An Introduction to Clouds

From the Microscale to Climate

Clouds, in their various forms, are a vital part of our lives. Their effects on the Earth's energy budget and the hydrological cycle depend on processes on the microphysical scale, encompassing the formation of cloud droplets, ice crystals and precipitation. Cloud formation, in turn, depends on the large-scale environment as well as the characteristics and availability of aerosol particles. An integrated approach drawing on information from all these scales is essential to gain a complete picture of the behavior of clouds in the atmosphere.

An Introduction to Clouds provides a fundamental understanding of clouds, ranging from cloud microphysics to the large-scale impacts of clouds on climate. On the microscale, phase changes and ice nucleation are covered comprehensively, including aerosol particles and the thermodynamics relevant for the formation of clouds and precipitation. At larger scales, cloud dynamics, mid-latitude storms and tropical cyclones are discussed, leading to the role of clouds in the hydrological cycle and their effect on climate.

Each chapter ends with problem sets and multiple-choice questions that can be completed online; important equations are highlighted in boxes for ease of reference. Combining mathematical formulations with qualitative explanations of the underlying concepts, this accessible book requires relatively little previous knowledge, making it ideal for advanced undergraduate and graduate students in atmospheric science, environmental sciences and related disciplines.

Ulrike Lohmann is a professor at the Institute for Atmospheric and Climate Science, ETH Zurich. She obtained her Ph.D. in climate modeling and her research now focuses on the role of clouds and aerosol particles in the climate system, with an emphasis on clouds containing ice. Professor Lohmann has published more than 200 peer-reviewed articles and several book chapters, and was a lead author of the Fourth and Fifth IPCC Assessment Reports. She was awarded the Canada Research Chair in 2002 and was the recipient of the AMS Henry G. Houghton Award in 2007. She is a fellow of the American Geophysical Union and the German Academy of Sciences, Leopoldina. Ulrike Lohmann has been teaching classes in cloud microphysics and cloud dynamics for almost 20 years at both undergraduate and graduate levels.

Felix Lüönd is a researcher at the Swiss Federal Institute of Metrology, METAS. He obtained his Ph.D. in atmospheric ice nucleation, for which he was awarded the ETH medal. His experimental work focused on cloud microphysics. He specialized in the development of dedicated instrumentation to study the aerosol-induced freezing of cloud droplets and the interpretation of the resulting experimental data in the framework of nucleation theory and its advancements. Currently, Dr. Lüönd's research activities are concentrated on aerosol metrology, particularly in the generation of ambient-like aerosols dedicated to establish traceability in measurements of ambient particulate matter and particle number concentration.

Fabian Mahrt is a Ph.D. student at the Institute for Atmospheric and Climate Science, ETH Zurich. He obtained a Master's degree in Atmospheric and Climate Sciences from ETH. Early in his career he developed a passion for cloud microphysics. He is particularly interested in aerosol particles and their role in cloud droplets and ice crystal formation. Fabian Mahrt's work is experimental in nature, measuring and understanding aerosol–cloud interactions in both the laboratory and the field.

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ULRIKE LOHMANN, FELIX LÜÖND AND FABIAN MAHRT
ETH Zurich, Institute for Atmospheric and Climate Science, Switzerland

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To our families
Kassiem, Stefanie, Claudia, Jana and Rainer

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Preface

Clouds, in their various forms, are a vital part of our lives. They are a crucial part of the global hydrological cycle, redistributing water to Earth's surface in the form of precipitation. In addition, they are a key element for the global energy budget since they interact with both shortwave (solar) and longwave (terrestrial) radiation. These so-called cloud–radiation interactions depend strongly on the type of cloud. Clearly clouds affect the global climate and thus understanding clouds is an important factor for future climate projections. The effects on Earth's energy budget and on the hydrological cycle both depend on processes on the microphysical scale, encompassing the formation of cloud droplets, ice crystals, raindrops, snowflakes, graupel and hailstones.

Establishing an understanding of clouds and precipitation requires a knowledge of the environment in which they form, i.e. the atmosphere, with all the gases and airborne particles present there. The latter are usually referred to as aerosol particles and encompass a wide range of solid and liquid particles suspended in air. Some aerosol particles can act as nuclei to form cloud droplets or ice crystals and thus initiate the formation of clouds or change their phase from liquid to solid. Thus they influence the microphysical properties of clouds. In turn aerosol particles are removed from the atmosphere when clouds precipitate. In order to gain a complete picture of the behavior of clouds in the atmosphere, the strong interplay between aerosol particles and clouds requires one to tackle the subject in an integrated approach.

This book is intended to offer a fundamental understanding of clouds in the atmosphere. It is primarily written for students at an advanced undergraduate level who are new to the field of atmospheric sciences. The content of this book evolved from the atmospheric physics lectures held at ETH Zurich. This book is intended to serve students with a multidisciplinary background as an introduction to cloud physics, assuming that most readers will have a basic understanding of physics.

The book is organized into 12 chapters, each focusing on a particular topic. Chapter 1 introduces the major cloud types found in the atmosphere and discusses them from a macroscopic point of view. Chapters 2–4 focus on the meteorological conditions and atmospheric dynamics needed for cloud formation and the thermodynamic principles needed to describe atmospheric processes, including phase transitions.

Chapter 5 treats atmospheric aerosol particles and their physical characteristics. The sources and sinks of aerosol particles are discussed at the process level as well as in terms of their global distributions and lifetimes.

Chapters 6–8 cover cloud microphysics. Chapter 6 discusses the fundamental equations that describe the formation of cloud droplets. Chapter 7 introduces the processes which ultimately lead to the formation of rain drops. Ice formation and other microphysical processes occurring in cold clouds are presented in Chapter 8.

Chapter 9 combines the macroscopic view of Chapter 1 with the microscopic view needed to understand the physics of precipitation as well as the differences between stratiform and convective precipitation. Also, the change in precipitation since pre-industrial times and projections into the future are included.

To understand convective clouds, knowledge about cloud dynamics is needed. This is provided in Chapter 10, where convective clouds at all scales, from isolated thunderstorms with lightning and thunder to multicells, supercells and mesoscale convective systems, including tropical cyclones, are discussed.

Finally, Chapters 11 and 12 bring the reader to the global scale. Chapter 11 outlines the physical principles of the global energy budget and discusses the effects of clouds on it. On the basis of the information in Chapter 11 the impact of aerosols and clouds on the climate since pre-industrial times and in future climate projections is considered in Chapter 12.

To strengthen concepts and test the reader's understanding, qualitative exercises and mathematical problems are provided at the end of each chapter. This allows the reader to apply directly the material of the text and provides an opportunity for further learning. To this end, online solutions are provided and can be accessed at www.cambridge.org/clouds. For some of the problem sets the usage of a tephigram will be helpful. This, along with some other material can be accessed from: www.cambridge.org/clouds. Some useful online information about atmospheric science includes the following links:

- Glossary of Meteorology: http://glossary.ametsoc.org/wiki
- Encyclopedia of Atmospheric Sciences: http://app.knovel.com/web/toc.v/cid:kpEASV0002/viewerType:toc/root_slug: encyclopedia-atmospheric/url_slug:encyclopedia-atmospheric/?
- NOAA glossary: http://w1.weather.gov/glossary/
- Fifth Assessment Report of the Intergovernmental Panel on Climate Change: http://www.climatechange2013.org

Throughout the book, important equations are underlaid in gray. All quantities are given in SI units unless stated otherwise. However, as we often refer to processes occurring above or below 0 °C, we will use degrees celsius whenever convenient, keeping in mind that temperatures need to be in kelvins in the equations given (if not noted otherwise).

The outline of the book follows a similar structure to the classic book *A Short Course in Cloud Physics* by Rogers and Yau (1989), which served the present authors not only for their own studies but also for over a decade of teaching at undergraduate level in the atmospheric physics course. Inspired by the straightforwardness of Rogers and Yau (1989) in explaining complex concepts of cloud physics and their style of imparting knowledge to readers new to the atmospheric sciences, paired with the enormous developments in this field over recent years, the authors decided to come up with this new introductory textbook, which places a stronger focus on ice clouds, cloud dynamics and climate change.

We felt that, although there are many excellent textbooks at the graduate level, a textbook introducing the physics of clouds, aerosols and precipitation in an integrated manner combining quantitative discussions at the undergraduate level was lacking. We believe that this