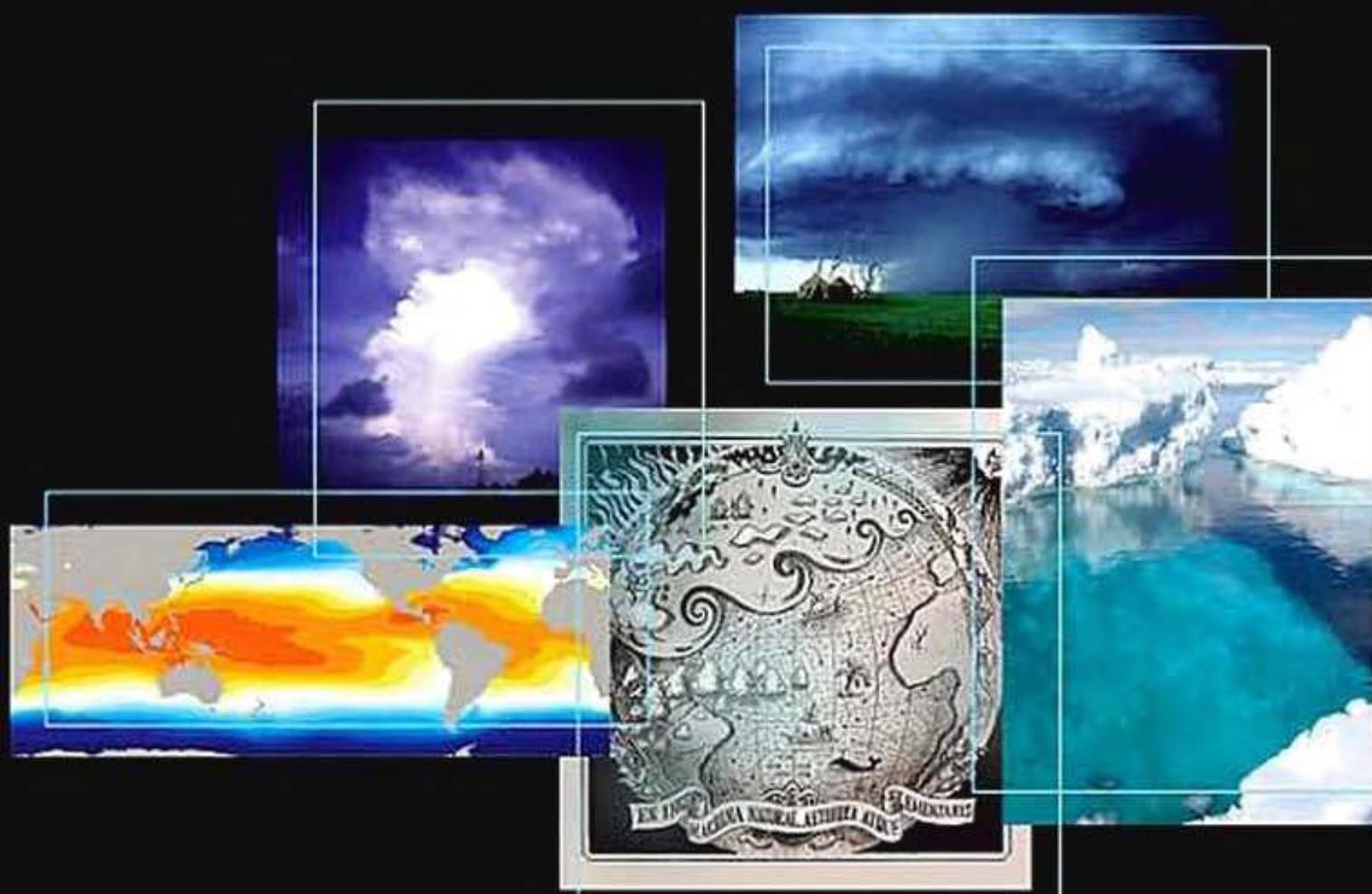


ATMOSPHERIC SCIENCE

AN INTRODUCTORY
SURVEY

JOHN M. WALLACE • PETER V. HOBBS



Atmospheric Science

Second Edition

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Atmospheric Science

An Introductory Survey

Second Edition

John M. Wallace • Peter V. Hobbs
University of Washington



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In Memory of Peter V. Hobbs (1936–2005)



I am the daughter of Earth and Water,
And the nursling of the Sky;
I pass through the pores of the ocean and shores;
I change, but I cannot die.
For after the rain when with never a stain
The pavilion of Heaven is bare,
And the winds and sunbeams with their convex gleams
Build up the blue dome of air,
I silently laugh at my own cenotaph,
And out of the caverns of rain,
Like a child from the womb, like a ghost from the tomb,
I arise and unbuild it again.

PERCY BYSSHE SHELLEY
The Cloud

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Preface to the Second Edition

In the 30 years that have passed since we embarked on the first edition of this book, atmospheric science has developed into a major field of study with far-reaching scientific and societal implications. Topics such as climate and atmospheric chemistry, which were not deemed sufficiently important to warrant chapters of their own 30 years ago, are now major branches of the discipline. More traditional topics such as weather forecasting, understanding the processes that lead to severe storms, and the radiation balance of the Earth have been placed on firmer foundations. Satellite-borne sensors that were in the early stages of development 30 years ago are now providing comprehensive observations of Earth's atmosphere. Those who have witnessed these accomplishments and contributed to them, if only in minor ways, have been fortunate indeed.

As we drafted new section after new section describing these exciting new developments, we began to wonder whether we would still be capable of cramming a summary of the entire field of atmospheric science into a book light enough to be carried in a student's backpack. This second edition does, in fact, contain much more material than its predecessor, but thanks to the double column formatting and the supplementary Web site, it is not correspondingly heavier. In deciding which of the recent developments to include and which ones to leave out, we have elected to emphasize fundamental principles that will stand students in good stead throughout their careers, eschewing unnecessary details, interesting though they may be, and important to the specialist.

The second edition contains new chapters on atmospheric chemistry, the atmospheric boundary layer, the Earth system, and climate dynamics. The chapters in the first edition entitled *Clouds and*

Storms, the Global Energy Balance, and the General Circulation have been dropped, but much of the material that was contained in them has been moved to other chapters. The coverage of atmospheric dynamics, radiative transfer, atmospheric electricity, convective storms, and tropical cyclones has been expanded. The treatment of atmospheric thermodynamics has been modernized by using the skew $T - \ln p$ chart as the primary format for plotting soundings. The second edition contains many more illustrations, most of which are in color.

A popular feature of the first edition that is retained in the second edition is the inclusion of quantitative exercises with complete solutions embedded in the text of each chapter, as well as additional exercises for the student at the end of each chapter. The second edition retains these features. In addition, we have included many new exercises at the end of the chapters, and (available to instructors only) a nearly complete set of solutions for the exercises. Boxes are used in the second edition as a vehicle for presenting topics or lines of reasoning that are outside the mainstream of the text. For example, in Chapter 3 a qualitative statistical mechanics interpretation of the gas laws and the first law of thermodynamics is presented in a series of boxes.

Academic Press is providing two web sites in support of the book. The first web site includes information and resources for all readers, including a printable, blank skew $T - \ln p$ chart, answers to most of the exercises, additional solved exercises that we did not have space to include in the printed text, errata, an appendix on global weather observations and data assimilation, and climate data for use in the exercises. The second web site, which will be accessible only to

instructors, contains a short instructor's guide, solutions to most of the exercises, electronic versions of most of the figures that appear in the book, and electronic versions of a set of supplementary figures that may be useful in customizing classroom presentations.

To use the book as a text for a broad survey course, the instructor would need to be selective, omitting much of the more advanced material from the quantitative Chapters 3, 4, 5, and 7, as well as sections of other, more descriptive chapters. Selected chapters of the book can be used as a text for several different kinds of courses. For example, Chapters 3–6 could be used in support of an atmospheric physics and chemistry course; Chapters 1, 3, 7, and 8 for a course emphasizing weather; and Chapters 1 and 2 and parts of 3, 4, and 9 and Chapter 10 in support of a course on climate in a geosciences curriculum.

Corrigenda and suggestions for the instructor's guide will be gratefully received.

John M. Wallace
Peter V. Hobbs
Seattle, January 2005

Acknowledgments

In 1972, I accepted Peter Hobbs' invitation to collaborate with him in writing an introductory atmospheric science textbook. We agreed that he would take the lead in drafting the thermodynamics and cloud physics chapters and I would be primarily responsible for the chapters dealing with radiative transfer, synoptic meteorology, and dynamic meteorology. Over the course of the following few years we struggled to reconcile his penchant for rigor and logic with my more intuitive, visually based writing style. These spirited negotiations tested and ultimately cemented our friendship and led to a text that was better than either of us could have produced working in isolation.

Three years ago, on a walk together in the rain, Peter warned me that if I wanted to produce that long overdue second edition, we needed to get started soon because he was contemplating retirement in a few years. When I agreed, he immediately set to work on his chapters, including an entirely new chapter on atmospheric chemistry, and completed drafts of them by the end of 2003. Soon afterward, he was diagnosed with pancreatic cancer.

Despite his illness, Peter continued to revise his chapters and offer helpful feedback on mine. Even after he was no longer able to engage in spirited debates about the content of the book, he continued to wield his infamous red pen, pointing out grammatical mistakes and editorial inconsistencies in my chapters. A few months before his death, July 25, 2005, we enjoyed a party celebrating (albeit a bit prematurely) the completion of the project that he had initiated.

For the dedication of the first edition, it was Peter's choice to use Shelley's poem, "Clouds," a visual metaphor for life, death, and renewal. For the second edition, I have chosen the same poem, this time in memory of Peter.

Several members of Peter's "Cloud and Aerosol Research Group" were instrumental in preparing the book for publication. Debra Wolf managed the manuscript and produced many of the illustrations, Judith Opacki obtained most of the permissions, Arthur Rangno provided several cloud photos, and he and Mark Stoelinga provided valuable scientific advice.

Peter and I are indebted to numerous individuals who have generously contributed to the design, content, and production of this edition. Roland Stull at the University of British Columbia is the primary author of Chapter 9 (the Atmospheric Boundary Layer). Three of our colleagues in the Department of Atmospheric Sciences at the University of Washington served as advisors for portions of other chapters. Qiang Fu advised us on the design of Chapter 4 (Radiative Transfer) and provided some of the material for it. Lynn McMurdie selected the case study presented in Section 8.1 (Extratropical Cyclones) and advised us on the content for that section. Robert A. Houze advised us on the design and content of Section 8.3 (Convective Storms) and Section 8.4 (Tropical Cyclones). Other colleagues, Stephen Warren, Clifford Mass, Lyatt Jaegle, Andrew Rice, Marcia Baker, David Catling, Joel Thornton, and Greg Hakim, read and provided valuable feedback on early drafts of chapters. Others who provided valuable feedback and technical advice on specific parts of the manuscript include Edward Sarachik, Igor Kamenkovich, Richard Gammon, Joellen Russell, Conway Leovy, Norbert Untersteiner, Kenneth Beard, William Cotton, Hermann Gerber, Shuyi Chen, Howard Bluestein, Robert Wood, Adrian Simmons, Michael King, David Thompson, Judith Lean, Alan Robock, Peter Lynch, Paquita Zuidema, Cody Kirkpatrick, and J. R. Bates. I also thank the graduate

students who volunteered their help in identifying errors, inconsistencies, and confusing passages in the numerous drafts of the manuscript.

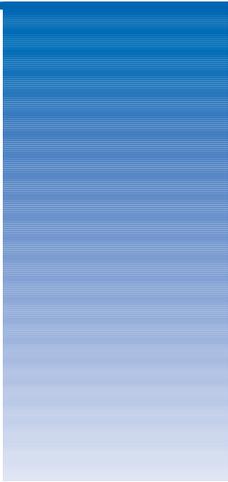
Jennifer Adams, a research scientist at the Center for Ocean–Land–Atmosphere Studies (COLA), produced most of the illustrations that appear in Section 8.1, under funding provided by COLA and using graphics software (GrADS) developed at COLA. Some of the design elements in the illustrations were provided by David W. Ehlert. Debra Wolf, Candace Gudmundson, Kay Dewar, and Michael Macaulay and Beth Tully prepared many of the illustrations. Steven Cavallo and Robert Nicholas provided the table of units and numerical values. Most of the

photographs of clouds and other atmospheric phenomena that appear in the book were generously provided free of charge.

I am deeply indebted to Qiang Fu and Peter Lynch who generously volunteered their time to correct errors in the equations, as well as James Booth, Joe Casola, Ioana Dima, Chaim Garfinkel, David Reidmiller Kevin Rennert, Rei Ueyama, Justin Wettstein and Reddy Yatavelli who identified many errors in the cross-referencing.

Finally, I thank Peter's wife, Sylvia, and my wife, Susan, for their forbearance during the many evenings and weekends in which we were preoccupied with this project.

Preface to the First Edition



This book has been written in response to a need for a text to support several of the introductory courses in atmospheric sciences commonly taught in universities, namely introductory survey courses at the junior or senior undergraduate level and beginning graduate level, the undergraduate physical meteorology course, and the undergraduate synoptic laboratory. These courses serve to introduce the student to the fundamental physical principles upon which the atmospheric sciences are based and to provide an elementary description and interpretation of the wide range of atmospheric phenomena dealt with in detail in more advanced courses. In planning the book we have assumed that students enrolled in such courses have already had some exposure to calculus and physics at the first-year college level and to chemistry at the high school level.

The subject material is almost evenly divided between physical and dynamical meteorology. In the general area of physical meteorology we have introduced the basic principles of atmospheric hydrostatics and thermodynamics, cloud physics, and radiative transfer (Chapters 2, 4, and 6, respectively). In addition, we have covered selected topics in atmospheric chemistry, aerosol physics, atmospheric electricity, aeronomy, and physical climatology. Coverage of dynamical meteorology consists of a description of large-scale atmospheric motions and an elementary interpretation of the general circulation (Chapters 3, 8, and 9, respectively). In the discussion of clouds and storms (Chapter 5) we have attempted to integrate material from physical and dynamical meteorology. In arranging the chapters we have purposely placed the material on synoptic meteorology near the beginning of the book (Chapter 3) in order to have it available as an introduction to the daily weather map

discussions, which are an integral part of many introductory survey courses.

The book is divided into nine chapters. Most of the basic theoretical material is covered in the even-numbered chapters (2, 4, 6, and 8). Chapters 1 and 3 are almost entirely descriptive, while Chapters 5, 7, and 9 are mainly interpretive in character. Much of the material in the odd-numbered chapters is straightforward enough to be covered by means of reading assignments, especially in graduate courses. However, even with extensive use of reading assignments we recognize that it may not be possible to completely cover a book of this length in a one-semester undergraduate course. In order to facilitate the use of the book for such courses, we have purposely arranged the theoretical chapters in such a way that certain of the more difficult sections can be omitted without serious loss of continuity. These sections are indicated by means of footnotes.

Descriptive and interpretive material in the other chapters can be omitted at the option of the instructor.

The book contains 150 numerical problems and 208 qualitative problems that illustrate the application of basic physical principles to problems in the atmospheric sciences. In addition, the solutions of 48 of the numerical problems are incorporated into the text. We have purposely designed problems that require a minimum amount of mathematical manipulation in order to place primary emphasis on the proper application of physical principles. Universal constants and other data needed for the solution of quantitative problems are given on pages xvi–xvii.

It should be noted that many of the qualitative problems at the ends of the chapters require some original thinking on the part of the student. We have

found such questions useful as a means of stimulating classroom discussion and helping the students to prepare for examinations.

Throughout the book we have consistently used SI units, which are rapidly gaining acceptance within the atmospheric sciences community.

A list of units and symbols is given on pages xv–xvi.

The book contains biographical footnotes that summarize the lives and work of scientists who have made major contributions to the atmospheric sciences. Brief as these are, it is hoped that they will give the student a sense of the long history of meteorology and its firm foundations in the physical sciences. As a matter of policy we have included footnotes only for individuals who are deceased or retired.

We express our gratitude to the University of Washington and the National Science Foundation for their support of our teaching, research, and other

scholarly activities that contributed to this book. While working on the book, one of us (J.M.W.) was privileged to spend 6 months on an exchange visit to the Computer Center of the Siberian Branch of the Soviet Academy of Sciences, Novosibirsk, USSR, and a year at the US National Center for Atmospheric Sciences under the auspices of the Advanced Study Program. The staff members and visitors at both of these institutions made many important contributions to the scientific content of the book. Thanks go also to many other individuals in the scientific community who provided help and guidance.

We wish especially to express our gratitude to colleagues in our own department who provided a continuous source of moral support, constructive criticism, and stimulating ideas. Finally, we acknowledge the help received from many individuals who aided in the preparation of the final manuscript, as well as the many interim manuscripts that preceded it.

Introduction and Overview

1

1.1 Scope of the Subject and Recent Highlights

Atmospheric science is a relatively new, applied discipline that is concerned with the structure and evolution of the planetary atmospheres and with the wide range of phenomena that occur within them. To the extent that it focuses mainly on the Earth's atmosphere, atmospheric science can be regarded as one of the *Earth* or *geosciences*, each of which represents a particular fusion of elements of physics, chemistry, and fluid dynamics.

The historical development of atmospheric sciences, particularly during the 20th century, has been driven by the need for more accurate weather forecasts. In popular usage the term “meteorologist,” a synonym for atmospheric scientist, means “weather forecaster.” During the past century, weather forecasting has evolved from an art that relied solely on experience and intuition into a science that relies on numerical models based on the conservation of mass, momentum, and energy. The increasing sophistication of the models has led to dramatic improvements in forecast skill, as documented in Fig. 1.1. Today's weather forecasts address not only the deterministic, day-to-day evolution of weather patterns over the course of the next week or two, but also the likelihood of hazardous weather events (e.g., severe thunderstorms, freezing rain) on an hour-by-hour basis (so called

“nowcasting”), and departures of the climate (i.e., the statistics of weather) from seasonally adjusted normal values out to a year in advance.

Weather forecasting has provided not only the intellectual motivation for the development of atmospheric science, but also much of the infrastructure. What began in the late 19th century as an assemblage of regional collection centers for real time teletype transmissions of observations of surface weather variables has evolved into a sophisticated *observing system* in which satellite and in situ measurements of many surface and upper air variables are merged (or *assimilated*) in a dynamically consistent way to produce optimal estimates of their respective three-dimensional fields over the entire globe. This global, real time atmospheric dataset is the envy of oceanographers and other geo- and planetary scientists: it represents both an extraordinary technological achievement and an exemplar of the benefits that can derive from international cooperation. Today's global weather observing system is a vital component of a broader Earth observing system, which supports a wide variety of scientific endeavors, including climate monitoring and studies of ecosystems on a global scale.

A newer, but increasingly important organizing theme in atmospheric science is *atmospheric chemistry*. A generation ago, the principal focus of this field was urban air quality. The field experienced

2 Introduction and Overview

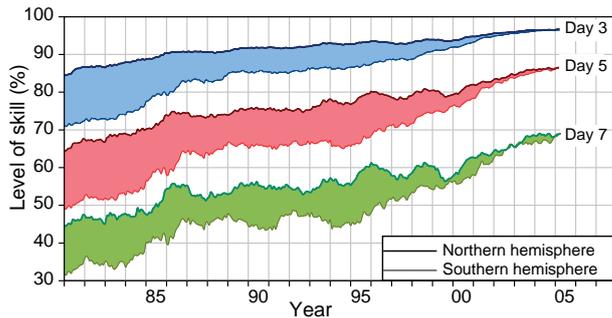


Fig. 1.1 Improvement of forecast skill with time from 1981 to 2003. The ordinate is a measure of forecast skill, where 100% represents a perfect forecast of the hemispheric flow pattern at the 5-km level. The upper pair of curves is for 3-day forecasts, the middle pair for 5-day forecasts, and the lower pair for 7-day forecasts. In each pair, the upper curve that marks the top of the band of shading represents the skill averaged over the northern hemisphere and the lower curve represents the skill averaged over the southern hemisphere. Note the continually improving skill levels (e.g., today's 5-day forecasts of the northern hemisphere flow pattern are nearly as skillful as the 3-day forecasts of 20 years ago). The more rapid increase in skill in the southern hemisphere reflects the progress that has been made in assimilating satellite data into the forecast models. [Updated from *Quart. J. Royal Met. Soc.*, **128**, p. 652 (2002). Courtesy of the European Centre for Medium-Range Weather Forecasting.]

a renaissance during the 1970s when it was discovered that forests and organisms living in lakes over parts of northern Europe, the northeastern United States, and eastern Canada were being harmed by *acid rain* caused by sulfur dioxide emissions from coal-fired electric power plants located hundreds and, in some cases, thousands of kilometers upwind. The sources of the acidity are gaseous oxides of sulfur and nitrogen (SO_2 , NO , NO_2 , and N_2O_5) that dissolve in microscopic cloud droplets to form weak solutions of sulfuric and nitric acids that may reach the ground as raindrops.

There is also mounting evidence of the influence of human activity on the composition of the global atmosphere. A major discovery of the 1980s was the *Antarctic "ozone hole"*: the disappearance of much of the stratospheric ozone layer over the southern polar cap each spring (Fig. 1.2). The ozone destruction was found to be caused by the breakdown of chlorofluorocarbons (CFCs), a family of synthetic gases that was becoming increasingly

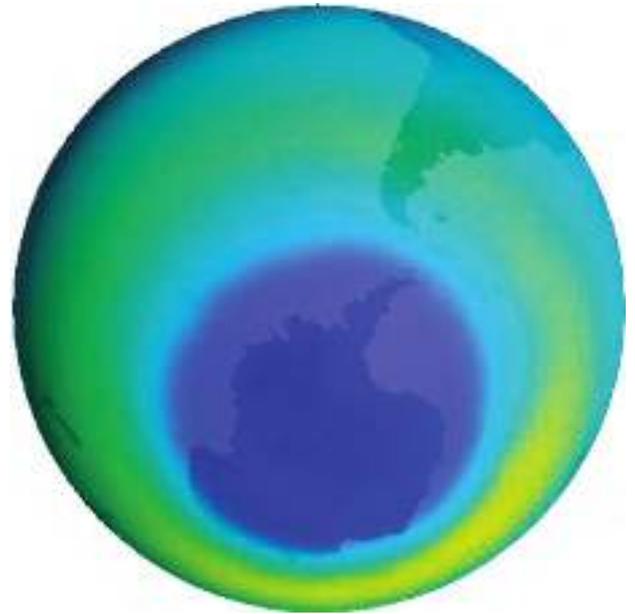


Fig. 1.2 The Antarctic ozone hole induced by the buildup of synthetic chlorofluorocarbons, as reflected in the distribution of vertically integrated ozone over high latitudes of the southern hemisphere in September, 2000. Blue shading represents substantially reduced values of total ozone relative to the surrounding region rendered in green and yellow. [Based on data from NASA TOMS Science Team; figure produced by NASA's Scientific Visualization Studio.]

widely used for refrigeration and various industrial purposes. As in the acid rain problem, heterogeneous chemical reactions involving cloud droplets were implicated, but in the case of the "ozone hole" they were taking place in wispy polar stratospheric clouds. Knowledge gained from atmospheric chemistry research has been instrumental in the design of policies to control and ultimately reverse the spread of acid rain and the ozone hole. The unresolved scientific issues surrounding *greenhouse warming* caused by the buildup of carbon dioxide (Fig. 1.3) and other trace gases released into the atmosphere by human activities pose a new challenge for atmospheric chemistry and for the broader field of geochemistry.

Atmospheric science also encompasses the emerging field of *climate dynamics*. As recently as a generation ago, climatic change was viewed by most atmospheric scientists as occurring on such long timescales that, for most purposes, today's climate could be described in terms of a standard set of

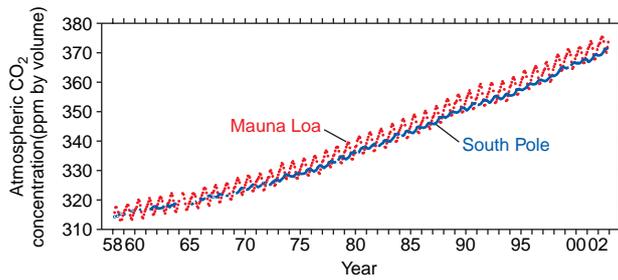


Fig. 1.3 Time series showing the upward trend in monthly mean atmospheric CO₂ concentrations (in parts per million by volume) at Mauna Loa and the South Pole due to the burning of fossil fuels. A pronounced annual cycle is also evident at Mauna Loa, with minimum values in the summer. [Based on data of C. D. Keeling. Courtesy of Todd P. Mitchell.]

statistics, such as January climatological-mean (or “normal”) temperature. In effect, climatology and climate change were considered to be separate subfields, the former a branch of atmospheric sciences and the latter largely the province of disciplines such as geology, paleobotany, and geochemistry. Among the factors that have contributed to the emergence of a more holistic, dynamic view of climate are:

- documentation of a coherent pattern of year-to-year climate variations over large areas of the globe that occurs in association with El Niño (Section 10.2).
- proxy evidence, based on a variety of sources (ocean sediment cores and ice cores, in particular), indicating that large, spatially coherent climatic changes have occurred on time scales of a century or even less (Section 2.6.4).
- the rise of the global-mean surface air temperature during the 20th century and projections of a larger rise during the 21st century due to human activities (Section 10.4).

Like some aspects of atmospheric chemistry, climate dynamics is inherently multidisciplinary: to understand

the nature and causes of climate variability, the atmosphere must be treated as a component of the *Earth system*.

1.2 Some Definitions and Terms of Reference

Even though the Earth is not perfectly spherical, atmospheric phenomena are adequately represented in terms of a spherical coordinate system, rotating with the Earth, as illustrated in Fig. 1.4. The coordinates are latitude ϕ , longitude λ , and height z above sea level, z .¹ The angles are often replaced by the distances

$$dx \equiv r d\lambda \cos \phi \quad (1.1)$$

and

$$dy \equiv r d\phi$$

where x is distance east of the Greenwich meridian along a latitude circle, y is distance north of the

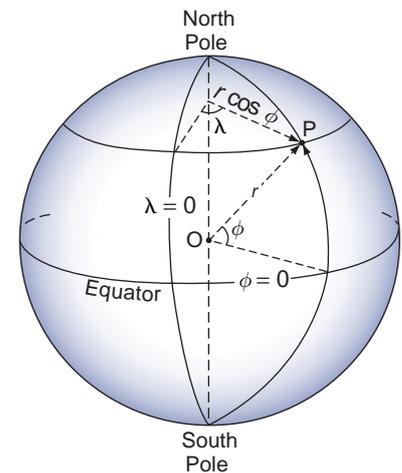


Fig. 1.4 Coordinate system used in atmospheric science. Angle ϕ is latitude, defined as positive in the northern hemisphere and negative in the southern hemisphere, and λ is longitude relative to the Greenwich meridian, positive eastward. The radial coordinate (not shown) is height above sea level.

¹ Oceanographers and applied mathematicians often use the colatitude $\theta = \pi/2 - \phi$ instead of ϕ .



Fig. 1.5 The limb of the Earth, as viewed from space in visible satellite imagery. The white layer is mainly light scattered from atmospheric aerosols and the overlying blue layer is mainly light scattered by air molecules. [NASA Gemini-4 photo. Photograph courtesy of NASA.]

equator, and r is the distance from the center of the Earth. At the Earth's surface a degree of latitude is equivalent to 111 km (or 60 nautical miles). Because 99.9% of the mass of the atmosphere is concentrated within the lowest 50 km, a layer with a thickness less than 1% of the radius of the Earth, r , is nearly always replaced by the mean radius of the Earth (6.37×10^6 m), which we denote by the symbol R_E . Images of the limb of the Earth (Fig. 1.5) emphasize how thin the atmosphere really is.

The three velocity components used in describing atmospheric motions are defined as

$$u \equiv \frac{dx}{dt} = R_E \cos \phi \frac{d\lambda}{dt} \quad (\text{the zonal velocity component}) \quad (1.2)$$

$$v \equiv \frac{dy}{dt} = R_E \frac{d\phi}{dt} \quad (\text{the meridional velocity component}),$$

and

$$w \equiv \frac{dz}{dt} = \frac{dr}{dt} \quad (\text{the vertical velocity component}).$$

where z is height above mean sea level. The adjectives *zonal* and *meridional* are also commonly used in reference to averages, gradients, and cross sections. For example, a *zonal average* denotes an average around latitude circles; a *meridional cross section* denotes a north–south slice through the atmosphere. The *horizontal velocity vector* \mathbf{V} is given by $\mathbf{V} \equiv u\mathbf{i} + v\mathbf{j}$, where \mathbf{i} and \mathbf{j} are the unit vectors in the zonal and meridional directions, respectively. Positive and negative zonal velocities are referred to as *westerly* (from the west) and *easterly* (from the east) winds, respectively; positive and negative meridional velocities are referred to as *southerly* and *northerly* winds (in both northern and southern hemispheres, respectively).² For scales of motion in the Earth's atmosphere in excess of 100 km, the length scale greatly exceeds the depth scale, and typical magnitudes of the horizontal velocity component \mathbf{V} exceed those of the vertical velocity component w by several orders of magnitude. For these scales the term *wind* is synonymous with *horizontal velocity component*. The SI unit for velocity (or speed) is m s^{-1} . One meter per second is equivalent to 1.95 knots (1 knot = 1 nautical mile per hour). Vertical velocities in large-scale atmospheric motions are often expressed in units of cm s^{-1} : 1 cm s^{-1} is roughly equivalent to a vertical displacement of 1 kilometer per day.

Throughout this book, the local derivative $\partial/\partial t$ refers to the rate of change at a fixed point in rotating (x, y, z) space and the total time derivative d/dt refers to the rate of change following an air parcel as it moves along its three-dimensional trajectory through the atmosphere. These so-called *Eulerian*³

² Dictionaries offer contradictory definitions of these terms, derived from different traditions.

³ **Leonhard Euler** (1707–1783) Swiss mathematician. Held appointments at the St. Petersburg Academy of Sciences and the Berlin Academy. Introduced the mathematical symbols e , i , and $f(x)$. Made fundamental contributions in optics, mechanics, electricity, and magnetism, differential equations, and number theory. First to describe motions in a rotating coordinate system. Continued to work productively after losing his sight by virtue of his extraordinary memory.

and *Lagrangian*⁴ rates of change are related by the chain rule

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}$$

which can be rewritten in the form

$$\frac{\partial}{\partial t} = \frac{d}{dt} - u \frac{\partial}{\partial x} - v \frac{\partial}{\partial y} - w \frac{\partial}{\partial z} \quad (1.3)$$

The terms involving velocities in Eq. (1.3), including the minus signs in front of them, are referred to as *advection terms*. At a fixed point in space the Eulerian and Lagrangian rates of change of a variable ψ differ by virtue of the advection of air from upstream, which carries with it higher or lower values of ψ . For a hypothetical *conservative tracer*, the Lagrangian rate of change is identically equal to zero, and the Eulerian rate of change is

$$\frac{\partial}{\partial t} = -u \frac{\partial}{\partial x} - v \frac{\partial}{\partial y} - w \frac{\partial}{\partial z}$$

The fundamental thermodynamic variables are pressure p , density ρ , and temperature T . The SI unit

of pressure is $1 \text{ N m}^{-2} = 1 \text{ kg m}^{-1} \text{ s}^{-2} = 1 \text{ pascal (Pa)}$. Prior to the adoption of SI units, atmospheric pressure was expressed in millibars (mb), where $1 \text{ bar} = 10^6 \text{ g cm}^{-1} \text{ s}^{-2} = 10^6 \text{ dynes}$. In the interests of retaining the numerical values of pressure that atmospheric scientists and the public have become accustomed to, atmospheric pressure is usually expressed in units of hundreds of (i.e., hecto) pascals (hPa).⁵ Density is expressed in units of kg m^{-3} and temperature in units of $^{\circ}\text{C}$ or K, depending on the context, with $^{\circ}\text{C}$ for temperature differences and K for the values of temperature itself. Energy is expressed in units of joules ($\text{J} = \text{kg m}^2 \text{ s}^{-2}$).

Atmospheric phenomena with timescales shorter than a few weeks, which corresponds to the theoretical limit of the range of deterministic (day-by-day) weather forecasting, are usually regarded as relating to *weather*, and phenomena on longer timescales as relating to *climate*. Hence, the adage (intended to apply to events a month or more in the future): “Climate is what you expect; weather is what you get.” Atmospheric variability on timescales of months or longer is referred to as *climate variability*, and statistics relating to conditions in a typical (as opposed to a particular) season or year are referred to as *climatological-mean* statistics.

1.1 Atmospheric Predictability and Chaos

Atmospheric motions are inherently unpredictable as an initial value problem (i.e., as a system of equations integrated forward in time from specified initial conditions) beyond a few weeks. Beyond that time frame, uncertainties in the forecasts, no matter how small they might be in the initial conditions, become as large as the observed variations in atmospheric flow patterns. Such exquisite *sensitivity to initial conditions* is characteristic of a broad class of mathematical models of real phenomena, referred to as *chaotic nonlinear systems*. In fact, it was the growth of errors in a highly simplified

weather forecast model that provided one of the most lucid early demonstrations of this type of behavior.

In 1960, Professor Edward N. Lorenz in the Department of Meteorology at MIT decided to rerun an experiment with a simplified atmospheric model in order to extend his “weather forecast” farther out into the future. To his surprise, he found that he was unable to duplicate his previous forecast. Even though the code and the prescribed initial conditions in the two experiments were identical, the states of the model in the two fore-

Continued on next page

⁴ **Joseph Lagrange** (1736–1813) French mathematician and mathematical physicist. Served as director of the Berlin Academy, succeeding Euler in that role. Developed the calculus of variations and also made important contributions to differential equations and number theory. Reputed to have told his students “Read Euler, read Euler, he is our master in everything.”

⁵ Although the pressure will usually be expressed in hectopascals (hPa) in the text, it should be converted to pascals (Pa) when working quantitative exercises that involve a mix of units.

1.1 Continued

casts diverged, over the course of the first few hundred time steps, to the point that they were no more like one another than randomly chosen states in experiments started from entirely different initial conditions. Lorenz eventually discovered that the computer he was using was introducing round-off errors in the last significant digit that were different each time he ran the experiment. Differences between the “weather patterns” in the different runs were virtually indistinguishable at first, but they grew with each time step until they eventually became as large as the range of variations in the individual model runs.

Lorenz’s model exhibited another distinctive and quite unexpected form of behavior. For long periods of (simulated) time it would oscillate around some “climatological-mean” state. Then, for no apparent reason, the state of the model would undergo an abrupt “regime shift” and begin to oscillate around another quite different state, as illustrated in Fig. 1.6. Lorenz’s model exhibited two such preferred “climate regimes.” When the state of the model resided within one of these regimes, the “weather” exhibited quasi-periodic oscillations and consequently was predictable quite far into the future. However, the shifts between regimes were abrupt, irregular, and inherently unpredictable beyond a few simulated days. Lorenz referred to the two climates in the model as *attractors*.

The behavior of the real atmosphere is much more complicated than that of the highly simplified model used by Lorenz in his experiments. Whether the Earth’s climate exhibits such regime-like behavior, with multiple “attractors,” or whether it should be viewed as varying about a single state that varies in time in response to solar, orbital, volcanic, and anthropogenic forcing is a matter of ongoing debate.

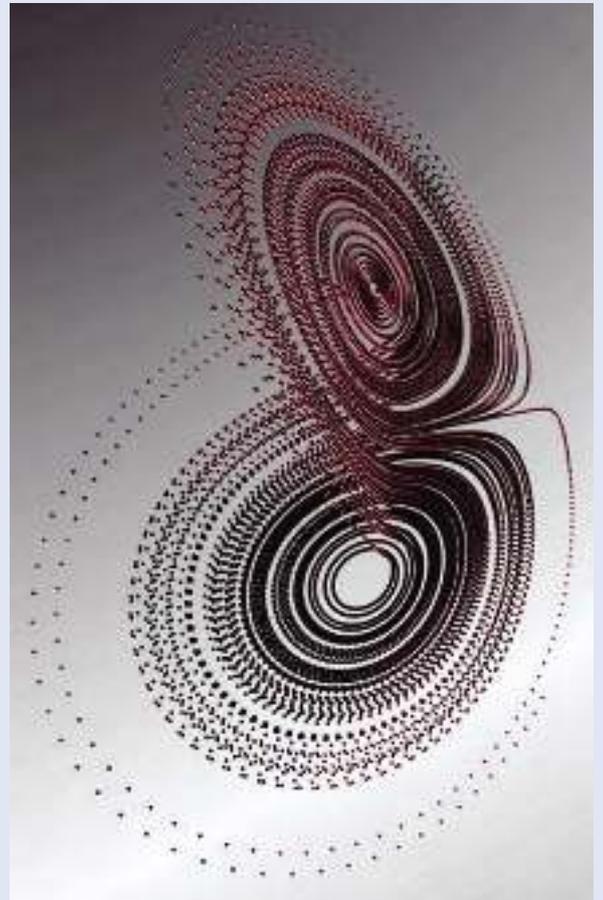


Fig. 1.6 The history of the state of the model used by Lorenz can be represented as a trajectory in a three-dimensional space defined by the amplitudes of the model’s three dependent variables. Regime-like behavior is clearly apparent in this rendition. Oscillations around the two different “climate attractors” correspond to the two, distinctly different sets of spirals, which lie in two different planes in the three-dimensional phase space. Transitions between the two regimes occur relatively infrequently. [Permission to use figure from *Nature*, **406**, p. 949 (2000). © Copyright 2000 Nature Publishing Group. Courtesy of Paul Bourke.]

1.3 A Brief Survey of the Atmosphere

The remainder of this chapter provides an overview of the optical properties, composition, and vertical structure of the Earth’s atmosphere, the major wind systems, and the climatological-mean distribution of precipitation. It introduces some of the terminology that will be used in subsequent chapters and some of

the conventions that will be used in performing calculations involving amounts of mass and rates of movement.

1.3.1 Optical Properties

The Earth’s atmosphere is relatively transparent to incoming solar radiation and opaque to outgoing radiation emitted by the Earth’s surface. The blocking

of outgoing radiation by the atmosphere, popularly referred to as the *greenhouse effect*, keeps the surface of the Earth warmer than it would be in the absence of an atmosphere. Much of the absorption and re-emission of outgoing radiation are due to air molecules, but cloud droplets also play a significant role. The radiation emitted to space by air molecules and cloud droplets provides a basis for remote sensing of the three-dimensional distribution of temperature and various atmospheric constituents using satellite-borne sensors.

The atmosphere also scatters the radiation that passes through it, giving rise to a wide range of optical effects. The blueness of the outer atmosphere in Fig. 1.5 is due to the preferential scattering of incoming short wavelength (solar) radiation by air molecules, and the whiteness of lower layers is due to scattering from cloud droplets and atmospheric aerosols (i.e., particles). The backscattering of solar radiation off the top of the deck of low clouds off the California coast in Fig. 1.7 greatly enhances the



Fig. 1.7 A deck of low clouds off the coast of California, as viewed in reflected visible radiation. [NASA MODIS imagery. Photograph courtesy of NASA.]

whiteness (or reflectivity) of that region as viewed from space. Due to the presence of clouds and aerosols in the Earth's atmosphere, $\sim 22\%$ of the incoming solar radiation is backscattered to space without being absorbed. The backscattering of radiation by clouds and aerosols has a cooling effect on climate at the Earth's surface, which opposes the greenhouse effect.

1.3.2 Mass

At any point on the Earth's surface, the atmosphere exerts a downward force on the underlying surface due to the Earth's gravitational attraction. The downward force, (i.e., the *weight*) of a unit volume of air with density ρ is given by

$$F = \rho g \quad (1.4)$$

where g is the acceleration due to gravity. Integrating Eq. (1.4) from the Earth's surface to the "top" of the atmosphere, we obtain the atmospheric pressure on the Earth's surface p_s due to the weight (per unit area) of the air in the overlying column

$$p_s = \int_0^{\infty} \rho g dz \quad (1.5)$$

Neglecting the small variation of g with latitude, longitude and height, setting it equal to its mean value of $g_0 = 9.807 \text{ m s}^{-2}$, we can take it outside the integral, in which case, Eq. (1.5) can be written as

$$p_s = m g_0 \quad (1.6)$$

where $m = \int_0^{\infty} \rho dz$ is the vertically integrated mass per unit area of the overlying air.

Exercise 1.1 The globally averaged surface pressure is 985 hPa. Estimate the mass of the atmosphere.

Solution: From Eq. (1.6), it follows that

$$\bar{m} = \frac{\bar{p}_s}{g_0}$$

where the overbars denote averages over the surface of the Earth. In applying this relationship the pressure

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