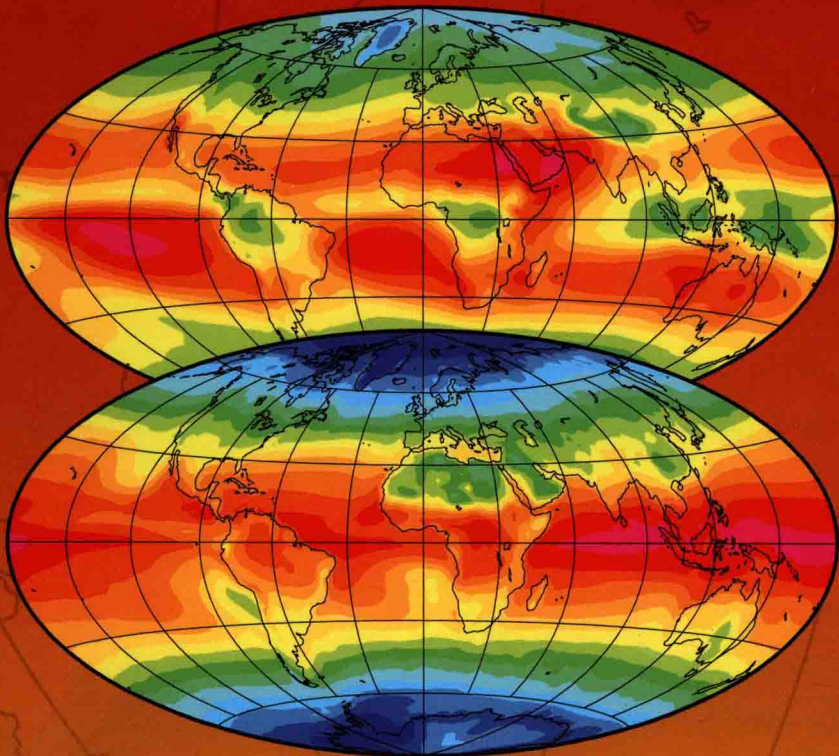


Global Physical Climatology

Second Edition



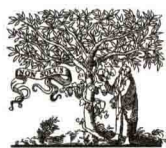
Dennis L. Hartmann

GLOBAL PHYSICAL CLIMATOLOGY

SECOND EDITION

DENNIS L. HARTMANN

*Department of Atmospheric Sciences,
University of Washington, Seattle, WA, USA*



ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Elsevier

Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

Copyright © 2016, 1994 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-328531-7

For information on all Elsevier publications
visit our website at <http://store.elsevier.com/>



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

GLOBAL
PHYSICAL
CLIMATOLOGY

SECOND EDITION

Preface to the Second Edition

I had not intended that 21 years should pass between the first edition of this book and the second, but much else has intervened to command my attention and time. The timing of this second edition is nonetheless propitious, as I started in earnest just after finishing participation in the Intergovernmental Panel on Climate Change (IPCC) Working Group I Fifth Assessment in late 2013. So I had good familiarity with a recent summary of the state of knowledge as a starting point. Another advantage of waiting so long is that the easy availability of data sets and modern tools to manipulate them made it possible for me to make most of the new figures myself. The second edition is thus heavy with color figures of data from observations and models.

The basic outline of the book is the same as that of the first edition, except that I have added a new Chapter 8 on natural internal variability that is captured by the instrumental record. This chapter makes use of some statistical and mathematical techniques that I do not explain in detail, but I feel that by looking at the pictures and trusting me, the student will gain an intuitive sense of the structures of atmospheric and oceanic variability. The first seven chapters are suitable for a course for undergraduate science majors, and the final six chapters are more appropriate for an introductory overview course for graduate students. When I use the book to teach third-year atmospheric sciences majors, I go through the first seven chapters and mix in material from Chapters 9, 12, and 13 to add spice and relevance.

Many people contributed to the second edition. Marc L. Michelsen made many of the figures in Chapter 6 and on many occasions rescued me when my own computer skills led me into blind alleys. Bryce E. Harrop did the radiative–convective equilibrium calculations in Chapters 3 and 13. I wanted to update Manabe and Wetherald (1967) with more physical clouds, but I have to say that modern calculations are not very different from theirs. Paulo Ceppi provided me with multimodel mean data from CMIP5. Mark D. Zelinka generated some key figures in Chapter 11. I have made liberal use of figures from the IPCC Fifth Assessment, and I am grateful to the IPCC authors for producing them and the IPCC for letting me use them here. I thank all the people who created data sets and put them on the web in handy format. Some of these are acknowledged in figure captions.

A number of people have used the first edition over the years and provided feedback, and some have used the draft of second edition

and provided editorial and content suggestions. I will forget to mention some of them, and for that I apologize. David W. J. Thompson used the draft of second edition in a class and provided a particularly insightful critique of the new Chapter 8. Donald J. Wuebbles also used the draft and provided suggestions and corrections. Tsubasa Kohyama did a very careful edit of most chapters of the second edition. Hansi K. A. Singh read Chapter 7 and provided comments that improved it. Casey Wall provided useful suggestions on the later chapters. Sara Berry, Paulo Ceppi, Bryce Harrop, Tsubasa Kohyama, Daniel McCoy, and Casey Wall helped with proof correction. Many students helped me involuntarily by using the book in class, and I thank them also for the insights I gained from their work. My present and former graduate students have taught me a lot. It is also a great boon for me to work in the Department of Atmospheric Sciences at the University of Washington, where excellence is combined with collegiality to good effect.

I am grateful for continued climate research support from the federal government through the National Science Foundation, National Aeronautics and Space Administration, National Oceanographic and Atmospheric Administration, and the Department of Energy. Climate research is a public good activity and without the support of the US taxpayer we would know much less about climate and the particular challenges that climate change presents to the world. Of course, other nations have also contributed greatly to what we have learned, and US citizens have benefited from their efforts too.

The dedication of the second edition remains the same as the first – to my family – who share their love and strengthen my spirit. It is also good to have great friends and colleagues. Thanks.

Dennis L. Hartmann
Seattle, October 2015

Preface to the First Edition

The science of climatology began to evolve rapidly in the last third of the twentieth century. This rapid development arose from several causes. During this period, the view of Earth from its moon made people more aware of the exceptional nature of their planetary home at about the same time that it became widely understood that humans could alter our global environment. Scientific and technological developments gave us new and quantitative information on past climate variations, global observations of climate parameters from space, and computer models with which we could simulate the global climate system. These new tools together with concern about global environmental change and its consequences for humanity caused an increase in the intensity of scientific research about climate.

Modern study of the Earth's climate system has become an interdisciplinary science incorporating the atmosphere, the ocean, and the land surface, which interact through physical, chemical, and biological processes. A fully general treatment of this system is as yet impossible, because the understanding of it is just beginning to develop. This textbook provides an introduction to the physical interactions in the climate system, viewed from a global perspective. Even this endeavor is a difficult one, since many earth science subdisciplines must be incorporated, such as dynamic meteorology, physical oceanography, radiative transfer, glaciology, hydrology, boundary-layer meteorology, and paleoclimatology. To make a book of manageable size about such a complex topic requires many difficult choices. I have endeavored to provide a sense of the complexity and interconnectedness of the climate problem without going into excessive detail in any one area. Although the modern approach to climatology has arisen out of diverse disciplines, a coherent collection of concepts is emerging that defines a starting point for a distinct science. This textbook is my attempt to present the physical elements of that beginning with occasional references to where the chemical and biological elements are connected.

This book is intended as a text for upper-division undergraduate physical science majors and, especially in the later chapters, graduate students. I have used the first seven chapters as the basis for a 10-week undergraduate course for atmospheric sciences majors. A graduate course can be fashioned by supplementing the text with readings from the current literature. Most climatology textbooks are descriptive and written from the perspective of geographers, but this one is written from the perspective of a physicist. I have attempted to convey an intuition for the workings

of the climate system that is based on physical principles. When faced with a choice between providing easy access to an important concept and providing a rigorous and comprehensive treatment, I have chosen easy access. This approach should allow students to acquire the main ideas without great pain. Instructors may choose to elaborate on the presentation where their personal interests and experience make it desirable to do so.

This book could not have been produced without the assistance of many people. It evolved from 15 years of teaching undergraduate and graduate students, and I thank the ATMS 321 and ATMS 571 students at the University of Washington who have endured my experimentation and provided comments on early drafts of this book. Professor Steve Esbensen and his AtS 630 class at Oregon State University provided commentary on a near final draft of Chapters 1–7 in the spring of 1993. Valuable comments and suggestions on specific chapters were also provided by David S. Battisti, Robert J. Charlson, James R. Holton, Conway B. Leovy, Gary A. Maykut, Stephen G. Porter, Edward S. Sarachik, J. Michael Wallace, and Stephen G. Warren. The encouragement and advice given by James R. Holton were critical for the completion of this book. Many people contributed graphics, and I am particularly grateful for the special efforts given by Otis Brown, Frank Carsey, Jim Coakley, Joey Comiso, Scott Katz, Gary Maykut, Pat McCormick, Robert Pincus, Norbert Untersteiner, and Stephen Warren.

Grace C. Gudmundson applied her professional editorial skills to this project with patience, dedication, and good humor. Her efforts greatly improved the quality of the end product. Similarly, Kay M. Dewar's artistic and computer skills produced some of the more appealing figures. Marc L. Michelsen's genius with the computer extracted data from many digital archives and converted them into attractive and informative computer graphics. Luanna Huynh and Christine Rice were especially helpful with the appendices and tables.

My efforts to understand the climate system have been generously supported over the years by research grants and contracts from the US government. I am particularly happy to acknowledge support from the Climate Dynamics Program in the Atmospheric Sciences Division of the National Science Foundation, and the Earth Radiation Budget Experiment and Earth Observing System programs of the National Aeronautics and Space Administration. I also thank all of my colleagues from whom I have learned, who have shared their ideas with me, and who have given me the respect of serious argument.

This book is dedicated to my family, especially my wife, Lorraine, and my children, Alan and Jennifer, whose love and sacrifice were essential to its completion. I hope this book will help to explain why I spend so many evenings and weekends in my study. I thank my parents, Alfred and Angeline, for a good start in life and support along the way toward happy employment.

Dennis L. Hartmann

Contents

Preface to the Second Edition	ix
Preface to the First Edition	xi
1. Introduction to the Climate System	
1.1 Atmosphere, Ocean, and Land Surface	1
1.2 Atmospheric Temperature	3
1.3 Atmospheric Composition	6
1.4 Hydrostatic Balance	9
1.5 Atmospheric Humidity	11
1.6 Atmospheric Thermodynamics, Vertical Stability and Lapse Rate	13
1.7 The World Ocean	17
1.8 The Cryosphere	20
1.9 The Land Surface	20
Exercises	23
2. The Global Energy Balance	
2.1 Warmth and Energy	25
2.2 The Solar System	25
2.3 Energy Balance of Earth	27
2.4 Emission Temperature of a Planet	30
2.5 Greenhouse Effect	32
2.6 Global Radiative Flux Energy Balance	33
2.7 Distribution of Insolation	36
2.8 The Energy Balance at the Top of the Atmosphere	40
2.9 Poleward Energy Flux	45
Exercises	48
3. Atmospheric Radiative Transfer and Climate	
3.1 Photons and Minority Constituents	49
3.2 The Nature of Electromagnetic Radiation	50
3.3 Description of Radiative Energy	51
3.4 Planck's Law of Blackbody Emission	53
3.5 Selective Absorption and Emission by Atmospheric Gases	54
3.6 The Lambert–Bouguer–Beer Law: Formulation of Flux Absorption	62
3.7 Infrared Radiative Transfer Equation: Absorption and Emission	66
3.8 Heuristic Model of Radiative Equilibrium	71
3.9 Clouds and Radiation	74
3.10 Radiative–Convective Equilibrium Temperature Profiles	78
3.11 The Role of Clouds in the Energy Balance of Earth	83

3.12	A Simple Model for the Net Radiative Effect of Cloudiness	87
3.13	Observations of Real Clouds	89
	Exercises	93
4.	The Energy Balance of the Surface	
4.1	Contact Point	95
4.2	The Surface Energy Budget	96
4.3	Storage of Heat in the Surface	97
4.4	Radiative Heating of the Surface	101
4.5	The Atmospheric Boundary Layer	107
4.6	Sensible and Latent Heat Fluxes in the Boundary Layer	115
4.7	Diurnal Variation of the Surface Energy Balance	120
4.8	Seasonal Variation of the Energy Balance of Land Areas	123
4.9	Geographic Variation of the Surface Energy Balance	126
	Exercises	129
5.	The Hydrologic Cycle	
5.1	Water, Essential to Climate and Life	131
5.2	The Water Balance	133
5.3	Surface Water Storage and Runoff	137
5.4	Precipitation and Dewfall	138
5.5	Evaporation and Transpiration	140
5.6	Annual Variation of the Terrestrial Water Balance	147
5.7	Modeling the Land Surface Water Balance	152
	Exercises	157
6.	Atmospheric General Circulation and Climate	
6.1	The Great Communicator	159
6.2	Energy Balance of the Atmosphere	160
6.3	Atmospheric Motions and the Meridional Transport of Energy	161
6.4	The Angular-Momentum Balance	176
6.5	Large-Scale Circulation Patterns and Climate	180
	Exercises	192
7.	The Ocean General Circulation and Climate	
7.1	Cauldron of Climate	195
7.2	Properties of Seawater	196
7.3	The Mixed Layer	200
7.4	The Wind-Driven Circulation	206
7.5	Theories for Wind-Driven Circulations	216
7.6	The Deep Thermohaline Circulation	221
7.7	Transport of Energy in the Ocean	227
7.8	Mechanisms of Transport in the Ocean	229
	Exercises	231
8.	Natural Intraseasonal and Interannual Variability	
8.1	Stuff Happens	233
8.2	Internal Atmospheric Variability	235

8.3	El Niño, La Niña, and the Southern Oscillation	246
8.4	Decadal Variations of Weather and Climate	254
	Exercises	258
9.	History and Evolution of Earth's Climate	
9.1	Past is Prologue	261
9.2	The Instrumental Record	262
9.3	The Historical Record	265
9.4	Natural Recording Systems: The Paleoclimatic Record	266
9.5	A Brief Survey of Earth's Climate History	271
9.6	Uses of Paleoclimatic Data	288
	Exercises	290
10.	Climate Sensitivity and Feedback Mechanisms	
10.1	Fools' Experiments	293
10.2	Objective Measures of Climate Sensitivity and Feedback	294
10.3	Basic Radiative Feedback Processes	296
10.4	Ice–Albedo Feedback	304
10.5	Dynamical Feedbacks and Meridional Energy Transport	311
10.6	Longwave and Evaporation Feedbacks in the Surface Energy Balance	313
10.7	Cloud Feedback	317
10.8	Biogeochemical Feedbacks	318
	Exercises	323
11.	Global Climate Models	
11.1	Mathematical Modeling	325
11.2	Historical Development of Climate Models	326
11.3	The Atmospheric Component	329
11.4	The Land Component	334
11.5	The Ocean Component	335
11.6	Sea Ice Models	336
11.7	Validation of Climate Model Simulations	340
11.8	Feedback Strength and Sensitivity Estimates from Climate Models	342
11.9	Coupled Atmosphere–Ocean Processes and the Thermohaline Circulation	356
	Exercises	359
12.	Natural Climate Change	
12.1	Natural Forcing of Climate Change	361
12.2	Solar Luminosity Variations	362
12.3	Natural Aerosols and Climate	366
12.4	Volcanic Eruptions and Stratospheric Aerosols	371
12.5	The Orbital Parameter Theory of Ice Ages	377
12.6	Modeling of Ice Age Climates	391
	Exercises	394
13.	Anthropogenic Climate Change	
13.1	The Wings of Daedalus	397
13.2	Humans and the Greenhouse Effect	398

13.3	Carbon Dioxide	399
13.4	Methane	401
13.5	Halocarbons	402
13.6	Nitrous Oxide	402
13.7	Ozone	403
13.8	Anthropogenic Aerosols and Climate	403
13.9	Changing Surface Conditions	404
13.10	Climate Forcing by Humans	404
13.11	Global Warming Potential	406
13.12	Equilibrium Climate Changes	407
13.13	Detection and Attribution	410
13.14	Time-Dependent Climate Changes	412
13.15	Projections of Future Climate	415
13.16	Outlook for the Future	421
13.17	Climate Intervention: Geoengineering the Climate of Earth	422
	Exercises	424
Appendix A: Calculation of Insolation Under Current Conditions		427
Appendix B: Symbol Definitions		431
Appendix C: Système International (SI) Units		443
Appendix D: Useful Numerical Values		447
Appendix E: Answers to Selected Exercises		449
Glossary		455
References		461
Subject Index		471

Introduction to the Climate System

1.1 ATMOSPHERE, OCEAN, AND LAND SURFACE

Climate is the synthesis of the weather in a particular region. It can be defined quantitatively by using the expected values of the meteorological elements at a location during a certain month or season. The expected values of the meteorological elements can be called the climatic elements and include variables such as the average temperature, precipitation, wind, pressure, cloudiness, and humidity. In defining the climate, we usually employ the values of these elements at the surface of Earth. Thus, one can characterize the climate of Seattle by stating that the average annual mean precipitation is 38 in. and the annual mean temperature is 52°F. However, one might need a great deal more information than the annual means. For example, a farmer would also like to know how the precipitation is distributed through the year and how much rain would fall during the critical summer months. A hydroelectric plant engineer needs to know how much interannual variability in rainfall and snow accumulation to expect. A homebuilder should know how much insulation to be installed and the size of the heating or cooling unit needed to provide for the weather in the region. Sailors might like to know that the wind blows in the winter, but not so much in the summer.

The importance of climate is so basic that we sometimes overlook it. If the climate were not more or less as it is, life and civilization on this planet would not have developed as they have. The distribution of vegetation and soil type over the land areas is determined primarily by the local climate. Climate affects human lives in many ways; for example, climate influences the type of clothing and housing that people have developed. In the modern world, with the great technological advances of the past century, one might think that climate no longer constitutes a force capable of changing the course of human history. It is apparent, on the contrary,

that we are as sensitive now as we have ever been to climate fluctuations and climate change.

Because food, water, and energy supply systems are strained to meet demand and are optimized to the current average climatic conditions, fluctuations or trends in climate can cause serious difficulties for humanity. Moreover, since the population has grown to absorb the maximum agricultural productivity in much of the world, the absolute number of human lives at risk of starvation during climatic anomalies has never been greater. In addition to natural year-to-year fluctuations in the weather, which are an important aspect of climate, we must be concerned with the effects of human activities in producing long-term trends in the climate. It is now clear that humans are affecting the global climate, and this influence is growing. The actions of humankind that can change the global climate include altering the composition of the atmosphere and the nature of Earth's surface.

The surface climate of Earth varies greatly with location, ranging from the heat of the tropics to the cold of the polar regions, and from the drought of a desert to the moisture of a rain forest. Nonetheless, the climate of Earth is favorable for life, and living creatures exist in every climatic extreme. The climate of a region depends on latitude, altitude, and orientation in relation to water bodies, mountains, and the prevailing wind direction. In this book, we are concerned primarily with the global climate and its geographic variation on scales of hundreds to thousands of kilometers. In order to focus on these global issues, climate variations on horizontal spatial scales smaller than several tens of kilometers are given only minimal discussion.

The climate of Earth is defined in terms of measurable weather elements. The weather elements of most interest are temperature and precipitation. These two factors together largely determine the species of plants and animals that survive and prosper in a particular location. Other variables are also important, of course. The *humidity*, the amount of water vapor in the air, is a critical climate factor that is related closely to the temperature and precipitation. Condensation of water in the atmosphere produces clouds of water droplets or ice particles that greatly change the radiative properties of the atmosphere. The occurrence of clouds is important in itself for aviation and other activities, but clouds also play a role in determining both precipitation and surface temperature. Cloudiness influences the transmission of terrestrial radiation through the atmosphere and the amount of solar radiation that reaches the surface. The mean wind speed and direction are important considerations for local climate, air-pollution dispersion, aviation, navigation, wind energy, and many other purposes. The climate system of Earth determines the distribution of energy and water near the surface and consists primarily of the atmosphere, the oceans, and the land surface. The workings of this global system are the topic of this book (Fig. 1.1).

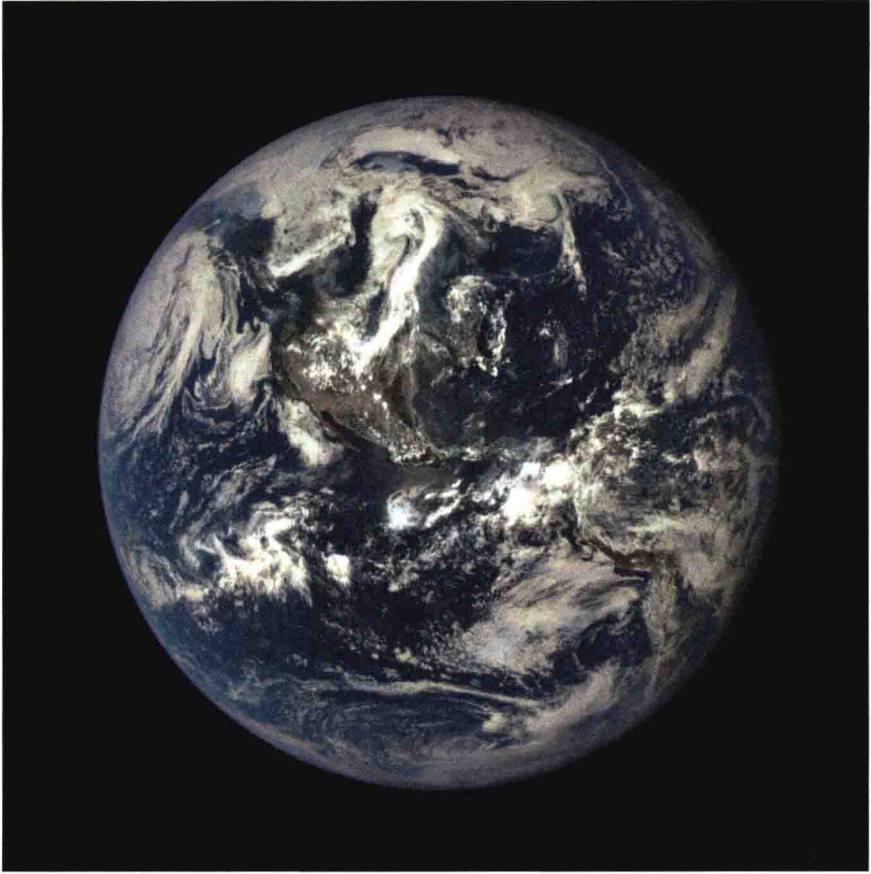


FIGURE 1.1 Earth as seen on July 6, 2015 by the NASA Earth Polychromatic Imaging Camera aboard the NOAA Deep Space Climate Observatory spacecraft one million miles from Earth.

1.2 ATMOSPHERIC TEMPERATURE

Temperature is the most widely recognized climatic variable. The global average temperature at the surface of Earth is about 288 K, 15°C, or 59°F. The range of temperatures encountered at the surface is favorable for the life forms that have developed on Earth. The extremes of recorded surface temperature range from the coldest temperature of -89.2°C (-128.6°F) at Vostok, Antarctica to the warmest temperature of 56.7°C (134°F) at Furnace Creek Ranch in Death Valley, California. These temperature extremes reflect the well-known decrease of temperature from the tropics, where the warmest temperatures occur, to the polar regions that are much colder. Both the warm temperature in Death Valley and the cold temperature at Vostok also

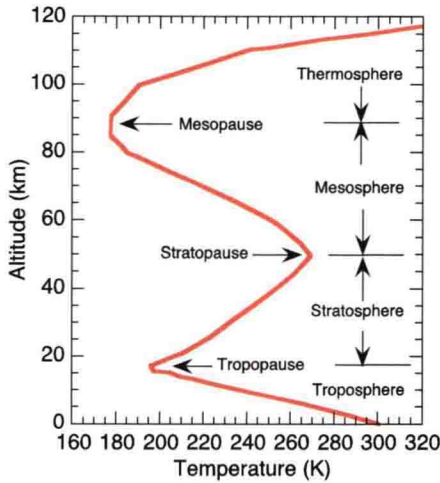


FIGURE 1.2 The main zones of the atmosphere defined according to the temperature profile of the standard atmosphere profile at 15°N for annual-mean conditions. Data from U.S. Standard Atmosphere Supplements (1966).

result partly from the decrease of temperature with altitude because Death Valley is below sea level and Vostok is 3450 m above sea level.

An important feature of the temperature distribution is the decline of temperature with height above the surface in the lowest 10–15 km of the atmosphere (Fig. 1.2). This rate of decline, called the *lapse rate*, is defined by

$$\Gamma \equiv -\frac{\partial T}{\partial z} \quad (1.1)$$

where T is the temperature and z is altitude and the deltas indicate a partial derivative. The global mean tropospheric lapse rate is about 6.5 K km^{-1} , but the lapse rate varies with altitude, season, and latitude. In the upper *stratosphere*, the temperature increases with height up to about 50 km. The increase of temperature with height that characterizes the stratosphere is caused by the absorption of solar radiation by ozone. Above the stratopause at about 50 km the temperature begins to decrease with height in the *mesosphere*. The temperature of the atmosphere increases rapidly above about 100 km because of heating produced by absorption of ultraviolet radiation from the sun, which dissociates oxygen and nitrogen molecules and ionizes atmospheric gases in the *thermosphere*.

The decrease of temperature with altitude in the *troposphere* is crucial to many of the mechanisms whereby the warmth of the surface temperature of Earth is maintained. The lapse rate in the troposphere and the mechanisms that maintain it are also central to the determination of