PHYSICS AND CHEMISTRY OF CLOUDS

Clouds affect our daily weather and play key roles in the global climate. Through their ability to precipitate, clouds provide virtually all of the fresh water on Earth and are a crucial link in the hydrologic cycle. With ever-increasing importance being placed on quantifiable predictions – from forecasting the local weather to anticipating climate change – we must understand how clouds operate in the real atmosphere, where interactions with natural and anthropogenic pollutants are common.

This textbook provides students – whether seasoned or new to the atmospheric sciences – with a quantitative yet approachable path to learning the inner workings of clouds. Comprehensive treatments are given of the mechanisms by which cloud droplets form and grow on soluble aerosol particles, ice crystals evolve into diverse shapes, precipitation develops in warm and cold clouds, trace gases and aerosol particles are scavenged from the atmosphere, and electrical charge is separated in thunderstorms.

Developed over many years of the authors' teaching at Penn State University, *Physics and Chemistry of Clouds* is an invaluable textbook for advanced students in atmospheric science, meteorology, environmental sciences/engineering, and atmospheric chemistry. It is also a useful reference text for researchers and professionals.

DENNIS LAMB is Professor Emeritus of Meteorology at the Pennsylvania State University. He has been fascinated with clouds ever since growing up in the Midwestern United States, and the true nature of clouds and the processes that form them have been gradually revealed to him through years of formal training and self study. Professor Lamb worked as a researcher for nearly 14 years at the Desert Research Institute (Reno) before embarking on a teaching career at Penn State University. With more than 40 years of observational and laboratory research experience, and more than 20 years teaching cloud physics and atmospheric chemistry at both the undergraduate and graduate levels, he now realizes that the best path toward understanding clouds is to understand water itself, at the molecular level. The deeper the understanding, the greater becomes the appreciation of clouds as gate keepers in the water cycle and energy budget of Earth. This book is the culmination of his career studying the physics and chemistry of water and clouds.

HANS VERLINDE is an Associate Professor of Meteorology at the Pennsylvania State University. He is an observational meteorologist who has studied clouds in the Antarctic, at the equator, and in the Arctic. He is currently the site scientist for the US Department of Energy Atmospheric Radiation Measurement Program Climate Research Facility at Barrow on the North Slope of Alaska, and he teaches classes in atmospheric thermodynamics, cloud physics, mesoscale meteorology, and radar meteorology at Penn State University. After a start in meteorology as a weather forecaster, he developed a passion

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for clouds, and likes to look at clouds from all sides now, from up and down, from inside out. He enjoys seeing the surprised looks on student faces when, on the first day of every semester, he asks “Who can tell me what clouds are in the sky today?” which inevitably leads to the next question, “Who can tell me what the sky looks like today?”

PHYSICS AND CHEMISTRY OF CLOUDS

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To our families
Pat and Julie
Terri, Anneke, Kris, Katrina, and Maarten

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Preface

Clouds contribute to our lives in both direct and indirect ways. Clouds are at once the most visible elements of the sky and the dominant contributors to the weather we experience every day. Less apparent, but perhaps even more important, are the roles clouds play in the global energy and water budgets that determine the climate of Earth. Through their ability to precipitate, clouds provide virtually all of the fresh water on Earth and a crucial link in the hydrologic cycle. Clouds are also the most effective agents cleansing the atmosphere, although some terrestrial and aquatic ecosystems pay the price for anthropogenic emissions of chemicals into the air. With ever-increasing importance being placed on quantifiable predictions, whether to forecast the local weather or to anticipate changes in global climate, we must learn how clouds operate in the real atmosphere, where two-way interactions with natural and anthropogenic pollutants are common.

Clouds have been the subject of observation for centuries, but serious systematic investigations began only a few decades ago. For all practical purposes, the study of clouds can be traced back to Luke Howard, the English pharmacist who began, around 1803, the system of naming cloud types that we still use today (see Appendix A). Speculation about the composition and nature of clouds persisted for many years. Direct observations from balloons and aircraft helped greatly to develop a base of empirical knowledge upon which the research community could later build testable hypotheses. With ongoing improvements in instrumentation and measurement techniques, the invention of cloud chambers, and an ability to test hypotheses quantitatively, the research community of atmospheric scientists has gradually developed a broad and quantitative understanding of clouds.

The atmosphere, with all its dynamical and chemical complexity, is the environment in which clouds form. We cannot understand clouds divorced from that parental setting. The atmosphere is a mixture of a huge number of chemical compounds, some gaseous, some particulate in nature. Indeed, water is just one of those myriad components, but the only one of note that changes phase under ordinary conditions. The atmosphere is far more than "dry air" and water vapor, so any modern treatment of clouds must deal with this mixture head-on. Indeed, cloud droplets form on the more soluble subset of the particulate matter, and they subsequently absorb some of the trace gases. The microphysical properties, even the macrophysical forms, of clouds are significantly affected by the chemicals in the air. In turn, many of those chemicals are altered and removed from the atmosphere by clouds and the precipitation they produce. The physics and chemistry of the atmosphere go hand in hand when developing a complete picture of clouds and how they behave in the atmosphere.

The need for a new textbook arose partly out of our frustrations with identifying textbooks suitable for teaching cloud physics, mainly at the graduate level, but also as part of the undergraduate curriculum that meteorology majors take. Many of our first-year graduate students come from disciplines other than meteorology or the atmospheric sciences. They typically have strong backgrounds in science, engineering, or math, but few have had any formal course dealing with clouds. The graduate course offered at Penn State University therefore starts out with few assumptions other than that the students are bright and skillful in mathematics and scientific reasoning. An ideal text parallels the course structure by presenting the atmospheric context and showing how fundamental scientific principles lead to the phase changes of water we know of as clouds. We hope that we have met the challenge with this textbook by emphasizing the basic disciplines of physics and chemistry.

This textbook offers students, whether seasoned or new to the atmospheric sciences, a quantitative, yet approachable path to learning the inner workings of clouds. Comprehensive treatments are given of the mechanisms by which cloud droplets form and grow on soluble aerosol particles, ice crystals evolve into diverse shapes, precipitation develops in warm and cold clouds, trace gases and aerosol particles get scavenged from the atmosphere, and electrical charge becomes separated in thunderstorms. Overall, the book emphasizes how clouds ultimately depend on the molecular properties of matter.

The book is broken down into five parts to allow the reader to focus separately on the several main areas. Part I provides background material of use to those either unfamiliar with the atmospheric sciences or wishing a brief refresher of concepts and terminology. This first part could serve as the basis for a survey course in physical meteorology. Alternatively, it may be skimmed or skipped by readers with strong backgrounds in atmospheric physics and chemistry. Part II shows how transformations, both physical and chemical, come about in nature when a system deviates from equilibrium. Special attention is paid to the concepts of equilibria pertinent to phase changes because of their central role in theories of cloud formation. Part III discusses clouds from a macroscopic point of view. At this level, one need not know much about the composition of clouds other than that they are composed of water in condensed form. Part IV elucidates the processes responsible for the microstructure of clouds, the phases, sizes, and shapes of the individual particles making up a cloud. Part V brings the reader back to the cloud scale and the effects of large populations of cloud particles.

The units used for dimensioned quantities in this book are based on the International System of Units (Système International d'Unités, SI). The SI uses decimal units of measure, with the base units being the meter [m], kilogram [kg], second [s], ampere [A], kelvin [K], and mole [mol]. A standard set of prefixes are used to allow quantities to be specified with convenient values. Some accommodation has been made in this book for nonstandard units that are still in common use. For instance, hPa is the SI equivalent of mbar [or mb], the unit of pressure so commonly used by meteorologists. It is expected that readers are familiar with or have access to the complete guidelines of SI symbols and usage.

This textbook is intended to augment lectures in upper-division and graduate courses in physical meteorology or cloud physics. Introductory material in each major section is intentionally descriptive in nature in order to present students with a qualitative feel for the subject. Where the subject matter is presented from a theoretical viewpoint, mathematics through vector calculus and differential equations is employed. It is intended that students in a graduate course would read further into each subject than would undergraduates. The instructor is best able to decide the dividing points. Each chapter ends with a bibliography for further reading and a set of problems to emphasize certain points and give opportunities for further learning. The instructor should feel free to modify or expand on problems to meet the particular goals of his/her course.

Authors of textbooks invariably depend on the hard work of and discussions with many others. The research literature has been heavily exploited, but citations have been limited to sources of graphical material in order to ease the reading of technical material by beginning students. We are indebted to the many authors of prior texts and reference books, upon which we have relied to develop material for teaching the subjects of cloud physics and atmospheric chemistry over many years. Among the books we have relied on most are those by Pruppacher and Klett (*Microphysics of Clouds and Precipitation*, 2nd edn.), Rogers and Yau (*A Short Course in Cloud Physics*, 3rd edn.), Seinfeld and Pandis (*Atmospheric Chemistry and Physics*), Cotton and Anthes (*Storm and Cloud Dynamics*), and Houze (*Cloud Dynamics*). We think this book should find a niche somewhere between the short course by Rogers and Yau and the extensive reference book of Pruppacher and Klett. We would also like to think of it as complementing the comprehensive work on atmospheric chemistry by Seinfeld and Pandis.

Special acknowledgment is graciously extended to the many individuals who have, in one way or another, enabled us to carry out this ambitious project. At the onset, Raymond Shaw graciously provided a quality environment in the Physics Department at Michigan Technological University, where the first author spent a sabbatical leave in 2006 and began the actual process of writing. Many subsequent discussions with him and other colleagues there and elsewhere have contributed enormously over the years to the development of the material presented in this book. Among those individuals, the authors wish to thank (in alphabetical order) Alex Avramov, Chad Bahrman, William Brune, Will Cantrell, J.P. Chen, Eugene Clothiaux, William Cotton, Graham Feingold, Jose Fuentes, Barry Gardiner, Jerry Harrington, Alex Kostinski, Zev Levin, Nathan Magee, Paul Markowski, Alfred Moyle, Yvette Richardson, Lindsay Sheridan, Nels Shirer, Ariel Stein, and Huiwen Xue. The first author also benefited greatly from the opportunity, offered by Huiwen Xue and Chunsheng Zhao, to teach part of a graduate course in cloud physics in the Department of Atmospheric Sciences at Peking University in 2009. The feedback on various chapters of the book that was received from the students there and at Penn State University has helped us greatly during revisions of the text. We are especially grateful to Eugene Clothiaux, Barry Gardiner, and Nels Shirer for their careful and critical reading of parts of the manuscript at various stages. The publication process was made relatively painless by the able assistance provided by Laura Clark and Matt Lloyd at Cambridge University Press. Finally, we are ever thankful for the patience of and encouragement given by our respective families, to whom this book is dedicated.