbed by ozone in the stratosphere and by water vapor in the troposphere. About half of the incident energy reaches the surface of Earth, where it is partially compensated for by the loss of infrared radiation to the atmosphere. An energy surplus of 104 W/m^2 (Fig. 1.2) remains available at the surface. This energy warms up the surrounding air and causes evaporation of water from the surface of oceans and land, feeding into the water cycle on our planet. The water vapor is then transported by winds until it condenses as precipitation, releasing into the atmosphere the energy acquired at the surface during evaporation. Thus, the cycle of evaporation and precipitation of water takes energy from the surface of the oceans and land and redistributes it in the atmosphere. This transfer of latent heat cools the surface and warms up the atmosphere, thus lessening the differences in temperature between the upper and lower layers of the atmosphere, as well as between the equator and the poles. The water cycle thus plays a fundamental role in the redistribution of energy between the surface and the atmosphere.

Evaporation and condensation continuously renew the store of water vapor in the atmosphere. However, the amount of water vapor in the air at any given moment remains quite low. If it were completely condensed, the liquid layer thus formed would cover the Earth's surface in a layer 2.5 cm thick. Yet, on average, the water cycle involves the evaporation and the precipitation of water which would correspond to a layer of about 80 cm per year. The recycling time of water in the atmosphere is therefore very fast and the water vapor is completely renewed in ten days. The water, most of which evaporates from the oceans (86%), returns there either by precipitation or through the flow of rivers and streams after runoff from land. Globally, on average, evaporation and rainfall balance each other exactly, thereby maintaining a constant concentration of water vapor in air, as long as the average temperature of the air remains constant.

Sun-Related Variability

Variations in energy emitted by the Sun and the variations in the solar energy received by the Earth will affect the climate. In the first case, the solar activity cycles and the evolution of the Sun since the formation of the solar system modify the amount of energy it emits. In the second case, the slow variations of the movement of the Earth around the Sun influence the seasonal and geographical distribution of energy received in a given place on our planet.

Solar Cycles

In the mid-nineteenth century, the German astronomer, H. Schwabe, discovered spots on the Sun's surface that appear and disappear over an eleven-year cycle. When solar activity is more intense, marked by a greater number of spots, the Sun emits more energy. Since the 1980s, satellite measurements allow the estimation of variations in intensity of solar energy. These are around 0.1%, which corresponds to a very small perturbation (0.24 W/m^2) in the radiation balance of the Earth. Solar activity directly reflects changes in the Sun's magnetic field. The spots reappear in larger numbers when the magnetic field intensifies. Solar flares then become stronger; they eject a larger number of particles toward outer space and thus reinforce the solar wind. These electrically charged particles, mainly electrons and protons, reach the Earth's atmosphere where they cause magnetic storms—strong disturbances in the magnetic field—as well as magnificent auroras in the polar regions.

The influence of solar activity on climate has been debated for many years. In the second half of the seventeenth century, documented observations indicate an almost total disappearance of spots for a period of several decades, during the Little Ice Age (Fig. 1.3). At the end of the nineteenth century, the German astronomer H. Spörer and his English colleague W. Maunder linked these two phenomena, thus starting a controversy that persists today. The nature of the connection between the minimum solar activity (called the Maunder minimum) and a decrease in the intensity of solar radiation sufficient to induce a marked cooling that coincided with that time, still needs to be explained.

As the direct disruption in the solar radiation balance is too small to explain the phenomenon, it is believed that solar activity may affect climate through circulation in the upper atmosphere. Nevertheless, the link between variations in solar activity and the Earth's climate remains a subject of research and a source of controversy given the absence of a recognized physical mechanism. The relative role of external forcing (solar radiation) and internal/geological forcing (volcanism) in explaining the Little Ice Age still needs to be assessed.

The Sun exhibits variations over longer periods. These can be seen not only in the number of sunspots, but also in variations in solar diameter. This varies with a periodicity of 900 days, but this oscillation is influenced by solar activity. It is minimal when the activity is at its maximum. Like sunspots, solar diameter measurements started in the

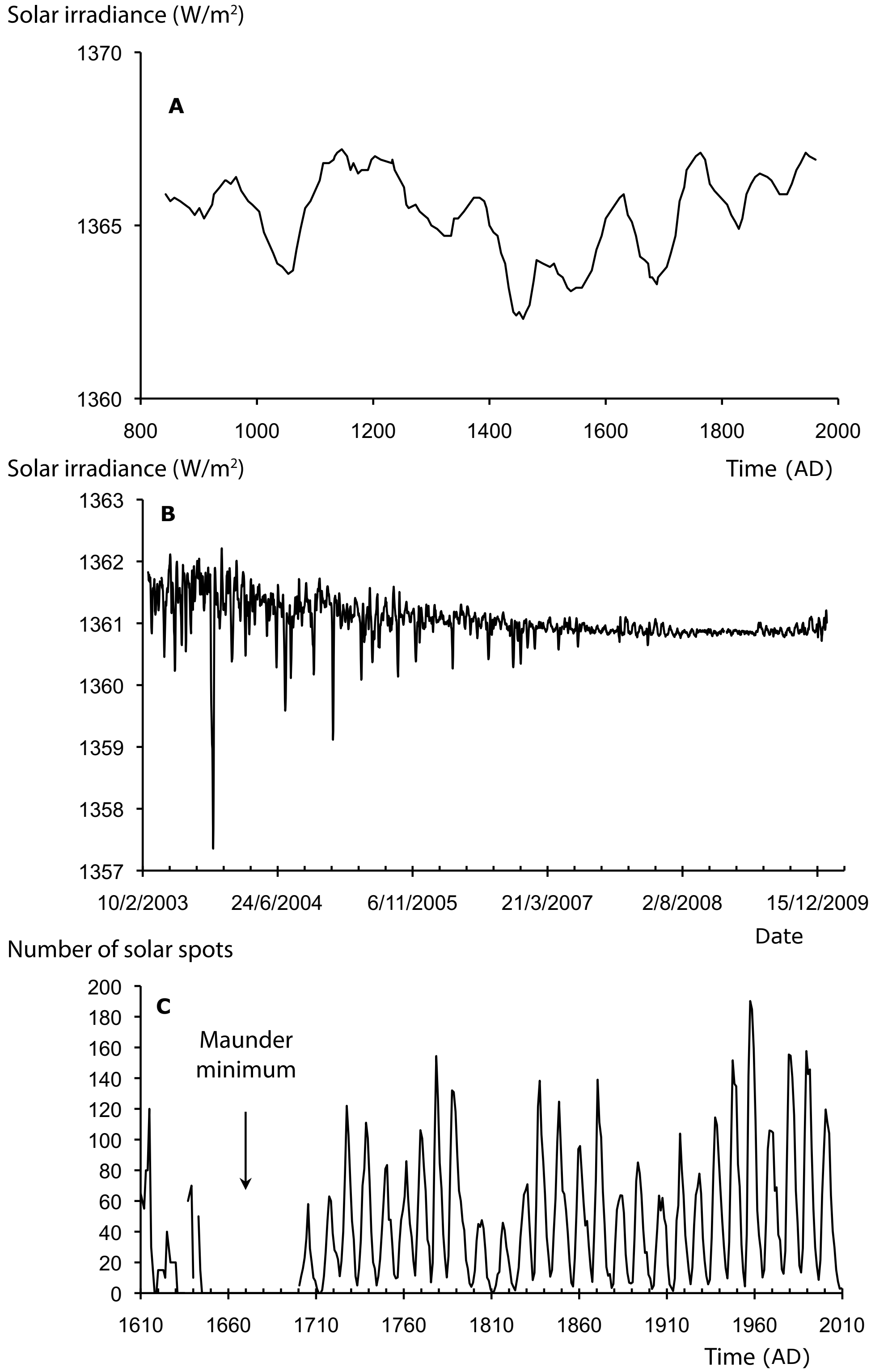

Fig. 1.3 **a** Variations in solar energy reconstructed from changes in the beryllium content of polar ice and from the modeling of stellar activity. It should be noted that the mean values calculated using stellar-activity modeling are higher, by about 5 W/m^2, compared with values measured using satellites. **b** Variations in energy emitted by the Sun, NASA satellite measurements. **c** Changes in the number of sunspots observed by astronomers since 1610

seventeenth century. They led to the discovery of a cycle of 80–90 years, called the Gleisberg cycle, which modulates the Schwabe cycle.

Solar wind plays only a minor role in the flow of charged particles received by the Earth. Most comes from galactic cosmic rays, which consists of electrons, protons, α particles (ionized helium nuclei) and heavier ions in very small quantities. It is isotropic and comes from everywhere in space. In periods of high solar activity, intense solar wind, through the magnetic field it creates, acts as a shield repelling the galactic cosmic radiation falling to Earth. This phenomenon inspired a geochemical method for determining variations in solar activity. Indeed, galactic cosmic rays, through spallation reaction on the atoms in the upper atmosphere, are responsible for the production of several cosmonucleides, the most well-known of which is Carbon-14. Less Carbon-14 is produced during intense solar activity. Measurements by geochemists on well-dated tree rings showed pseudo-periodic variations in the production of this cosmonucleide. This is attributed to fluctuations in solar activity, with periods of about 150–300 years (Suess cycles) and 2300 years (Hallstattzeit cycles). The existence of these cycles has been confirmed by the measurement of other cosmonucleides, such as beryllium-10, in polar ice. These are trapped in ice in Greenland, whose location in time can be determined simply by visually counting the annual layers or, for earlier periods, through more complex methods described in Chap. 9. The paleoclimatologists are now investigating if these periodicities can be reflected in geological records.

Long-Term Variations in the Movement of the Earth Around the Sun

The movement of the Earth around the Sun varies over time under the influence of the gravitational attraction of other planets (see Chap. 28, Volume 2). The orbit traveled by the Earth over a full year is almost exactly an ellipse with an eccentricity (the parameter which defines the degree of flattening of the ellipse with respect to a circle) that can vary over time. With periodicities close to 100,000 and to 400,000 years, the orbit goes from a circle with an eccentricity of zero to a slightly flattened ellipse with a maximum eccentricity of 6%.

The tilt in the axis of the Earth relative to the ecliptic plane is known as its obliquity and it influences the amount of sunshine received at different latitudes in different seasons. It is the reason for phenomena such as the polar night in winter and the midnight sun in summer at the highest latitudes. For this reason, the climate at high latitudes is especially sensitive to variations in the obliquity. With a periodicity of around 41,000 years, the obliquity angle oscillates between 22° and 25°, the current value being close to 23° 26′.

Because of the elliptical nature of the Earth's orbit, the distance between the Earth and the Sun varies at different times of the year. Currently, in the northern hemisphere, this distance is at its minimum in winter and at its maximum in summer, and the opposite is true for the southern hemisphere. In fact, the amount of solar radiation intercepted by the Earth decreases as the distance increases. This causes milder winters and cooler summers in the northern hemisphere, while the seasonal contrasts are accentuated in the southern hemisphere (although this impact is minor compared with the seasonal variations in high latitudes caused by obliquity).

Over the millennia, the position of the solstices and equinoxes slowly moves along the ellipse resulting in a variation in the solar energy received during each season. This movement of precession of the equinoxes is caused by a combination of two rotational movements. The first is the rotation of the Earth around an axis running through the poles which is perpendicular to the elliptic plane. A gradual shift in the orientation of the axis of rotation is caused by the attraction of the Sun and the Moon and traces out a circle over the North Pole in a cycle of approximately 26,000 years. The second is the elliptical orbit of the Earth around the sun which is superimposed on the first. The combination of these two movements results in a periodicity of the precession of the equinoxes of about 22,000 years. More specifically, the Earth's distance from the Sun fluctuates, not only due to the precession movement of the equinoxes, but also due to variations in the eccentricity of its orbit which varies according to a set of cyclical changes occurring over two proximate periods, one of 19,000 years and the other 23,000 years. Thus, approximately 10,000 years ago, the Earth reached its closest point to the Sun at the time of the summer solstice and not at the boreal winter solstice as it does today. At that time, the northern hemisphere received more solar energy in summer than it does today and obviously less in winter.

All of these modifications in the orbital parameters affect sunshine levels (still referred to as the insolation) at the different bands of latitude on Earth, and particularly the intensity of the seasonal cycle. Already, in 1924, the Serbian mathematician, Milutin Milankovitch, proposed that these slow variations of the movement of the Earth around the Sun could explain the glacial cycles. Indeed, as these slow variations induce a decrease in solar energy received in the summer at 60° N, snow, which has fallen in the winter, does not melt completely. Furthermore, it strongly reflects solar radiation, facilitating the snow to persist. Gradually, the snow accumulates and turns into an ice cap. This hypothesis has been debated for many years and was strongly opposed until the 1970s, when the cycles predicted by this theory were clearly confirmed by paleoclimate records in marine sediments and later in polar ice. We will see more precisely in Chap. 28 of

Volume 2 the state of our knowledge about the Milankovitch theory, or the 'astronomical theory' of paleoclimates.

The Sun's Evolution

Since the formation of the solar system, the Sun, like all stars of the same type, slowly consumes its hydrogen to produce helium, and the amount of heat it emits varies very slowly over long time scales. The standard stellar evolution models estimate that four billion years ago the luminosity of the Sun was 25–30% lower than it is today, and that it has increased more or less linearly over time. This model seems in accordance with observations made by astronomers of young stars. With the same Earth's atmosphere as today four billion years ago, the average temperature of the Earth would be below 0 °C, oceans would be frozen, and life would be impossible. Geological observations, however, indicate the presence of water in the liquid state and the first traces of life 3.5 billion years ago. This is the 'Pale Young Sun paradox' which is solved by assuming that the atmosphere had a very different chemical composition from that of today. Indeed, the elimination of carbon dioxide by the young Earth, and the low rates of weathering given the absence of continental crust, meant that the atmosphere during these ancient periods acquired an exceptionally high level of CO_2 and hence was responsible for a strong greenhouse effect, further enhanced by the presence of methane produced by bacteria. This will be discussed in detail in the chapter on the Precambrian (Chap. 26, Volume 2).

Reconstruction of the History of Atmospheric Composition

Although the Sun is the source of energy for the Earth, the energy made available depends essentially on the composition of the atmosphere: greenhouse gases and particles. Reconstructing the past history of the composition of the atmosphere is therefore an important element in understanding climate dynamics.

Again, the last hundreds of thousands of years constitute the best documented period because of the fossil air bubbles contained in the polar ice caps. The snow falling on the polar caps forms a porous firn, within which air circulates freely. Under the weight of accumulated snow, the pores gradually compact and the firn turns into ice that traps tiny air bubbles within it. This air keeps its original chemical composition, which allows the reconstitution of variations in the composition of the atmosphere over time, as long as we can find well-preserved ancient ice. The oldest ice is found in Antarctica, where a continuous recording of the greenhouse gas content (CO_2, CH_4) over the last 800,000 years has been established. These records show that the levels of carbon dioxide have not remained constant; they were high in warm periods, around 280 ppmv (280 cm^3 of CO_2 per m^3 of air) and only 200 ppmv during cold periods. Similarly, methane ranged from ~700 ppbv (mm^3 per m^3 of air) in warm periods to less than 400 ppbv during cold ones, with a high temporal variability (Fig. 1.4).

Polar ice is the only direct recording of the composition of the atmosphere. As ice in the ice caps flows very slowly and is continuously renewed throughout geological time, it is impossible to reconstruct a record of carbon dioxide levels before a million years ago. For earlier periods, it is therefore necessary to use indirect empirical methods which have a much lower level of precision. These indirect "proxies" to reconstruct atmospheric CO_2 may be derived from stomata, boron isotope or alkenone (Chap. 27, Volume 2). For example, botanists observed that the stomata—pores through which leaves absorb carbon dioxide from the air—are smaller and fewer when carbon dioxide is high. This plant characteristic has been used as a means of establishing CO_2 levels for the past. However, the results were not clear-cut. For one, the fossil species being studied must be the same as the current species on which the empirical relationship between the levels of carbon dioxide and the number or diameter of the stomata is being established. Moreover, the relationship, which can only be determined in the current conditions, also depends on the availability of water to the plant, so it is not clear whether changes observed in fossil stomata are due to variations in CO_2 or in moisture.

As the CO_2 content of the air is governed by the partial pressure of this gas in the surface waters of the ocean, geochemists have tried to use carbon-13, a tracer of the oceanic phase of the carbon cycle, as a tool to reconstruct changes in atmospheric CO_2. One of the proposed markers is the $^{13}C/^{12}C$ ratio in foraminifera, microscopic animals in the form of plankton living in the surface waters of the oceans. These animals secrete a calcareous shell whose size is a few tenths of a millimeter and which are found in abundance in marine sediments. The $^{13}C/^{12}C$ ratio of planktonic foraminifera therefore depends on the isotopic composition of dissolved CO_2 in the surface waters, and indirectly on that of the atmosphere.

This isotopic approach can be compared against the independent records provided by the polar ice cores, so that the method can be evaluated over the last few hundred thousand years. The correlation is only proximate due to the complexity of the oceanic carbon cycle which depends in particular on the temperature of the sea water, on the primary production of the ocean, on the decomposition of organic matter and on the circulation of the bodies of water. Biologists came up with another method when they noticed that the fractionation of carbon isotopes during the absorption of carbon dioxide by seaweed depends on the dissolved carbon dioxide content and therefore the partial pressure of CO_2 in the seawater. This led them to the hypothesis that variations

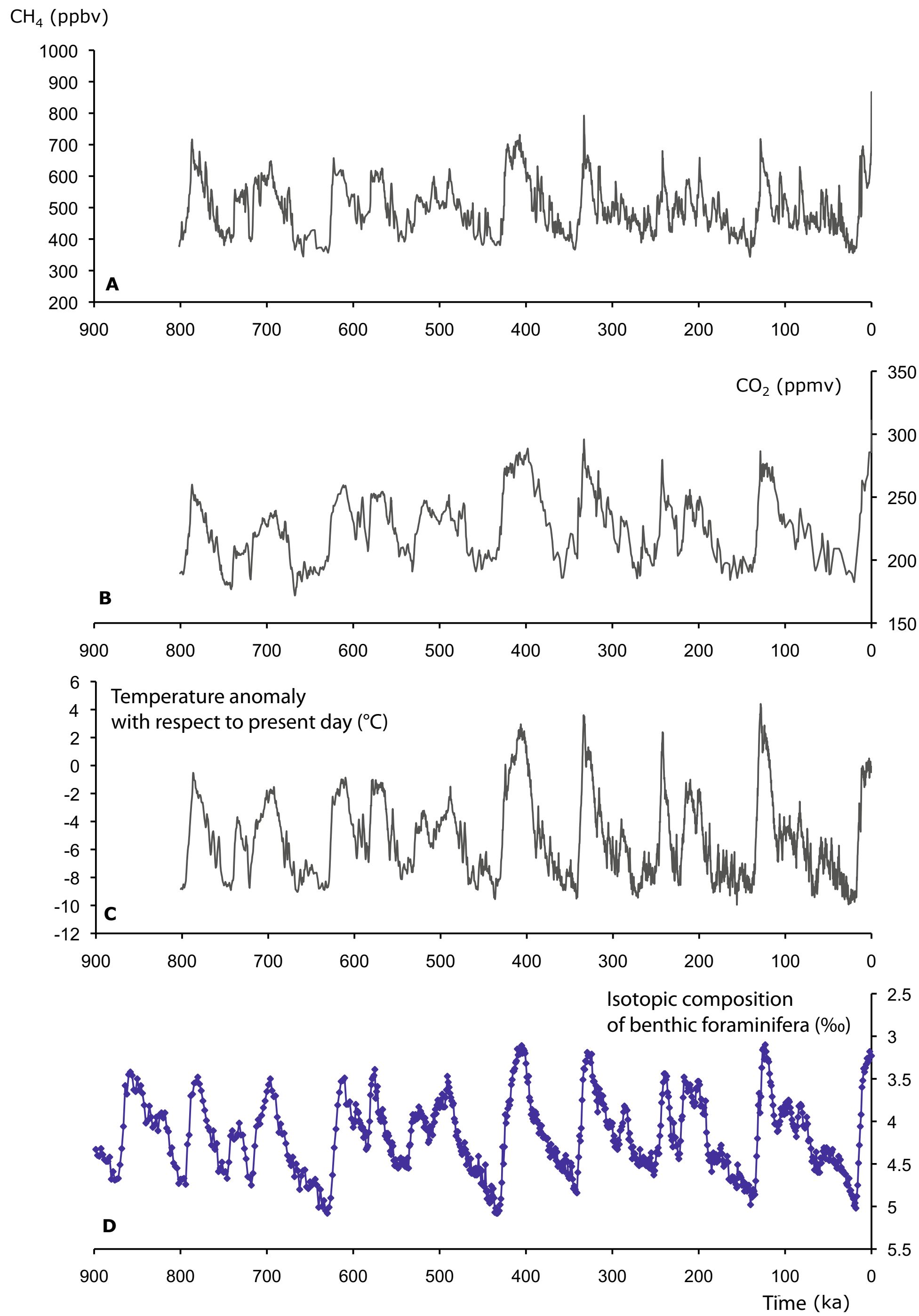

Fig. 1.4 **a** Variations in atmospheric methane concentrations inferred from variations in methane concentration in the air bubbles trapped in the ice cores drilled at Dome C (EPICA). **b** Variations in atmospheric carbon dioxide concentrations inferred from variations in carbon dioxide concentration in the air bubbles trapped in the ice cores drilled at Dome C (EPICA). **c** Air temperature variations in Antarctica inferred from changes in the isotopic composition of the ice cores drilled at Dome C (EPICA). **d** Changes in mean climate of the Earth estimated from variations in the isotopic composition of oxygen in benthic foraminifera, a proxy for variations in the volume of glaciers and ice caps on land surfaces over the last million years

in the $^{13}C/^{12}C$ ratio in specific compounds formed during photosynthesis, such as in alkenones found in marine cores, would reflect changes in the CO_2 composition of the surface waters of the ocean and of the air. However, the relationship obtained depends on the ratio of surface to volume of cells performing photosynthesis, which introduces a new uncertainty in the reconstructions. Finally, it is clear that even isotopic methods, which use accurately measurable geochemical parameters, produce only rough estimates of the carbon dioxide composition of the air and its variations.

At long time scales (>10^6 years), the changes in the levels of CO_2 in the atmosphere are determined by the relative extent of degassing by volcanoes and mid-ocean ridges on the one hand, and the consumption of CO_2 by chemical erosion of silicates on the other. This means that the key role is played by plate tectonics. Thus, a gradual reduction of

CO_2 in the air may be due to either a lower degassing rate or an increase in erosion of the surface of the continents. The latter depends on a complex set of parameters, themselves related to climate, such as air temperature, precipitation, continental runoff and vegetation. Geochemists therefore try to reconstruct the changing partial pressure of atmospheric CO_2 using models; CO_2 emissions are estimated using geological data on the speed of movement of the plates; consumption of the gas is taken into account in simplified models by coupling the carbon cycle to climate and by considering the geographical context resulting from plate tectonics. For example, the breaking-up of the arid super-continent Rodinia, into a multitude of small humid continental masses, 800–700 million years ago, led to the creation of basaltic regions, easily erodible chemically. This resulted in a significant drop in carbon dioxide levels in the air which may explain the great glaciations of the period.

Airborne dust also plays an important role in the radiation balance of the atmosphere, mainly by intercepting solar radiation and thereby reducing the amount of energy reaching ground level. Dust levels have varied considerably in the past, as is evidenced in polar ice. Falling snow brings down atmospheric dust with it which then remains trapped in the ice. The more the air is charged with dust, the more of it the snow absorbs. In this way, strong atmospheric dust levels during the glacial periods of the Quaternary have been demonstrated. The dust came from continental erosion which was then transported by winds. They gave rise to huge accumulations of very fine particles. These created the loess present in China, and in smaller quantities, in Western Europe (Chap. 13, Volume 1).

The Atmosphere

The Main Features of Atmospheric Circulation

The net balance between the radiation received from the Sun and that emitted into space does not have a uniform distribution. The net energy flux varies, depending on the latitude, geographic regions and season. Solar radiation decreases significantly between the equator and the poles, but there is little difference in emitted infrared radiation. The result is a surplus of energy in the tropics and a deficit in the north and south latitudes above 40°. Heated at the equator, cooled at the poles, the atmosphere and the ocean are activated and carry the excess energy from tropical regions to the deficient higher latitudes. According to currently available measurements, the two fluids of the planet contribute with relatively similar amplitude to this transport (Fig. 1.5).

A strong circulation in the atmosphere traveling from the equator to the poles is established in order to ensure the transport of energy necessary for the thermal balance of the planet. The warmer air, and therefore lighter, rises above the equator, before diverging and heading at high altitudes towards the poles. Above the polar regions, on the contrary, cold, dense air descends toward the surface, and travels toward the equator, which forms a large loop between the equator and poles. This mechanism, described in 1735 by the English scientist George Hadley, would happen if the Earth was turning very slowly. In reality, this large convection cell remains confined between the equator and the subtropical regions, where it forms the so-called 'Hadley' circulation. Associated with the Hadley circulation, low-pressure belts

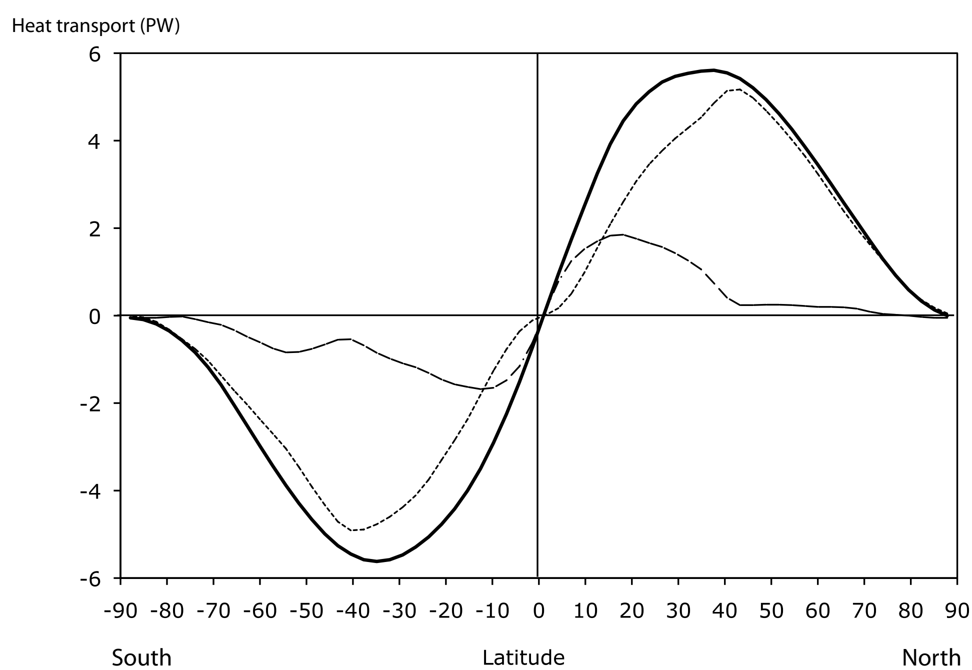

Fig. 1.5 Average transport of energy by the atmosphere (thin dotted) and ocean (dashed), and total transport (solid line). Positive transport towards the north and negative towards the south is recorded