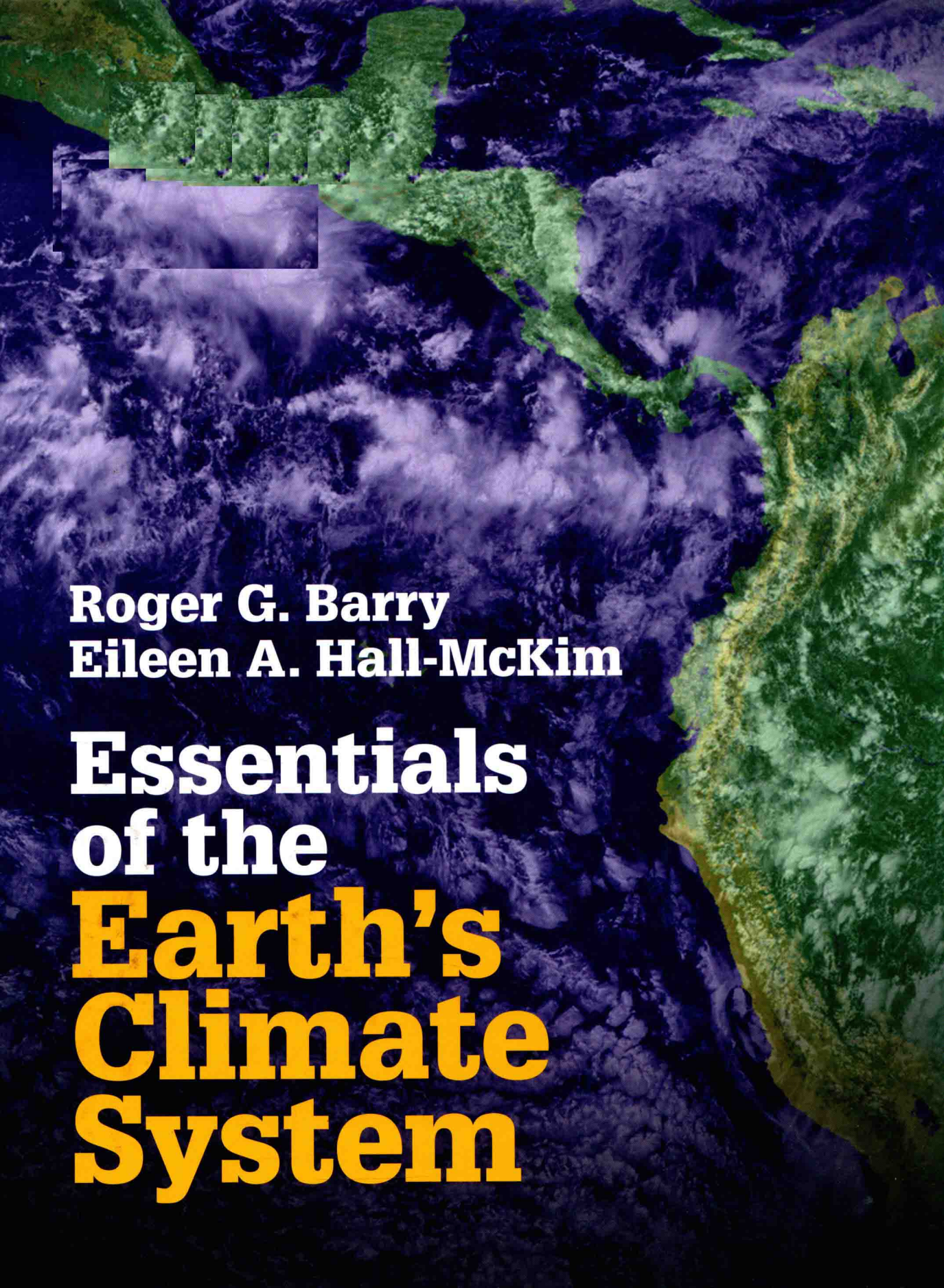

Roger G. Barry
Eileen A. Hall-McKim

# Essentials of the Earth's Climate System

"This delightful and readable textbook covers all the topics – and then some – likely to comprise an introductory or intermediate-level college course … essential reading for university undergraduate and graduate students alike … THE essential text on climatology … destined to become a classic."

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" … a very comprehensive and informative resource for teaching and for general reference … This book has an important place in the classroom and on any Earth scientist's bookshelf."

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- PowerPoint slides and JPEGS of all the figures in the book

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Barry and Hall-McKim

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- Each chapter concludes with a summary of the main points and a mixture of review and discussion questions that encourage students to check their understanding and think critically.

**Roger G. Barry** was born in Sheffield, England and worked for two years in the British Meteorological Office before attending Liverpool University, where he received a BA Honors in Geography. He received an MSc in Climatology from McGill University, Montreal, and a PhD from the University of Southampton in 1965. In October 1968 he moved to the University of Colorado, Boulder to become Associate Professor of Geography, Professor (1971–2004), and Distinguished Professor (2004–2010). In 1977 he became the Director of the World Data Center for Glaciology, which in 1980 merged into the National Snow and Ice Data Center (NSIDC). Roger's teaching and research has spanned climate change, Arctic and mountain climates, synoptic climatology, and snow and ice processes. Roger has published 25 textbooks, including: *Atmosphere, Weather and Climate* (with R. J. Chorley, tenth edition, 2010); *Mountain Weather and Climate* (third edition, 2008, Cambridge University Press); *Synoptic and Dynamic Climatology* (with A. M. Carleton, 2011, Routledge); *The Arctic Climate System* (with M. C. Serreze, 2005, Cambridge University Press); *The Global Cryosphere: Past, Present and Future* (with T. Y. Gan, 2011, Cambridge University Press). He has also published more than 250 research articles, and supervised 65 graduate students. Roger has been a Guggenheim Fellow, a Fulbright Teaching Fellow at Moscow State University, and a Visiting Professor in Australia, France, Germany, Japan, New Zealand, Switzerland, and the United Kingdom. His honors include: Fellow, American Geophysical Union; Foreign Member of the Russian Academy of Environmental Science (RAEN) Founder's Medal, Royal Geographical Society; Humboldt Prize Fellow. He is currently Director of the International CLIVAR Project Office at the National Oceanography Centre, Southampton, UK.

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"Absolutely the ultimate word on the physical, synoptic, and geographic underpinnings of modern climatology and its historic antecedents. This delightful and readable textbook covers all the topics – and then some – likely to comprise an introductory or intermediate-level college course . . . Discussions of the forcing, form, and function of the climate system – on scales ranging from local to global – will be essential reading for university undergraduate and graduate students alike, and a helpful review for seasoned researchers in the climate and atmospheric sciences. The easy-on-the-eye text style is complemented by the many incisive color figures, maps, and graphs, most of which are based on the latest analyses from satellites and global re-analysis data. Beginning and end-of-chapter overviews and summaries highlight the most important concepts and features of climatology study, while the glossary and bibliography are both comprehensive and fully up to date. *Essentials of the Earth's Climate System* is the essential text on climatology, and is destined to become a classic."

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**Nicholas Pepin**, *University of Portsmouth*

" . . . an excellent introduction to climate science, enabling coverage of the main issues in one semester and an inspiration for more in-depth studies. It is simple enough to be understood by geography and environmental science undergraduates without previous knowledge of climatology, but not oversimplified. It skillfully mixes complex concepts with observational data engaging the reader and making the challenging understandable and the seemingly tedious exciting . . . An immense advantage of this textbook is that its first part provides excellent explanations of the very basics of climate science . . . The authors manage to lay the foundations for more advanced studies and engage readers through the use of diverse examples from various parts of the world . . . The authors skillfully intermingle observational data with explanations of complex processes and concepts in an engaging and easy-to-follow manner . . . Overall, I highly recommend this book for undergraduate courses, and every university library should have a copy."

**Maria Shahgedanova**, *University of Reading*

"Drawing on more than 50 years of combined experience in climate study, Barry and Hall-McKim give the reader a compact, non-mathematical overview of the fundamental processes of the Earth's climate system. The book is surprisingly comprehensive, given its relatively brief length: coverage ranges from global to the local, from short-term phenomena to long-term climatic change. Complex topics are explained in straightforward, non-complex language, which in turn is supported by excellent color illustrations, and numerous place-specific examples are skillfully employed to illustrate general processes and concepts. *Essentials of the Earth's Climate System* is an ideal introduction to the topic for an upper-level undergraduate course in climate. It is likely to become the standard textbook in its field."

**Thomas Krabacher**, *California State University, Sacramento*

# Preface

This textbook seeks to provide a modern global overview of the world's climates on all space and time scales. It addresses microclimates to global scale processes and phenomena. It spans climate changes over geologic time and the future climates of the late twenty-first century. It is designed to serve as an introductory course in climatology, suitable for students in environmental sciences, geography, meteorology, and related disciplines. The purpose of the book is first to provide a firm foundation of the physical principles that underpin climatology; second, to describe the spatial climatic characteristics over the globe including local and microclimatic scales; third, to detail the past and projected future climates of the Earth; and fourth, to introduce some applications of climatic information.

The book is organized into 11 parts following a brief introduction on definitions, statistics, and the history of climatology. These are: a global view of the major climatic elements of energy and moisture followed by pressure, wind and storms, local and microclimates, the general circulation, circulation modes, synoptic climatology, the regional effects of land and sea, climatic types on land, past climates, future climate and its impacts, and different examples of applied climatology. Chapters 2, 3, 5, 6, and 7 are more meteorological in content. Chapters 8 and 9 provide detailed accounts of oceanic and land climates.

My meteorological experience began in the early 1950s, when I worked as a scientific assistant in the British Meteorological Office for two years at Royal Air Force (RAF) station Worksop in Nottinghamshire and then, following an undergraduate degree at the University of Liverpool, in 1957–1958 I was a graduate student weather observer at the McGill Subarctic Research Station at Schefferville in northern Quebec-Labrador.

I have carried out meteorological fieldwork in the Canadian Arctic, Papua New Guinea, the Colorado Rocky Mountains, and the Venezuelan Andes. Among the climatologists featured in text boxes, I have personally known Hubert Lamb, Jerry Namias, Murray Mitchell, Herman Flohn, and Herbert Riehl.

The text builds on over 50 years' experience in teaching climatology to geography students at the University of Southampton, UK (1960–1968) and the University of Colorado, Boulder, Colorado, USA (1968–2010).

This textbook contains many **pedagogical features**:

- The treatment is non-mathematical, but physical processes are explained. Where simple equations are introduced, their meaning is fully explained.
- Clear illustrations in full colour support the topics introduced in the text.
- Two types of boxes are used: 'A' boxes for elaborations of points made in the text; and 'B' boxes for wider topics that can be used by teachers and students to expand their information and awareness.
- The main points of each chapter are recapped in a summary section at the end of chapters.
- A mixture of review and discussion questions encourage students to check their understanding and think critically.
- Students are further supported by a glossary, a list of useful websites, and an appendix on units.

The book is supported by a number of **online resources**, to be found at www.cambridge.org/climatesystem:

- Web links to data and other key resources.
- Solutions and hints to answers to the student questions (password-protected for access by course instructors).
- PowerPoint slides and JPEGS of all the figures in the book for the use of course instructors.

Roger G. Barry
Distinguished Professor of Geography Emeritus
Director, NSIDC/WDC for Glaciology, 1976–2008,
Director, International CLIVAR Project Office,
National Oceanography Centre, NERC, Southampton

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*J. Geophys. Res.*, 2002, 116: D11108, Fig. 3

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*J. Climate*, 1993, 6: p. 2168, Fig. 4; 2008, 21: p. 2322, Fig. 7d
*Mon. Weather. Rev.*, 2004, 132: p. 1743, Fig. 23
Frederick Sanders Symposium, American Meteorological Society, 12 January 2004, Seattle, WA, Paper 16.3, Figures 1 and 2.

**Cambridge University Press,** *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds. Solomon, S. and Qin, D. H. *et al.*) p. 767, Fig. 10.9

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www.globvapour.info, User Help Desk

**Food and Agriculture Organization**, FAO Fisheries Technical Paper. No. 410. 2001. Rome. L. B. Klyashtorin, p. 7, Fig. 2.2

**C. Godske**, 1966. "Methods of statistics and some applications to climatology," in *Statistical Analysis and Prognosis in Meteorology*. Tech, Note No. 71 (WMO

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R. G. Barry in R. J. Chorley and P. Haggett, "Models in Geography," 1967, p.101, Figs. 4.1, 4.2, 4.3; p. 115, Fig. 4.9.

**UCAR Comet**, Boulder, Colorado. Milankovitch cycles, Fig. 10.2.

**Wiley and Sons,** *J. Climatol.*, 1984, Whittaker and Horn: 4, p. 300, Fig. 2a and p. 306, Fig. 4a

**Wikipedia**

**World Meteorological Organization, Geneva**

**K. Wyrtki**, 1985, *The Global Climate System: A Critical Review of the Climate System During 1982–1984*, WMO, Geneva, p. 15, figure 11.

# Contents


Preface *page* ix
Acknowledgments xi

1 Introduction 1
1.1 Climate and weather 2
1.2 Why climate matters 3
1.3 Climate statistics 4
1.4 History of world climatology 6
1.5 The use of weather satellites 11

2 The elements of climate: a global view of energy and moisture 14
2.1 Energy 15
(a) Solar radiation 15
(b) Cloud effects 18
(c) Aerosol effects 19
(d) Surface receipt of solar radiation 20
(e) Infrared radiation 21
(f) Net radiation 23
(g) Heat fluxes 23
(h) Temperature 25
2.2 Moisture 29
(a) Vapor content, vapor pressure, relative humidity, and precipitable water 29
(b) Clouds 31
(c) Lightning 32
(d) Precipitation 34
(e) Evaporation 40
(f) Visibility 45

3 The elements of climate: a global view of pressure, winds, and storms 47
3.1 Pressure and winds 48
(a) Pressure 48
(b) Winds 50
(c) Horizontal moisture flux 57
3.2 Air masses 59
3.3 Frontal zones 61

3.4 Storm frequency and tracks 64
3.5 Thunderstorms 71
3.6 Mesoscale convective systems 71

4 Local and microclimates 74
4.1 Local climate 75
4.2 Forest climate 79
4.3 Lake climate 80
4.4 Urban climate 81
(a) Pollution 82
(b) Urban heat island 82
(c) Moisture effects 84
4.5 Microclimate 85
4.6 Human bioclimatology 86

5 The general circulation 91
5.1 Factors 92
5.2 Meridional cells and zonal winds 94
5.3 Zonal wind belts 96
5.4 Zonal circulations 100

6 Circulation modes 103
6.1 Introduction 103
6.2 The Southern Oscillation and El Niño 104
6.3 The North Atlantic Oscillation 109
6.4 The Northern Annular Mode 109
6.5 The Southern Annular Mode 110
6.6 The semiannual oscillation 110
6.7 The North Pacific Oscillation 110
6.8 The Pacific Decadal Oscillation 111
6.9 The Atlantic Multidecadal Oscillation 111
6.10 Southern Hemisphere wave number-three pattern 112
6.11 The Madden–Julian Oscillation 112

7 Synoptic climatology 116
7.1 Introduction 117
7.2 Regional classifications 117
7.3 Continental classifications 122
7.4 Hemispheric classifications 122
7.5 Modern applications of synoptic climatology 125

8 Land and sea effects 127
8.1 Oceans 128
(a) Northern Hemisphere currents 129
(b) The Arctic Ocean 132
(c) Southern Hemisphere currents 134
(d) The Southern Ocean 134
8.2 Air–sea interaction 135
(a) Tropical cyclones 138
8.3 Land 138

9 Climatic types on land 145
9.1 Classifying climates 146
9.2 Major climatic types on land 146
(a) Deserts 146
(b) Monsoons 149
(c) High plateaus 154
(d) Wet lowlands 157
(e) Tropical and subtropical steppe 160
(f) Humid subtropical 160
(g) Mediterranean 161
(h) Temperate lowlands 162
(i) Maritime west coasts 164
(j) Mid-latitude steppe and prairie 165
(k) Taiga/boreal forest 165
(l) Tundra 167
(m) Ice plateaus 168

10 Past climates 172
10.1 Geologic time 173
10.2 The Cenozoic 175
10.3 The Quaternary 176
10.4 The Anthropocene 186

11 Future climate 194
11.1 Global climate models 195
11.2 Projected changes 196
11.3 Impacts 199
11.4 Economic and socio-political issues 202

12 Applied climatology 206
12.1 Climatic extremes and disasters 207
12.2 Climatic aspects of vegetation and soils 209

12.3 Agriculture and climate 212
12.4 Water resources 214
12.5 Renewable energy 217
12.6 Climate effects on transportation 219
12.7 Insurance and climate/weather disasters 220
12.8 Climate forecasts and climate services 221

Appendix A: Units 225
Appendix B: Web links 226
Glossary 228
Bibliography 245
Index 255

# Introduction

1

**Automatic weather station in the Apennine Hills near Madigliana, Romagna, Italy.**

WE BEGIN by defining climate and weather and then explaining their significance in everyday life. This helps clarify the scope and importance of climatology and its place in environmental sciences. Following a brief introduction to climatic data and frequently used statistics, we review the history of world climatology over the last two centuries. Finally, we examine the contribution of weather satellites to the study of weather and climate beginning in the 1960s.

## 1.1 Climate and weather

The word *climate* is derived from the Greek word "klima," meaning slope, and was linked to temperature gradients from Equator to Pole. It entered the English language from French in the thirteenth century. Its modern meaning evolved in the sixteenth century.

Climate is the sum total (or composite) of the weather conditions that generally prevail at a place or over a region. It encompasses the statistics (means, variability, and extremes) of temperature, humidity, atmospheric pressure, wind velocity, cloud cover, precipitation, and other meteorological variables over a long period of time. In contrast, weather is the condition of these same elements and their variations over time intervals of a few days. Conventionally, weather extends out to about 10–15 days – the limit of numerical weather prediction – while longer intervals, typically a month, are considered as part of climate. The "standard" interval used to define climatic characteristics by the World Meteorological Organization (WMO) is 30 years, and these data are called "normals." This term was first used for 1901–1930; the current normal is 1961–1990 or 1981–2010, depending on data availability. However, world weather records were earlier published for 1881–1920. The 30 years must be consecutive and the averages are unweighted. The normals are updated by national climate organizations and the WMO each decade.

Another, much broader definition, that recognizes the complexity of climate, was proposed by the US Committee for the Global Atmospheric Research Program in 1975. It refers to the climatic state as "the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric, and cryospheric variables over a specified period of time (monthly, seasonal, annual, decadal) in a specified domain of the earth–atmosphere system." Hydrospheric variables refer to all components of the global water cycle, while cryospheric variables refer to all forms of snow and ice. An updated version of this would also include the biospheric variables on land and in the ocean that affect transfers of energy, water, momentum, and gases between the surface and the atmosphere. The complexity of the climate system is illustrated in Figure 1.1, showing the atmosphere, oceans, hydrosphere, biosphere, and cryosphere. These components, their changes, and their interactions are the subject of this book. Hence, climate is a key element of the global and local environments that has enormous influence on most aspects of our daily lives, whether we live in rural or urban areas. It determines what crops can be grown, how much water is available for drinking and irrigation, and what kinds of shelter and clothing we need.

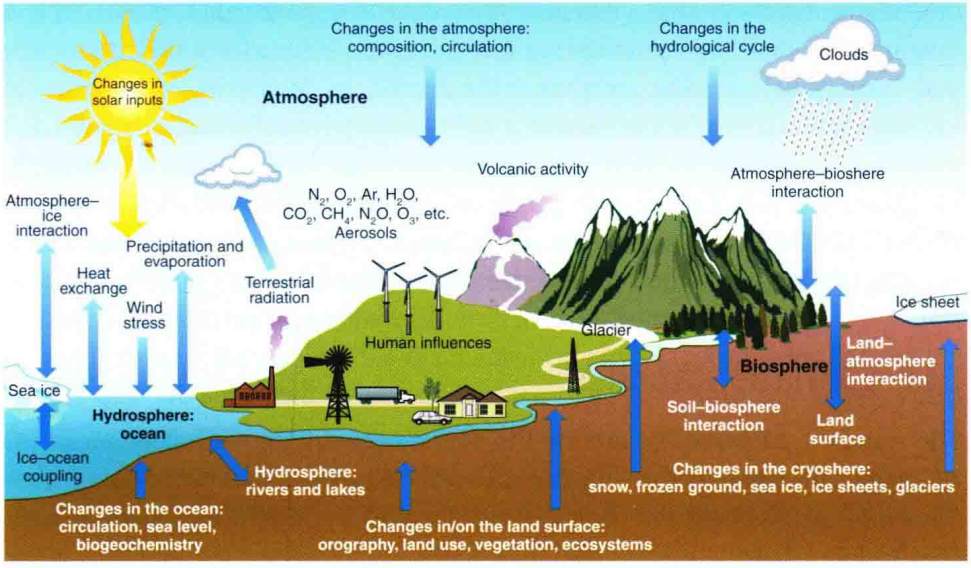


**Figure 1.1** The climate system (from Solomon *et al*. 2007, p. 767, Fig. 10.9).

## 1.2 Why climate matters

Weather affects our day-to-day life and decisions – whether we need an overcoat, umbrella, snow boots, or sunscreen and, in the case of severe weather like thunderstorms or tornadoes, when and where to take shelter. Weather also has major effects on all forms of transportation on land, at sea, and in the air. Climate influences what kind of house we build or buy, whether it has air conditioning or double-glazed windows, and whether it has a flat or sloping roof. It also determines the nature of the local vegetation and agriculture, whether irrigation is needed or not, and the character of the water supply.

Until the mid twentieth century it was considered that climate was essentially constant, but in the 1950s it became widely recognized that as well as ice age events in the distant past, there were important fluctuations on decadal to centennial time scales. We examine changes on these various time scales in Chapter 10. It is also now known that human activities are largely responsible for global warming that began in the late nineteenth or early twentieth centuries and has accelerated over the last few decades. There has been an increasing incidence of heat waves and droughts, as well as floods in other areas. The use of refrigerants (chlorofluorocarbons, or CFCs) led to the formation of the ozone hole in the Antarctic stratosphere, above 15 km, that allows dangerous levels of ultraviolet radiation from the sun to reach the surface in southern South America and Antarctica. While the Montreal Protocol, adopted by most nations of the world