Preface

As part of the Princeton Primers in Climate Science series, *Paleoclimate* is a broad introduction to the subject for a scientifically literate audience, a reference for information about specific topics in the field, and a textbook for courses in climate and paleoclimate.

Earth's climate has undergone dramatic changes since early in the history of the planet. At one extreme, Earth was glaciated to the equator, more than once, for intervals that may have lasted millions of years. At another, climates were so warm that the Canadian Arctic was heavily forested and large dinosaurs lived on Antarctica. Four key factors have caused these climate modifications: changes in atmospheric greenhouse gas concentrations, changes in the amount of sun's radiation reflected directly back to space, changes in the position of the continents that guide winds and ocean currents, and changes in the brightness of the sun.

The first task of paleoclimate science is to identify, from observations of the geological record, the nature of past climate changes. The effort devoted to this task has been huge, and paleoclimate scientists have developed and used a very broad array of methods, some wonderfully imaginative. The second task is to use the resulting observations to synthesize a coherent, falsifiable narrative describing major paleoclimate events. The third task is to understand the dynamics shaping the events that are observed and described.

The motivation for these activities is twofold. First, climate history is a compelling topic that examines a fundamental feature of the environment. Second, observations of climate history help us to understand the range of possible climate responses to anthropogenic perturbations, and to test models simulating or predicting these responses.

This book describes the study of paleoclimate. The first chapter explains the main attributes of climate on the planet, including controls on global average temperature, patterns of winds and precipitation, and other first-order features of the environment. The book then describes seminal events in Earth's climate history. The starting point is the "faint young sun" problem: How could there have been water on Earth's surface early in the history of the planet, when the sun shone only about 70% as brightly as today? The next topic is "snowball Earth," periods before 600,000,000 years ago when the planet was glaciated to the equator, perhaps for millions of years. The subsequent chapter describes a paradigm that accounts for the regulation of greenhouse gases and Earth's temperature over the Phanerozoic Eon, the last, fossiliferous, 543 Myr (million years) of Earth history. Then comes the Late Paleozoic ice ages, an interval from about 360 to 270 Ma (millions of years before present) when Earth was periodically glaciated. That event was followed, from about 250 to 50 Ma, by very warm conditions, with forests covering the islands of the Canadian Arctic, for example. Around 50 Ma, Earth began cooling, a process that still continues. Superimposed on this long cooling were global climate cycles, whose magnitude and duration have changed with time. The last ice age ended 11,700 years ago, and we entered the Holocene, the interglacial period of the current glacial-interglacial climate cycle that hosted the development of civilization. Over the past two centuries, humans have become agents in the global climate system, most notably by emitting CO_2 (carbon dioxide) and other greenhouse gases.

These climate events played out in Earth's dynamic surface environment. Three attributes of this environment are particularly important. First, volcanism and other processes occurring in Earth's interior continuously release CO_2 to the atmosphere. This CO_2 warms the planet until it is removed by "weathering," the chemical reactions in which CO_2 is consumed while interacting with the crystalline rocks of Earth's surface. Second, the positions of the drifting continents establish a boundary condition for the climate system. Third, the evolving biota affect concentrations of greenhouse gases in the atmosphere, weathering reactions, and the reflectance of the planet.

Other than water, CO_2 is by far the most important greenhouse gas. Its atmospheric concentration is regulated by the balance between release from Earth's interior and removal by weathering. "Feedbacks" are interactions that depend on the state of a system. A positive feedback occurs when an increase in one property leads another property to change in a way causing the first property to increase further. A negative feedback occurs when a rise in the first property leads the second to change in a way that lowers the first property, this stabilizing the system. Feedbacks within the Earth system maintain the habitability of the planet while still allowing quite significant variations in the atmospheric CO_2 concentration and climate.

Continental positions continuously change as seafloor spreading moves the continents over the surface of the planet. Positioning of continents close to the equator during periods of "snowball Earth" is thought to have enabled the descent into static, cold climates. Continental positions have also contributed to the two great periods of oscillating ice ages, the Late Paleozoic ice ages (about 360–270 Ma) and the glacial climates of the past 34 Myr. Today, for example, glaciation is abetted by the presence of a continent centered over South Pole. Antarctica is permanently glaciated, leading to high reflectance of sunlight by the bright surface, and the presence of very cold waters in the Southern Ocean. There is also a large temperate and subpolar landmass in the Northern Hemisphere, on which ice sheets can grow and decay with a cycle time of 40–100 Kyr (thousand years).

Biota affect climate by producing and consuming CO_2 and other biogenic greenhouse gases that are important in Earth's heat balance. Plants produce O_2 and are the immediate source of that gas in air. They also help darken Earth's surface, thereby influencing the amount of the sun's heat that is absorbed by the planet rather than being reflected back to space. Finally, plants enrich soils in organic matter and hence in metabolic CO_2 as well, thereby facilitating the uptake of CO_2 by weathering. The biota thus influences background climate and is also implicated in several of the events of interest to us.

Life began by about 3.9 Ga (3.9 billion years ago); photosynthesis originated by 2.7 Ga, and the O_2 concentration of air rose to significant levels at about 2.4 Ga. Its rise would have led to the demise of greenhouse gases, possibly explaining Earth's first snowball event. Large changes in Earth's carbon cycle are associated with two snowball events occurring between 720–610 Ma. Plants colonized land around 400 Ma. They would have enhanced weathering, perhaps contributing to the Late Paleozoic ice ages that soon followed. Interactions between plants and climate have had an influence on more recent climate change that is important, if more subtle.

In this book, one chapter is devoted to each of the seminal climate events listed above. Each chapter describes the physical evidence for the nature of the event; presents a picture of the relevant climate cycles, where appropriate; and discusses hypotheses that have been advanced to explain the episode. The book aims to be accessible and concise rather than exhaustive, but summarizes viable competing hypotheses.

Paleoclimate is perhaps the oldest discipline in Earth science; it began in the nineteenth century, and earlier, with the debate about whether the surface environment of temperate areas was shaped by the biblical flood or by glaciers. By the middle of the twentieth century, many climate features associated with the recent ice ages had been identified. Progress accelerated dramatically after the Second World War with the advent of the methods of nuclear geochemistry, including radiometric dating and stable isotope geochemistry. Around this time, ships and tools for sampling seafloor sediments also advanced, leading to great improvement in our understanding of climate change in the oceans. Methods were also developed for recovering and studying cores drilled through the Greenland and Antarctic ice sheets. A seminal advancement in our understanding of the ice ages occurred when Swiss and French scientists learned to use these samples to characterize the CO_2 concentration of the past atmosphere. In the mid-1960s, the plate tectonics revolution led to a coherent understanding of the physical environment in which major climate changes occurred. Improvements in characterizing climate by geochemical and other tools, together with the use of simple and complex climate models to analyze observations, have advanced the field. At the same time, there has been something of a return to the roots of paleoclimate research, with a growth of interest in fieldwork leading to spectacular new insights. Finally, the challenges of understanding past climates, together with the growing awareness it offers of anthropogenic global change, have led to the recruitment of distinguished scientists from other fields who have made major contributions to the discipline. This constellation of resources and activity leads to the story in this book.