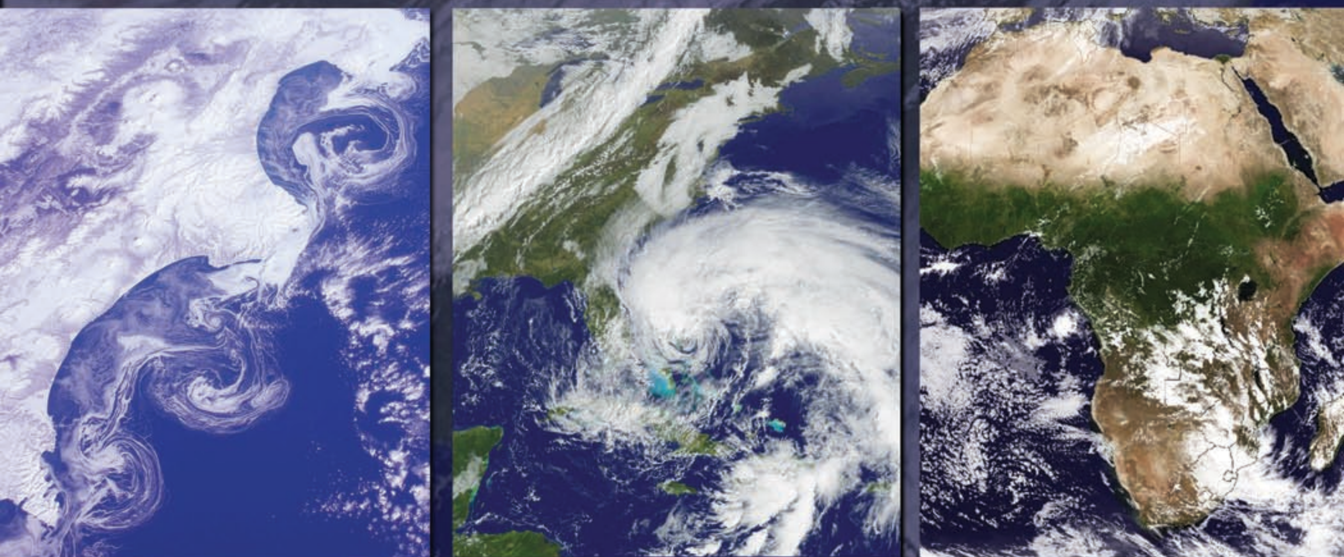
CLIMATE DYNAMICS



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Princeton University Press
Princeton and Oxford

Published by Princeton University Press, 41 William Street, Princeton, New Jersey 08540
In the United Kingdom: Princeton University Press, 6 Oxford Street, Woodstock, Oxfordshire OX20 1TW

press.princeton.edu

Library of Congress Cataloging-in-Publication Data

Cook, Kerry Harrison, 1953–
Climate dynamics / Kerry H. Cook.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-691-12530-5 (hardcover : alk. paper) 1. Climatology. 2. Human ecology. I. Title.
QC861.3.C66 2013
551.6—dc23
2012032005

British Library Cataloging-in-Publication Data is available

This book has been composed in Sabon and Trajan

Printed on acid-free paper. ∞

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Dedicated to my children,
Hilary and Jeffrey,
And in memory of my mother, Alva

Contents

Preface

The purpose of this book is to provide a foundation in the physical understanding of the earth's climate system. It is based on more than 20 years' experience teaching climate dynamics at Cornell University and, more recently, The University of Texas at Austin.

Most universities and colleges do not have a Department of Atmospheric Science, in which a technical course on climate dynamics would most likely be found. However, there is a pressing need to increase and promote an understanding of the climate system. Climate change will affect all fields of study and all professions in the coming decades, including the medical and engineering professions, and it will increasingly involve global political systems and economic planning. I wrote this book to support and broaden the teaching of climate dynamics.

The book assumes no background in atmospheric or ocean sciences and is written to be accessible for teaching by faculty in any field of science, mathematics, or engineering. The material is appropriate for any science or engineering undergraduate student who has completed two semesters of calculus and one semester of calculus-based physics. In combination with selected readings from the most recent Assessment Report of the Intergovernmental Panel on Climate Change, this book can be used to develop a course on contemporary climate change that emphasizes the physical understanding of the climate system.

The first section of the book (chapters 1–3) provides a description of the climate system based on observations of the mean climate state and its variability. It introduces the vocabulary of the field, the dependent variables that describe the climate system, and the typical approaches taken in displaying these variables. Taken together, chapters 2 and 3 form an atlas of the climate system, and figures from these chapters are referenced throughout the book.

The second section of the book (chapters 4–6) is aimed at developing a quantitative understanding of the processes that determine the climate state—radiation, heat balances, and the basics of geophysical fluid dynamics. The fluid dynamics application is developed on the premise that the student is familiar with Newton's laws of motion and basic thermodynamics from a first course in college physics. With an understanding of the basic processes, applications for the atmosphere, ocean, and hydrologic cycle are developed in chapters 7–9. The last three chapters of the book, chapters 10–12, are more directly related to contemporary climate change.

Many people contributed to this book, directly and indirectly. My daughter, Hilary, and my son, Jeffrey, always keep life interesting, and I appreciate their love and support. I also thank my father, Robert Harrison, for many years of encouragement. Professor Peter Gierasch taught the class with me for a number of years at Cornell, and his clear-sighted treatment of the material is reflected especially in the chapters on radiation and ocean dynamics. Major contributions to creating and improving figures came from Dr. Edward Vizy, Zachary Launer, and I especially thank Meredith Brown, who also helped with technical editing. I am also grateful to Ingrid Gnerlich and her colleagues at Princeton University Press for their patience and persistence. The hundreds of students in my climate classes over the years inspired this book and influenced its contents through their insightful questions, eagerness to *really* understand, and their genuine concern for the future of the planet. I am grateful to them all.

Climate Dynamics

1

An Introduction to the Climate System

Climate dynamics is the scientific study of how and why climate changes. The intent is not to understand day-to-day changes in weather but to explain average conditions over many years. Climate processes are typically associated with multidecadal time scales, and continental to global space scales, but one can certainly refer to the climate of a particular city.

Climate dynamics is a rapidly developing field of study, motivated by the realization that human activity is changing climate. It is necessary to understand the natural, or unperturbed, climate system and the processes of human-induced change to be able to forecast climate so that individuals and governments can make informed decisions about energy use, agricultural practice, water resources, development, and environmental protection.

Climate has been defined as "the slowly varying aspects of the atmosphere/hydrosphere/lithosphere system."[1] Other definitions of climate might also explicitly include the biosphere as part of the climate system, since life on the planet plays a well-documented role in determining climate. Anthropogenic climate change is just one example, but there are others, such as the influence of life on the chemical composition of the atmosphere throughout its 4.5 billion–year life span.

The word *climate* is derived from the Greek word *klima*, which refers to the angle of incidence of the sun. This is a fitting origin because solar radiation is the ultimate energy source for the climate system. But to understand climate we need to consider much more than solar heating. Processes within the earth system convert incoming solar radiation to other forms of energy and redistribute it over the globe from pole to pole and throughout the vertical expanses of the atmosphere and ocean. This energy not only warms the atmosphere and oceans but also fuels winds and ocean currents, activates phase changes of water, drives chemical transformations, and supports biological activity. Many interacting processes create the variety of climates found on the earth.

A schematic overview of the global climate system is provided in Figure 1.1. This diagram represents the climate system as being composed of five subsystems—the atmosphere, the hydrosphere, the biosphere, the cryosphere, and the land surface. It also depicts processes that are important for determining the climate state, such as the exchange of heat, momentum, and water among the subsystems, and represents the agents of climate change.

[1] From the *Glossary of Meteorology*, published by the American Meteorological Society.

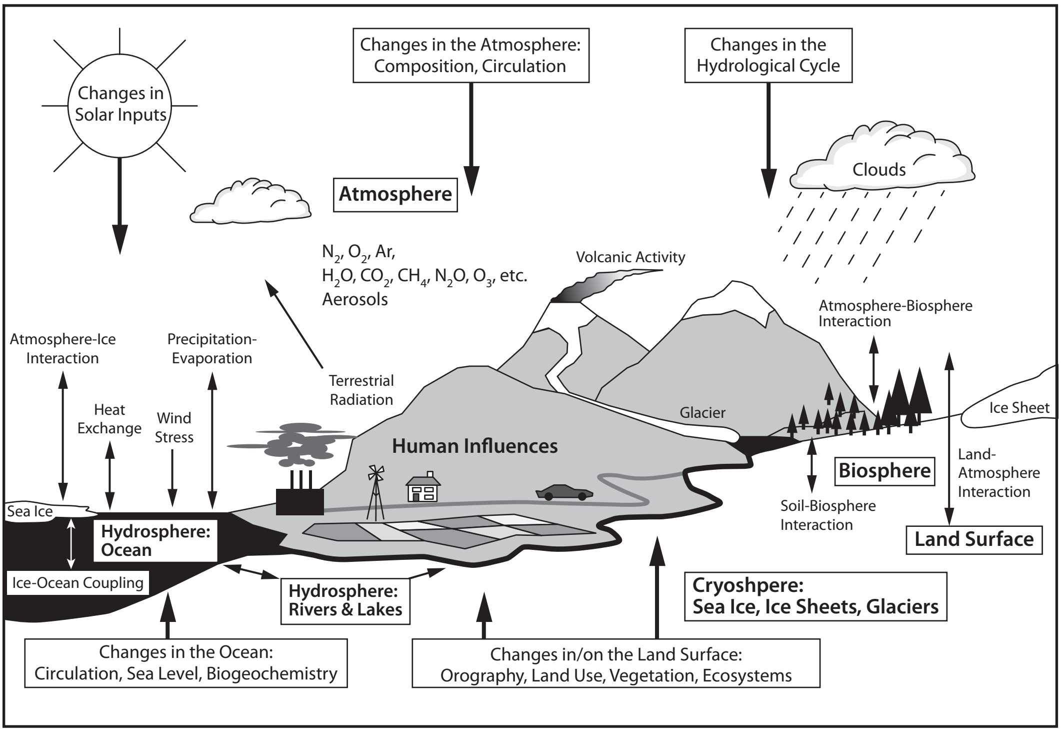

Figure 1.1 Schematic of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows). From IPCC, 2001.

Figure 1.1 provides an excellent summary of the climate system, and it is useful as a first-order, nontechnical description. At the other end of the spectrum is the *Bretherton diagram*, shown in Figure 1.2. This detailed, perhaps a bit overwhelming, schematic was constructed to characterize the full complexity of climate. It is a remarkable and rich representation of the system, illustrating the many processes that influence climate on all time scales. It coalesces historically separate fields of scientific inquiry—demonstrating that not only atmospheric science and oceanography are relevant to climate science but that various subdisciplines of geology, biology, physics, and chemistry—as well as the social sciences—are all integral to an understanding of climate.

This is a very exciting and critical time in the field of climate dynamics. There is reliable information that past climates were very different from today's climate, so we know the system is capable of significant change. We also understand that it is possible for the system to change quickly. The chemical composition of the atmosphere is changing before our eyes, and satellite- and earth-based observing networks allow us to monitor changes in climate fairly accurately.

Clearly, this one text on climate dynamics cannot cover the full breadth of this wide-ranging and rapidly developing field, but it provides the reader with the fundamentals—the background needed for a basic understanding of

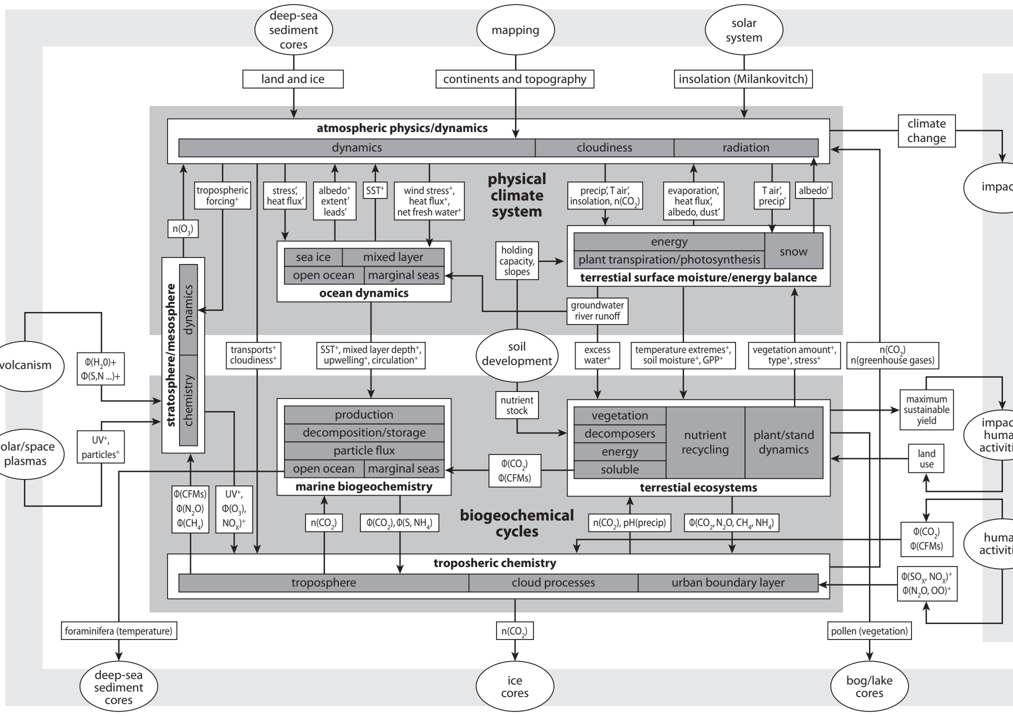

Figure 1.2 The Bretherton diagram, illustrating the components of the climate system and the interactions among them. (′ = on timescale of hours to days; * = on timescale of months to seasons; ϕ = flux; n = concentration; SST is sea surface temperature)

climate and climate change, and a launchpad for reading the scientific literature and, it is hoped, contributing to the profound challenge before humanity of managing climate change. With this fundamental understanding, science can address the questions, needs, and constraints of society in a reasonable and useful way, and offer informed answers to guide society's behavior.

Reference and Additional Reading

IPCC, 2001: Climate Change 2001: The Scientific Basis. Report of the Intergovernmental Panel on Climate Change. Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.). Cambridge University Press, Cambridge and New York.

2

The Observed Climatology

This chapter forms a concise atlas of the climate system. An overview of the system is presented using the variables and terminology commonly used to characterize climate. These terms are referenced in subsequent chapters as a deeper understanding of climate processes is developed.

Some features of the climate system are known accurately, while others are known only approximately. Climate observations can be limited by insufficient spatial and temporal resolution, inadequate global coverage, or a lack of long-term records. Precipitation observations are a good example. Because of the high variability of precipitation over a wide range of space and time scales, the observing requirements for establishing a precipitation climatology are demanding. Global measurements of precipitation or, more accurately, measurements of radiative fluxes that can be translated into rainfall rates have been available only since the beginning of the satellite era in the early 1970s. Pre-satellite coverage over vast regions of the oceans was particularly sparse, especially in regions where ships rarely traveled. Establishing a climatology for other variables, such as evaporation and soil moisture, is even more challenging.

Many of the figures in this text were drawn using *reanalysis* products, which combine simulations using state-of-the-art numerical models with observations. To produce a reanalysis climatology, computer models are run to stimulate many decades, with observed fields incorporated into the model at the time they were observed. This process is called *four-dimensional data assimilation*, for the three spatial dimensions plus time. (Data assimilation is also used routinely in generating weather forecasts.) Thus, the reanalysis product is not pure observations but a blend of observations and computer model output. Reanalysis values of variables that are assimilated—for example, winds and temperatures—are accurate. Other variables, however, are model-dependent output and may not be as reliable. Sometimes, as in the case of evaporation, the reanalysis product is the best information available with global coverage. For other variables, ground-based and satellite observations, if available, are preferred to the reanalysis product.

Maps of climate variables use latitude and longitude as coordinates with an equidistant cylindrical projection. Keep in mind that the area of middle and high latitudes is falsely large in this projection. In reality, half the surface area of the globe lies between 30°N and 30ºS latitude, whereas in the figures this region occupies only one-third of the area. Vertical profiles of climate variables are also shown, averaged globally or over certain regions using area weighting to correctly account for the decreasing distance between meridians (lines of constant longitude) away from the equator. Another useful way to display climate variables is as the *zonal mean*, in which the variable is averaged over all longitudes and displayed in the latitude/height plane.

The international system of units (SI) is used as reviewed in Appendix A.

2.1 THE ATMOSPHERE

We begin our description of the atmosphere with air pressure. Pressure is defined as "force per unit area" and is expressed in SI units of pascals (abbreviated Pa). Pressure is simply the weight of the overlying mass, m, per unit area:

$$p \equiv \frac{mg}{\text{area}} \quad \Rightarrow \quad \text{Pa} \sim \frac{\text{newton}}{\text{m}^2} = \frac{(\text{kg} \cdot \text{m})/\text{s}^2}{\text{m}^2} = \frac{\text{kg}}{\text{m} \cdot \text{s}^2}, \tag{2.1}$$

where g is the acceleration due to gravity. Figure 2.1 shows the global distribution of surface pressure in units of hectapascals (hPa), where 100 Pa = 1 hPa. This figure is not helpful for learning about the atmosphere, however, because surface topography dominates the distribution. Surface pressure is lowest over the highest mountains, and high and uniform over the oceans, because the overlying air column is thinner (less massive) at higher elevations. Consequently, surface pressures in the Himalayan Mountains and over Antarctica drop below 600 hPa but are close to 1000 hPa everywhere over the world's oceans.

Figure 2.1 demonstrates the close connection between pressure and elevation. Pressure is often used as a vertical coordinate in describing the atmosphere, replacing elevation, z. The average relationship between p and z in the earth's atmosphere, typical of large space and time scales, is in Figure 2.2. Note that p is not a linear function of z, that is, $p \neq az + b$, where a and b are constants. Instead, pressure decreases exponentially with height.

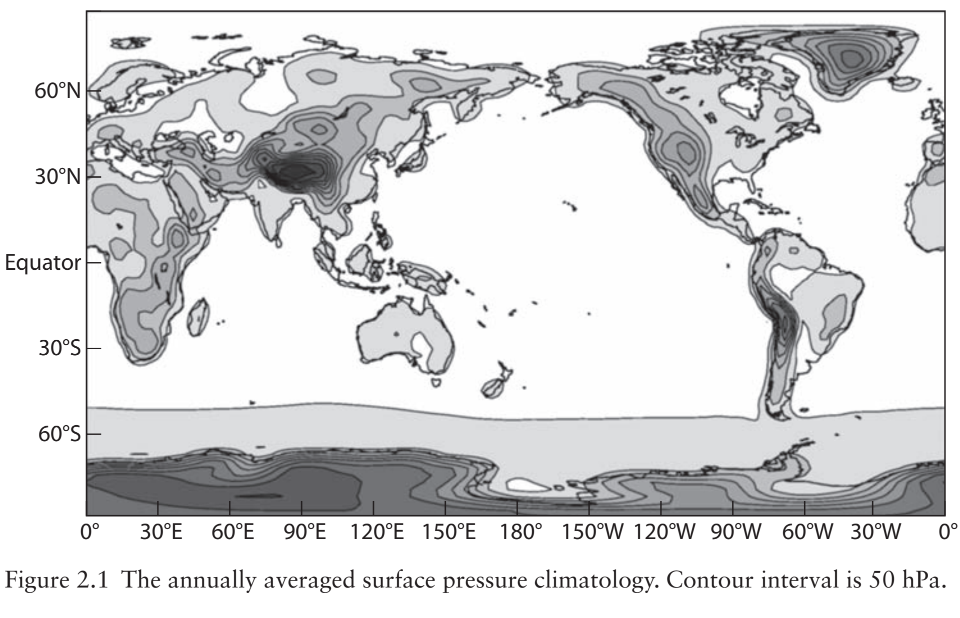

Figure 2.1 The annually averaged surface pressure climatology. Contour interval is 50 hPa.

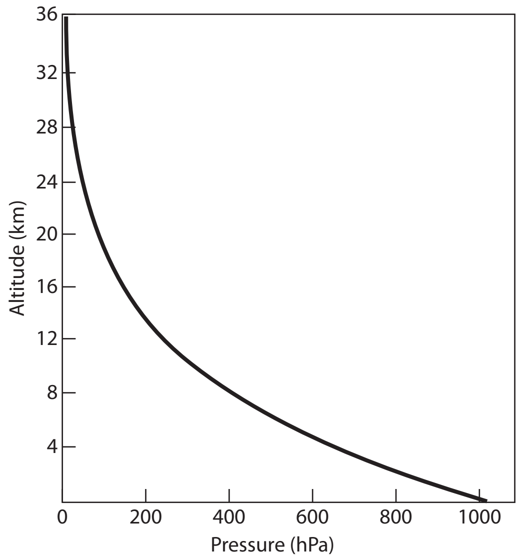

Figure 2.2 The average relationship between atmospheric pressure and altitude.

In the figures that follow, atmospheric variables are presented on surfaces of constant pressure, or *isobars*, instead of surfaces of uniform elevation. Figure 2.2 can be used to estimate the altitude of any pressure surface. Where topography extends up into the atmosphere, certain pressure levels may not exist. For example, since the surface pressure over Antarctica is 700 hPa or lower (see Fig. 2.1), there is no 900 hPa surface. Such regions may be specified as having missing data, or the data may be extrapolated to fill in the missing values.

When pressure is substituted for height as an *independent* variable, then the height of the pressure level becomes a *dependent* variable. (Recall that independent variables are the coordinate axes, and dependent variables describe the system. For the atmosphere, temperature and wind speeds are examples of dependent variables.) It is common to use *geopotential height*, Z, as the independent variable instead of height, z, where

$$Z \equiv \frac{1}{g_0}\int_0^z g\,dz. \tag{2.2}$$

In Eq. 2.2, g_0 is the acceleration due to gravity at the surface of the earth. Because the gravitational attraction between two bodies depends on the distance between them, the acceleration due to gravity decreases with increasing height—or decreasing pressure—in the atmosphere. At the earth's surface, $g = g_0 = 9.81$ m/s^2. At 10 km elevation, $g = 9.77$ m/s^2. This 0.4% reduction in g within the lower atmosphere is relatively small, so g can be taken as constant in Eq. 2.2. With this assumption, geopotential height, Z, can be interpreted as the elevation, z, of a pressure level.

Geopotential height is closely related to the gravitational potential energy, Φ, given by

$$\Phi(z) = \int_0^z g\,dz. \tag{2.3}$$

(Recall that work, which is a form of energy, is "force × distance".) Then Φ evaluated at some altitude z is the work that was done against gravity to lift a unit mass of air from the surface to that altitude. Equivalently, it is the "potential" energy that would be extracted if the unit mass were to fall to the surface. In common practice, Φ is referred to simply as the *geopotential*.

The annual mean geopotential height climatology at 900 and 200 hPa is displayed in Figure 2.3. Note the following:

- The 900 hPa surface is roughly 800 m from the surface in the subtropics (near 30°N and 30°S) and slopes down closer to the surface at higher latitudes and near the equator.

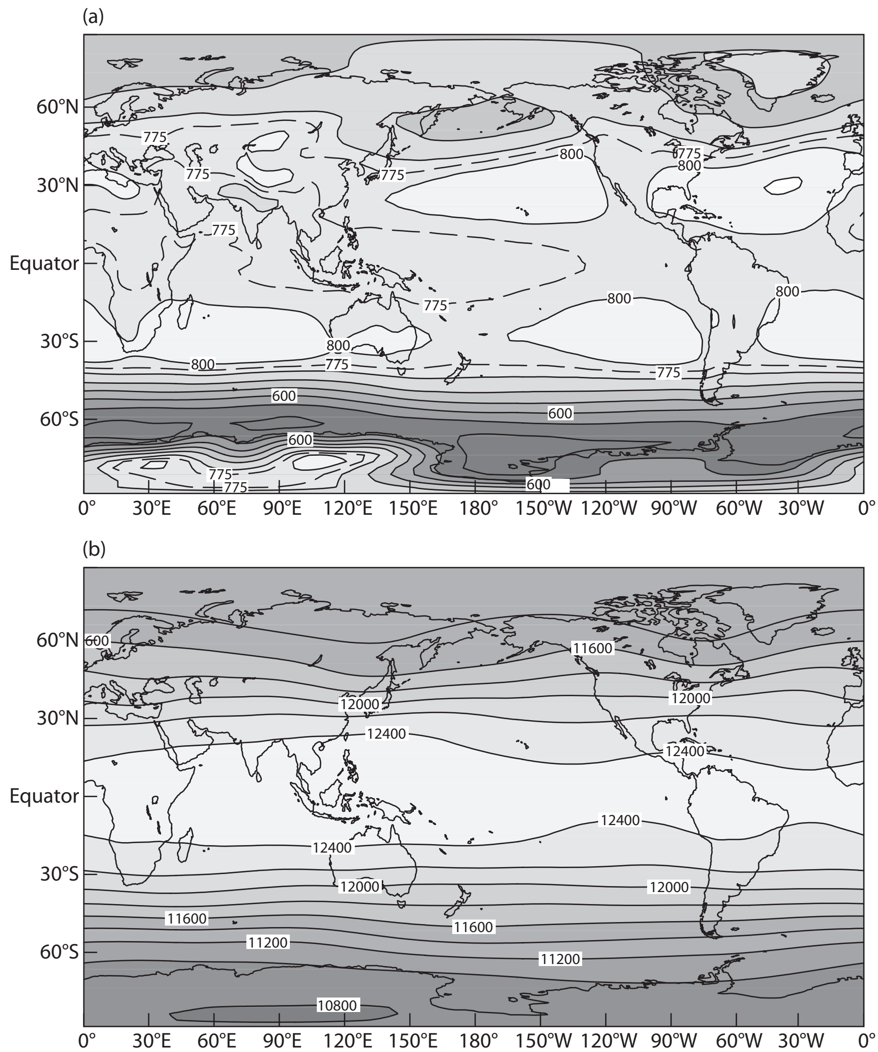

Figure 2.3 Annual mean geopotential height climatology in meters at 900 and 200 hPa. (a) The contour interval is 50 m; the 775 m contour is indicated with the dashed line. (b) The contour interval is 200 m.