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An Introduction to Atmospheric Physics

Second Edition

Robert G. Fleagle
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ATMOSPHERIC PHYSICS

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Preface to Second Edition

Since publication of the first edition in 1963, developments in science and in the relation of science to society have occurred that make this revised edition appropriate and, in fact, somewhat overdue. The principles of physics, of course, have not changed, and the atmosphere has changed little. What is different is that in some respects we are now better able to relate atmospheric processes and properties to physical principles. Research results have extended our understanding and brought the various topics of atmospheric physics closer together. At the same time the vital linkages of atmospheric processes to habitability of our planet have become increasingly apparent and have stimulated greater interest in atmospheric physics.

A new chapter on atmospheric motions has been included, reflecting (a) the essential coupling of motions with the state and physical processes of the atmosphere and (b) the recognition that other books published in the past decade make unnecessary the separate volume on motions that had been planned originally. Accordingly, in the new Chapter IV we concentrate on the fundamentals of atmospheric motions that interact with the topics of energy transfer and signal phenomena discussed in other chapters. Ionospheric and magnetospheric physics have developed in a specialized manner and to a high level of sophistication, so that these topics deserve separate treatment from the remainder of atmospheric physics. Also, the ionized upper atmosphere in most respects acts essentially independently of the neutral lower atmosphere. For these reasons, we have with some reluctance omitted ionospheric and magnetospheric physics from this revised edition. With these changes, the text now provides a reasonably concise but complete course in atmospheric physics that is suitable for upper division physics students, as well as for students of the atmospheric sciences.

The final two chapters on energy transfer and signal phenomena have been rewritten and extended, and other chapters have been revised in accordance with insights provided by recent research. The interrelationships of boundary layer structure and energy transfer, the roles of radiation and atmospheric motions in atmospheric composition and in climate, and the use of remote sensing in atmospheric measurement are some of the subjects that receive new emphasis. We have taken advantage of the opportunity to bring other material up to date, to make a variety of corrections, and to improve clarity. We have responded to the most frequent criticism of the earlier edition by including solutions to most of the problems.

In the process of revision, many individuals have responded to our questions and requests, and to each of them we are grateful. In particular, we

appreciate the reviews of separate sections and chapters by Peter V. Hobbs, James R. Holton, Conway B. Leovy, C. Gordon Little, and George A. Parks. The task of revision was greatly aided by Phyllis Brien's careful preparation and accurate review of the manuscript.

April 1980

Preface to First Edition

This book is addressed to those who wish to understand the relationship between atmospheric phenomena and the nature of matter as expressed in the principles of physics. The interesting atmospheric phenomena are more than applications of gravitation, of thermodynamics, of hydrodynamics, or of electrodynamics; and mastery of the results of controlled experiment and of the related theory alone does not imply an understanding of atmospheric phenomena. This distinction arises because the extent and the complexity of the atmosphere permit effects and interactions that are entirely negligible in the laboratory or are deliberately excluded from it. The objective of laboratory physics is, by isolating the relevant variables, to reveal the fundamental properties of matter; whereas the objective of atmospheric physics, or of any observational science, is to understand those phenomena that are characteristic of the whole system. For these reasons the exposition of atmospheric physics requires substantial extensions of classical physics. It also requires that understanding be based on a coherent "way of seeing" the ensemble of atmospheric phenomena. Only then is understanding likely to stimulate still more general insights.

In this book the physical properties of the atmosphere are discussed. Atmospheric motions, which are part of atmospheric physics and which logically follow discussion of physical properties, have not been included because they require more advanced mathematical methods than those used here. We hope to treat atmospheric motions in a later volume.

The content of the book has been used as a text for a year's course for upper division and beginning graduate students in the atmospheric sciences. In the course of time, it has filtered through the minds of more than a dozen groups of these critics. It also should be of useful interest to students of other branches of geophysics and to students of physics who want to extend their horizons beyond the laboratory. And, finally, we believe that the tough-minded amateur of science may find pleasure in seeking in these pages a deeper appreciation of natural phenomena.

Although an understanding of the calculus and of the principles of physics is assumed, these fundamentals are restated where they are relevant; and the book is self-contained for the most part. Compromise has been necessary in a few cases, particularly in Chapter VII, where full development would have required extended discussion of advanced and specialized material.

The text is not intended for use as a reference; original sources must be sought from the annotated general references listed at the end of each chapter. Exceptions have been made in the case of publications that are so recent that they have not been included in standard references and in a few cases where important papers are not widely known. In the case of new or controversial material, an effort has been made to cut through irrelevant detail and to present a clear, coherent account. We have felt no obligation to completeness in discussing details of research or in recounting conflicting views. Where it has not been possible for us to make sound judgments, we have tried to summarize the problem in balanced fashion, but we have no illusions that we have always been right in these matters. We accept the inevitable fact that errors remain imbedded in the book, and we challenge the reader to find them. In this way, even our frailties may make a positive contribution.

We are indebted for numerous suggestions to our colleagues who have taken their turns at teaching the introductory courses in Atmospheric Physics: Professors F. I. Badgley, K. J. K. Buettner, D. O. Staley, and Mr. H. S. Muench. Parts of the manuscript have profited from the critical comments of Professors E. F. Danielsen, B. Haurwitz, J. S. Kim, J. E. McDonald, B. J. Mason, H. A. Panofsky, T. W. Ruijgrok, and F. L. Scarf. Last, and most important of all, we acknowledge the silent counsel of the authors whose names appear in the bibliography and in the footnotes. We are keenly aware of the wisdom of the perceptive observer who wrote:

> Von einem gelehrten Buche abgeschrieben ist ein Plagiat,
> Von zwei gelehrten Büchern abgeschrieben ist ein Essay,
> Von drei gelehrten Büchern abgeschrieben ist eine Dissertation,
> Von vier gelehrten Büchern abgeschrieben ist ein fünftes gelehrtes Buch.

March 1963

Gravitational Effects

"We dance round in a ring and suppose,
But the Secret sits in the middle and knows." ROBERT FROST

We live at the bottom of an ocean of air which presses on us with a force of about 10^5 newtons for each square meter of surface (10^5 pascals or 10^3 millibars). Our senses give us limited impressions of the atmosphere immediately around us: its temperature, velocity, the precipitation of particles from, perhaps its humidity, its visual clarity, and its smell, but little of its pressure or its other properties. The atmosphere sustains our life in a variety of ways, but we of course take it for granted except occasionally when storms or drought, or some other examples of severe weather, threaten us, or when we notice a particularly striking or beautiful phenomenon.

Viewed from a fixed point in space at a distance of several earth radii, our planet appears as a smooth spheroid strongly illuminated by a very distant sun. As seen from above the northern hemisphere the earth rotates about its axis in a counterclockwise sense once in 23 hr 56 min and revolves about the sun in the same sense once a year in a nearly circular orbit. The axis of rotation is inclined to the plane of the earth's orbit at an angle of $66^\circ\ 33'$.

Photographs made from earth satellites provide an excellent description of the atmosphere on a nearly continuous basis. Satellites in nearly polar orbits observe the earth in north–south bands. They cover nearly the entire earth twice each 24-hr day, once during the day and once during the night as shown in the composite pictures in Fig. 1.1. The satellites regularly take pictures sensitive to infrared and others sensitive to visible light, and they also measure the vertical distributions of temperature and humidity by sensing radiation emitted from the atmosphere. "Synchronous" satellites at a height of about 36,000 km over fixed points on the equator photograph the field below them (extending to about 70° north and 70° south) once each 30 min. A sequence of these pictures can describe the motions of clouds in exquisite detail. Satellite cloud pictures are regularly seen on television and published in magazines, so that each of us is now able to see the earth and its atmosphere far more completely than anyone had ever seen it prior to the development of meteorological satellites which began in the 1960s. These pictures show that the atmosphere always contains regions of cloud extending over thousands of kilometers but imbedded in a layer no greater than 6–10 km in thickness lying just above the earth's surface. Each of these

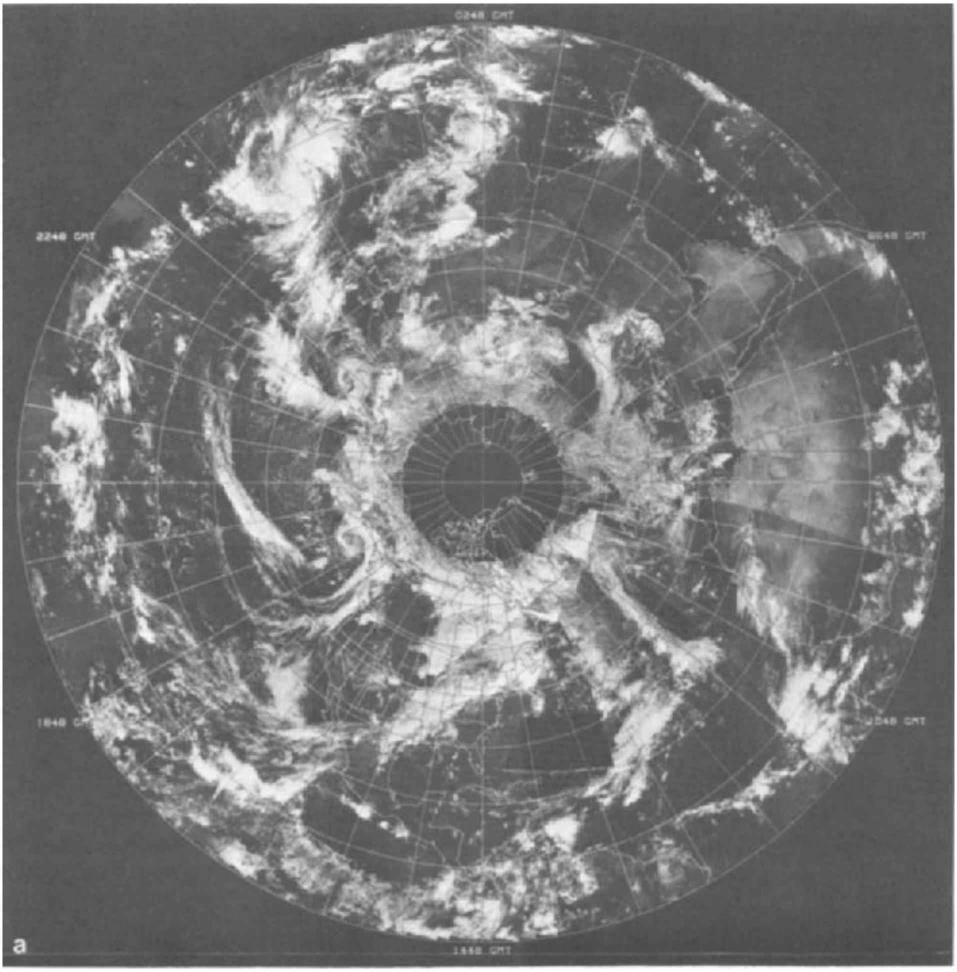

FIG. 1.1a. Northern hemisphere cloud distribution observed in visible light by polar orbiting satellite NOAA-3, 0636 GMT November 4 to 0745 GMT November 5, 1974. The picture is formed by computer from 13 successive north–south passes of the satellite at the times indicated along the equator.

cloud areas undergoes a characteristic life cycle. Within each large area there are smaller scale cloud systems exhibiting complex structures, movements, and life cycles. Systematic relations can be readily detected among the size and structure of the cloud areas and their latitude, the season of the year, and the underlying earth's surface.

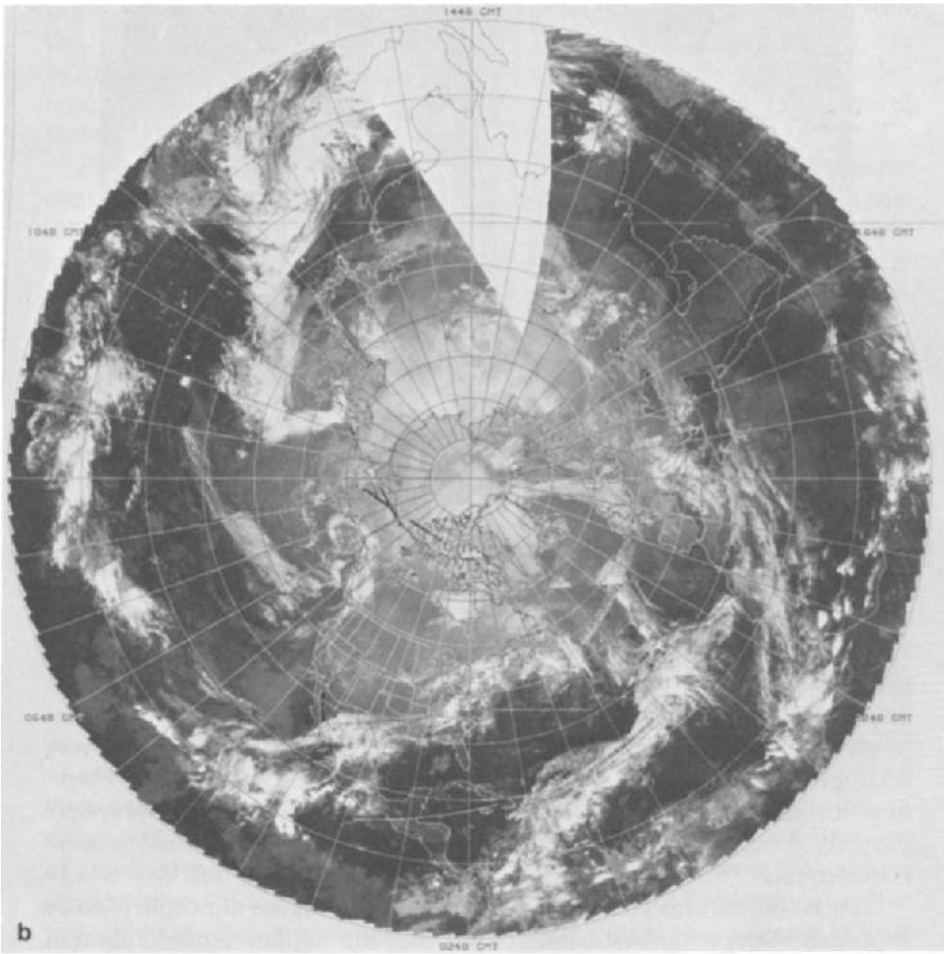

FIG. 1.1b. Northern hemisphere cloud distribution observed at night by infrared radiation by NOAA-3, 2040 GMT November 4 to 2001 GMT November 5, 1974. The picture is formed by computer from 13 successive passes of the satellite at the times indicated along the equator (by courtesy of National Environmental Satellite Service, National Oceanic and Atmospheric Administration).

Half of the atmosphere is always confined to the 6-km layer in which most of the clouds are found, and 99% is confined to the lowest 30 km. The relative vertical and horizontal dimensions of the atmosphere are suggested in Fig. 1.2, which shows the atmosphere as photographed by astronaut

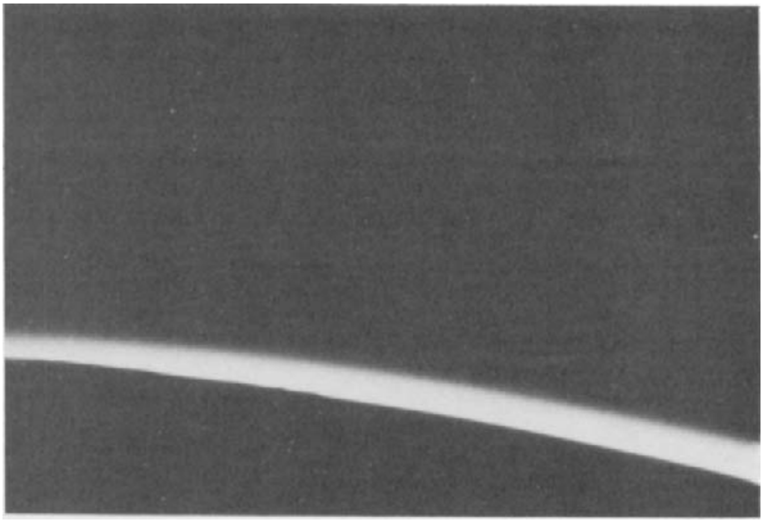

FIG. 1.2. The atmosphere as seen by John Glenn from a height of about 200 km over the Indian Ocean after sunset 20 February 1962. The photograph covers about 10° of latitude (by courtesy of Project Mercury Weather Support Group, U.S. Weather Bureau).

John Glenn in 1962 on his first flight around the earth. In this photograph the atmosphere is visible only to a height of about 40 km. Although the atmosphere is heavily concentrated close to the earth, air density sufficient to produce observable effects is present at a height of 1000 km, and a very small proportion of the atmosphere extends even farther into space. Therefore, for applications in which mass is the relevant factor, the atmosphere properly is considered a thin shell; for other applications the shell concept is inadequate.

How is this curious vertical distribution of mass in the atmosphere to be explained? Deeper understanding of this problem requires consideration of complex energy transformations which will be discussed at a later stage; we shall then have occasion to refer to this problem of the vertical distribution of density in the atmosphere. At this stage, however, we shall be concerned with understanding some of the effects of the earth's gravitation on the atmosphere. Before that, some of the elementary concepts and principles of mechanics will be reviewed briefly. Readers who are familiar with these principles should be able safely to skip the next three sections.

1.1 Fundamental Concepts

The fundamental concepts of physics, those defined only in terms of intuitive experience, may be considered to be space, time, and force. We utilize these concepts, which arise from direct sensory impressions, with the faith that they have the same meaning to all who use them. The choice of fundamental concepts is somewhat arbitrary; it is possible to choose other quantities as fundamental, and to define space, time, and force in terms of these alternate choices.

The events which are important in ordinary or Newtonian mechanics are considered to occur within a frame of reference having three spatial coordinates. These define the position of the event in terms of its distance from an arbitrary reference point; the distance may be measured along mutually perpendicular straight lines (Cartesian coordinates) or along any of a number of lines associated with other coordinate systems. Time is expressed in terms of the simultaneous occurrence of an arbitrary familiar event, for instance, the rotation of the earth about its axis or the characteristic period of an electromagnetic wave emitted by an atom. Force is measured by its effect on bodies or masses.

The primary system of units in this book is the SI system (Système International d'Unités). It is described in Appendix II.A. Note that length, time, and mass are the base quantities of mechanics in the SI system.

1.2 Law of Universal Gravitation

Sir Isaac Newton first recognized that the motions of the planets as well as many terrestrial phenomena (among which we may include the free-fall of apples) rest on a universal statement which relates the separation of two bodies (the separation must be large compared to the linear dimensions of either body), their masses, and an attractive force between them. This law of universal gravitation states that every point mass of matter in the universe attracts every other point mass with a force directly proportional to the product of the two masses and inversely proportional to the square of their separation. It may be written in vector form

$$\boxed{\mathbf{F} = -G\frac{Mm}{r^2}\frac{\mathbf{r}}{r}} \tag{1.1}$$

where $\mathbf{F}$ represents the force exerted on the mass m at a distance $\mathbf{r}$ from the mass M, and G represents the universal gravitational constant. Vector notation and elementary vector operations are summarized in Appendix I.B. The scalar equivalent of Eq. (1.1), $F = GMm/r^2$, gives less information than the vector form, and in this case the direction of the gravitational force must be specified by an additional statement. The universal gravitational constant has the value 6.67×10^{-11} N m^2 kg^{-2}.