LIGHT SCATTERING BY ICE CRYSTALS

Fundamentals and Applications

This research volume outlines the scientific foundations that are central to our current understanding of light scattering, absorption and polarization processes involving ice crystals. It also demonstrates how data from satellite remote sensing of cirrus clouds (comprising various ice crystal sizes and morphologies) can be combined with radiation parameterizations in climate models to estimate the role of these clouds in temperature and precipitation responses to climate change. Providing a balanced treatment of both the fundamentals and applications, this book synthesizes the authors' own work, as well as that of other leading researchers in this area, in a coherent and logical presentation. Numerous illustrations are included, including three-dimensional schematics, in order to provide a concise discussion of the subject and enable easy visualization of the key concepts.

This book is intended for active researchers and advanced graduate students in atmospheric science, climatology and remote sensing, as well as scholars in related fields such as ice microphysics, electromagnetic wave propagation, geometric optics, radiative transfer and cloud–climate interactions.

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Fundamentals and Applications

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Epigraph

To all the happy ice crystals in planetary atmospheres

Let there be light.
Let there be beautiful ice crystals in the air and mountain ranges.
And here come the reindeers and Santa Claus carrying Maxwell's equations, and light rays are shining in the wonderlands.
Let the glory of Geometric Optics for ice crystals, Newton's optics, and sun's light rays rise again from the horizon.
Let ice crystals' old friends – black carbon and dust – be not forgot for Auld Lang Syne.
And ice crystals are carried by the ceaseless winds; and
After traveling thousands of miles up and down, the sky looks very blue.
Let there be space missions to tender ubiquitous light rays in the sky,
And all things considered, let light scattering by ice crystals in remote sensing and climate change be a delight.

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Preface

The preparation of *Light Scattering by Ice Crystals: Fundamentals and Applications* began about seven years ago. We thought that sufficient material should be available to compose a high-level text reflective of the complex and intricate domain of ice crystals in the Earth's atmosphere and their interaction with "light" from the sun and that emitted from the Earth and the atmosphere, with applications to remote sensing and climate studies. This text was supposed to be a three- to four-year project; however, after sifting through the literature for about two years, gaps emerged on various subjects, including both fundamentals and applications. For this reason, we conducted additional research in an attempt to bridge various gaps that are essential, from our perspective, to the unification of all subjects in a coherent and logical manner with reference to light scattering by ice crystals. Accordingly, we are pleased to present this text for active researchers and advanced graduate students who are interested in general areas of atmospheric physics, atmospheric radiative transfer, atmospheric optics, computational modeling, cloud–climate interactions, and remote sensing of the atmosphere and oceans within the purview of atmospheric and climate sciences. It is intended to complement other researchers who work in the field of light scattering by non-spherical particles, which includes ice crystals.

"Ice in the Earth's atmosphere," the title of Chapter 1, plays a key role in the hydrological cycle and precipitation processes. Furthermore, ice clouds in the upper troposphere through their solar albedo and infrared greenhouse effects are critical elements in determining surface and atmospheric temperature patterns within the context of greenhouse warming and climate change induced by man-made perturbations in greenhouse gases and regional air pollution. In Chapter 1, we introduce cloud classification, a global view of clouds in general, and cirrus clouds in particular, followed by discussion of the formation and growth of ice crystals. We then illustrate the complex nature of ice crystals with reference to their size and three-dimensional morphology based on findings obtained from laboratory experiments and aircraft observations, to establish a correlation between ice water content and ice crystal size. This correlation is important in developing radiative transfer parameterizations in climate models and in understanding the role of ice in climate radiative forcing. Lastly, we present a two-dimensional cirrus cloud model to illustrate interactions of winds, ice microphysics, and radiative transfer.

In Chapter 2, "Fundamentals of light scattering by ice crystals," a number of fundamental subjects are presented in relation to light scattering by ice crystals. We discuss the scope and boundaries of light scattering by ice crystals and present the fundamental Maxwell's equations, leading to vector wave equations whose solutions require the imposition of boundary conditions. We show that exact analytic solutions of vector wave equations exist only for spherical, circular cylindrical, and spheroidal coordinates. The optical properties of ice are then introduced, followed by a discussion that defines the single-scattering and polarization properties of non-spherical ice crystals, including the meaning of the scattering phase matrix. We subsequently discuss the link between single-scattering properties of ice crystals, deduced from the independent scattering concept, and the transfer of radiation, including multiple scattering and emission within ice crystal clouds.

Chapter 3, entitled "Principles of geometric optics for application to light scattering by ice crystals," presents the geometric-optics approach to light scattering by ice crystals, starting with an overview of the essence of geometric optics, including diffraction and surface waves, from several historical perspectives. We then illustrate fascinating ice optics produced by randomly and horizontally oriented ice particles by means of Monte Carlo geometric ray tracing. Subsequently, we demonstrate that exact solutions for diffraction involving a number of ice crystal shapes can be analytically derived, followed by discussion of conventional and improved geometric-optics approaches, and, based on a number of postulations, introduce surface-wave contributions – the edge effect – for spheres with modification to hexagonal ice crystals. Lastly, we present a unified theory of light scattering by ice crystals on the basis of the geometric-optics surface-wave approach. In this discussion, theoretical phase functions are compared with those determined from controlled laboratory light scattering and spectroscopic experiments, as well as application to light absorption and scattering by snow grains internally contaminated by black carbon and dust particles wherein stochastic processes are further introduced.

In Chapter 4, "Other useful approaches to light scattering by ice particles," we confine our presentations to three contemporary numerical approaches to light scattering by non-spherical particles within the purview of their applications to light scattering by ice crystals, namely the finite-difference time domain method, the T-matrix numerical method, and the discrete dipole approximation. Single-scattering and phase matrix results determined from these methods for applicable ice crystal size and shape ranges have been used to cross check and calibrate those computed from a number of geometric-optics approaches. Moreover, we develop numerical techniques to improve the first two methodologies in terms of particle size applicability, as well as application to intricate particle shapes.

The subject of "Application of light scattering by ice crystals to remote sensing" is presented in Chapter 5, wherein we first discuss atmospheric composition and structure, the atmospheric absorption spectrum, sun–satellite geometry, radiative transfer, and the contemporary A-Train satellite constellation, which are important for cirrus cloud detection and quantification. From that base, we then present the subject of retrieving the optical depth and ice crystal size of cirrus clouds using reflected visible and near-infrared radiation and illustrate the importance of the phase function of ice crystals. A discussion follows on detecting thin cirrus and vertical sizing of cirrus cloud layers. We subsequently cover the subjects of remote sensing of ice clouds using reflected polarization and the principle of backscattering depolarization to differentiate ice crystals and water droplets. Lastly, we present reflected line spectra in the 1.38 μm band and the oxygen A-band for inferring the composition and optical properties of high clouds.

Chapter 6, the last chapter of the text, comprises discussions of "Application of light scattering by ice crystals to climate studies." Herein, we present the physical foundations for parameterization of the extinction and absorption coefficients and phase function, for ice crystals imbedded in gaseous absorption line formation. We then discuss delta-two-stream and delta-four-stream approximations for efficient radiative flux transfer in non-homogeneous plane-parallel atmospheres and compare theoretical results with aircraft and satellite observations. On this basis, we present radiative forcing of cirrus clouds from the viewpoint of theoretical calculations and point out the prevalence of the infrared greenhouse effect over its solar albedo counterpart. This is followed by a presentation of climatic effects of cirrus clouds from the perspective of one-dimensional climate models, where we point out that cloud cover, ice water path, and ice crystal size are influenced by temperature increases in greenhouse warming scenarios. Also discussed are examples of the impacts of microphysics on precipitation and radiative forcings using results analyzed from global climate model simulations. We then present a number of climatic issues associated with cirrus clouds, including contrails and induced contrail cirrus produced by high-flying aircraft, a man-made perturbation, their role in upper troposphere and lower stratosphere exchanges, and the usefulness of optically thin cirrus data determined from modern satellite instrumentation for ice cloud parameterization development in climate models.

In view of the above, the subject of light scattering by ice crystals as presented in this text has made definitive contributions to fundamental understanding of and insight into light scattering, absorption, and polarization processes involving ice crystals. Moreover, light scattering by ice crystals has provided a new dimension and valuable datasets to the development of satellite remote sensing of ubiquitous cirrus clouds comprising various ice crystal sizes and morphologies, as well as to radiation parameterizations for these clouds in climate models to investigate uncertainties surrounding their role in temperature and precipitation responses to global warming and climate change.

The senior author wishes to acknowledge the National Science Foundation for its support over the last 30 years or so of his basic research on light scattering by ice crystals and related subjects in radiative transfer at the University of Utah and the University of California, Los Angeles. In particular, he would like to thank the Atmospheric Sciences Section for a Creativity Award based on contributions to "Light Scattering by Ice Crystals: Theory and Experiment" (1996) through the recommendation of the late Ronald Taylor and subsequent support from R. R. Rogers, Bradley Smull, and Chungu Lu, Program Directors for Dynamical and Physical Meteorology. Additionally, he thanks Roberto Peccei, a particle physicist and UCLA Emeritus Vice Chancellor for Research, and Joseph Rudnick, a condensed matter physicist and Senior Dean of the UCLA College of Letters and Science, for unwavering support in his pursuit of academic and research excellence and the founding of the Joint Institute for Regional Earth System Science and Engineering at UCLA. He is also exceedingly grateful to Wilfried Brutsaert and Richard Goody for their encouragement and advice.

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