An Introduction to Atmospheric Radiation

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AN INTRODUCTION TO ATMOSPHERIC RADIATION
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PREFACE

During recent years, the problems involved in understanding and predicting climate and climatic changes have become topics of increasing interest among both scientists and the public. This upsurge of interest has resulted from the realization that human endeavors are vulnerable to uncertainties in climate, and that human activities may be causing climatic changes. The transfer of solar and infrared radiation represents the prime physical process that drives the circulation of the atmosphere and the ocean currents. It is apparent that an understanding of climate and the mechanisms of climatic changes must begin with detailed understanding of radiative processes and the radiative balance of the earth and the atmosphere.

Moreover, since the successive launches of meteorological satellites in the sixties, applications of the principle of radiative transfer have been fruitful. Using data gathered by these satellites and the principle of radiative transfer, we now are capable of deriving profiles of the temperature and various optically active gases such as water vapor and ozone in our atmospheres. Information of such profiles significantly enhance our understanding of weather and climate of the earth. With the progressive comprehension of the physical interaction of clouds and aerosols with solar and infrared radiation, the quantitative inference of the composition and structure of globally distributed cloud systems and aerosols appears feasible. It is evident that the sounding techniques developed for the earth’s atmosphere may be applied directly to other planetary atmospheres as well.
Although there have been a number of important reference books written in the field of atmospheric radiation, none of them can be adequately adopted as textbooks in atmospheric sciences. This is either because the books are oriented toward a literature survey or because they are lacking in presentations on one or several aspects of scattering and absorption processes in planetary atmospheres. Furthermore, none of the published books so far has presented applications of light scattering and radiative transfer principles to remote sensing and radiation climatology. At this time, when satellite sensing, laser applications, and radiative transfer are becoming increasingly important in conjunction with the study of weather and climate of planetary atmospheres, there is indeed an urgent need for a coherent and logical development on the subject of radiation processes in planetary atmospheres. It is the purpose of this book to present and to unify all of the topics associated with the fundamentals of atmospheric radiation. The level of presentation is in such a manner that seniors and graduate students in the atmospheric sciences, and research beginners in atmospheric radiation can follow and absorb the mathematical deductions and fundamental physical laws that govern the radiation field of planetary atmospheres.

The book is divided into eight chapters. Chapter 1 introduces concepts, definitions, various basic radiation laws, and the fundamental equations for radiative transfer. Chapter 2 describes the characteristics of the solar radiation that is available at the top of the earth’s atmosphere. Chapter 3 is concerned with the absorption and scattering processes of solar radiation in molecular atmospheres. Photochemical processes involving ultraviolet radiation and ozone are discussed, and the concept of polarization and the scattering of sunlight by Rayleigh molecules are presented. Chapter 4 deals with infrared radiative transfer in the earth–atmosphere system. The fundamental theory of infrared transfer is covered, and absorption band models and the principle of radiation charts are discussed. Chapter 5 presents the single scattering processes involving aerosols and cloud particles in the atmosphere. The Maxwell equations are first introduced, and the solution of the vector wave equation, which leads to the Mie theory, is derived. The geometrical ray optics approach to light scattering by spherical water drops and hexagonal ice crystals is outlined. In Chapter 6, the principles of multiple scattering in plane–parallel atmospheres are introduced. This chapter includes the presentation of the basic equations, some approximations for radiative transfer problems, the principles of invariance, and various methods for solving the fundamental transfer equation. Applications of the basic radiative transfer theory to remote sensing of the atmosphere are given in Chapter 7. Discussions are made on the inversion principles used in determining temperature and gaseous profiles by means of satellite infrared sounding channels. Various inversion methods also are introduced. The uses of microwave
sounders, and the reflected and transmitted sunlight as a means of remote sensing are further discussed. The basic principles of radar and lidar backscattering techniques for cloud and precipitation detection also are described. The subject matter associated with radiation climatology is covered in the final chapter. This chapter introduces broadband radiation observations from satellites, and reports the latitudinal and global radiation budgets determined from satellite measurements. Theoretical radiation budget studies, and simple climate models based on the radiative balance are further described. Problem sets with varying degrees of difficulty are prepared in each chapter.

In writing this book, I have assumed that the readers already have had introductory courses in physics and calculus. Although the book has been written primarily for students and researchers in the field of atmospheric sciences, students and researchers in other disciplines, including planetary exploration, electromagnetic scattering, optics, and geophysics, also may find various topics in the text of some interest and use. I have used materials in Chapters 1–4 in a senior and first-year graduate course entitled “Atmospheric Radiation: Physical Meteorology.” I also have utilized the subject matter in Chapters 5–6 and Chapters 7–8 in advanced graduate courses entitled “Radiative Transfer” and “Remote Sensing from Satellites,” respectively. Some of the materials presented in the text are original and have not been published elsewhere.

During the course of the writing, I have found an enormous amount of literature in the field of atmospheric radiation, resulting from the overlap of meteorology, astrophysics, planetology, electrical engineering, and applied physics. Generally, I have avoided citing the original reference on the topic discussed in the text. Interested readers who wish to further study the subject matter can find the relevant papers from the suggested references which are either published books or review papers. However, I have attempted to make reference to important contributions, which represent recent developments and significant finds in the field of atmospheric radiation and remote sensing. I have undertaken an almost impossible task of unifying diffuse notations used in fields of scattering, absorption and emission, radiative transfer, and satellite sensing. Unfortunately, I find that it is unavoidable to repeat some symbols to preserve the distinction of various content areas. Finally, a number of subject matters, which are not described in the text, are presented through exercises at the end of each chapter.

I am indebted to the following friends and colleagues who took the time to read various chapters of the manuscript and offered many helpful suggestions for improvements: P. Barber, K. L. Coulson, A. Fymat, J. F. King, C. B. Leovy, J. North, and T. Sasamori. During the course of the writing, my research programs have been continuously supported by the Atmospheric
Research Section of the National Science Foundation and the Air Force Geophysics Laboratory. Their support has made possible a number of presentations in the text. Appreciation is extended to the University of Utah for granting me a David P. Gardner Faculty Fellow Award which released my teaching duty in the winter quarter of the 1978/1979 academic year during which considerable writing was accomplished. I would also like to thank R. Coleman and K. Hutchison for independently working out most of the exercises and for assisting me in proofreading the manuscript, and Mrs. D. Plumhof for typing various versions of the manuscript.
In the northern darkness there is a fish and his name is Kun. The Kun is so huge that he measures many thousand miles. He changes and becomes a bird whose name is Peng. The back of the Peng also measures many thousand miles across and, when he rises up and flies off, his wings are like clouds all over the sky. When the sea begins to move, this bird journeys to the southern darkness, and the waters are roiled for three thousand miles. He beats the whirlwind and rises ninety thousand miles, setting off on the sixth month gale, wavering heat, bits of dust, living things blown about by the wind—the sky looks very blue. Is that its real color, or is it because it is so far away and has no end?

Chuang Tzu

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AN INTRODUCTION TO ATMOSPHERIC RADIATION
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1.1 CONCEPTS, DEFINITIONS, AND UNITS

1.1.1 Electromagnetic Spectrum

The most important of the processes responsible for energy transfer in the atmosphere is electromagnetic radiation. Electromagnetic radiation travels in the wave form, and all electromagnetic waves travel at the same speed, which is the speed of light. This is $2.99793 \pm 1 \times 10^8 \text{ m sec}^{-1}$ in a vacuum and at very nearly this speed in air. Visible light together with gamma rays, x rays, ultraviolet light, infrared radiation, microwaves, television signals, and radio waves form the electromagnetic spectrum.

The retina of the human eye is sensitive to electromagnetic waves with frequencies between $4.3 \times 10^{14}$ vibrations per second (usually written as cycles per second and abbreviated cps) and $7.5 \times 10^{14}$ cps. Hence, this band of frequencies is called the visible region of the electromagnetic spectrum. The eye, however, does not respond to frequencies of the electromagnetic waves higher than $7.5 \times 10^{14}$ cps. Such waves, lying beyond the violet edge of the spectrum, are called ultraviolet light. Moreover, if the waves have frequencies lower than $4.3 \times 10^{14}$ cps, the eye again does not respond to them. These waves, having frequencies lower than the lowest frequency of visible light at the red end of the spectrum and higher than about $3 \times 10^{12}$ cps, are called infrared light or infrared radiation. Just beyond the infrared portion of the spectrum are the microwaves, which cover the frequency from about $3 \times 10^{10}$ to $3 \times 10^{12}$ cps. The most significant spectral regions associated
### Fig. 1.1 The electromagnetic spectrum.

<table>
<thead>
<tr>
<th>Region</th>
<th>Wavelength (cm)</th>
<th>Frequency (cps)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gamma rays</strong></td>
<td>$10^{-9}$</td>
<td>$3 \times 10^{19}$</td>
</tr>
<tr>
<td>X-rays</td>
<td>$10^{-6}$</td>
<td>$3 \times 10^{16}$</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>$3 \times 10^{-5}$</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>Visible</td>
<td>$10^{-4}$</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Infrared</td>
<td>$10^{-1}$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td>Microwaves</td>
<td>$1$</td>
<td>$3 \times 10^{8}$</td>
</tr>
<tr>
<td>Spacecraft</td>
<td>$10^2$</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>Television &amp; FM</td>
<td>$10^3$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>Shortwave</td>
<td>$10^4$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>AM</td>
<td>$10^5$</td>
<td>$3 \times 10^5$</td>
</tr>
</tbody>
</table>
with the radiative energy transfer in planetary atmospheres lie between the ultraviolet light and microwaves.

The x-ray region of the electromagnetic spectrum consists of waves with frequencies ranging from about $3 \times 10^{16}$ to $5 \times 10^{18}$ cps, and is adjacent to the ultraviolet region in the spectrum. The gamma-ray region of the spectrum has the highest frequencies of all, ranging upward from about $3 \times 10^{19}$ cps. At the other end of the spectrum beyond the microwave region is the television and FM band of frequencies, extending from about $3 \times 10^8$ to $3 \times 10^9$ cps. Radio waves have the lowest frequencies in the spectrum, extending downward from about $3 \times 10^5$ cps.

Electromagnetic waves often are described in terms of their wavelength rather than their frequency. The following general formula connects frequency $\nu$ and wavelength $\lambda$:

$$\lambda = \frac{c}{\nu},$$

(1.1)

where $c$ represents the speed of light in a vacuum. The formula is valid for any type of wave, and is not restricted to electromagnetic waves. It is customary to use wave number $\nu$ to describe the characteristics of infrared radiation. It is defined by

$$\nu = \frac{c}{\lambda} = \frac{1}{\lambda}.$$ (1.2)

Thus, a 10 micrometer ($\mu$m) ($1 \mu$m = $10^{-4}$ cm) wavelength is equal to a 1000 cm$^{-1}$ wave number. In the microwave region, however, a frequency unit called gigahertz (GHz) is commonly used. One GHz is equal to $10^9$ cycles per second. Thus, 1 cm is equivalent to 30 GHz.

Figure 1.1 shows the complete electromagnetic spectrum with frequencies and wavelengths indicated. The names given to the various parts of the spectrum are also shown.

1.1.2 Solid Angle

The analysis of a radiation field often requires the consideration of the amount of radiant energy confined to an element of solid angle. The solid angle is defined as the ratio of the area $\sigma$ of a spherical surface intercepted by the core to the square of the radius, $r$, as indicated in Fig. 1.2. It can be written
Fig. 1.3 Illustration of a solid angle and its representation in polar coordinates. Also shown is a pencil of radiation through an element of area $dA$ in directions confined to an element of solid angle $d\Omega$.

as

$$\Omega = \frac{\sigma}{r^2}. \quad (1.3)$$

Units of the solid angle are expressed in terms of the steradian (sr). For a sphere whose surface area is $4\pi r^2$, its solid angle is $4\pi$ sr.

To obtain a differential elemental solid angle, we construct a sphere whose central point is denoted as $O$. Assuming a line through point $O$ moving in space and intersecting an arbitrary surface located at a distance $r$ from point $O$, then as evident from Fig. 1.3 the differential area in polar coordinates is given by

$$da = (r d\theta)(r \sin \theta d\phi). \quad (1.4)$$

Hence, the differential solid angle is

$$d\Omega = \frac{d\sigma}{r^2} = \sin \theta d\theta d\phi, \quad (1.5)$$

where $\theta$ and $\phi$ denote the zenithal and azimuthal angles, respectively, in polar coordinates.

1.1.3 Basic Radiometric Quantities

Consider the differential amount of radiant energy $dE_{\lambda}$ in a time interval $dt$ and in a specified wavelength interval $\lambda$ to $\lambda + d\lambda$, which crosses an element