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PHYSICS AND DYNAMICS OF CLOUDS AND PRECIPITATION

What does a cloud contain and how does it form? How and why does lightning occur? How might clouds change the Earth's climate?

This key textbook provides a state-of-the-art view of the physics of cloud and precipitation formation, covering the most important topics in the field: the microphysics, thermodynamics, and cloud-scale dynamics. Highlights include: the condensation process explained with new insights from chemical physics studies; the impact of particle curvature (the Kelvin equation) and solute effect (the Köhler equation); homogeneous and heterogeneous nucleation from recent molecular dynamics simulations; and the hydrodynamics of falling hydrometeors and their impact on collision growth. 3D cloud-model simulations demonstrate the dynamics and microphysics of the formation of deep convective clouds and cirrus, and each chapter contains problems that enable students to review and implement their new learning.

Packed with detailed mathematical derivations and cutting-edge stereographic illustrations, this is an ideal text for graduate and advanced undergraduate courses, and also serves as a reference for academic researchers and professionals working in atmospheric science, meteorology, climatology, remote sensing, and environmental science.

PAO K. WANG is a Professor in the Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, where he has been teaching and conducting research for more than 30 years. He has won much recognition for his contributions to atmospheric science, including the Alexander von Humboldt Award, an S. C. Johnson Distinguished Fellowship, and election as a Fellow of the American Meteorological Society and the Meteorological Society of Taiwan. Professor Wang has been the principal investigator of numerous research grants sponsored by NSF, EPA, NASA, and DOE, covering topics in cloud physics, cloud dynamics, aerosol physics, air pollution, and historical climatology. He is an associate editor of *Atmospheric Research* and *European Journal of Physics-Plus*, a member of the international advisory board of *Terrestrial, Atmospheric and Oceanic Sciences*, and is also currently an advisory committee member of the Research Center for Environmental Change (RCEC), Academia Sinica-Taiwan.

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Praise for this book:

"Finally a comprehensive textbook, filling an empty slot between mainly descriptive and encyclopaedic cloud physics books. It is carefully written, covering all relevant aspects, and starts from first principles in a pedagogic way: invaluable for cloud physics teachers and graduate students."
– **Professor Dr. Andrea Flossmann**, *Université Blaise Pascal de Clermont Ferrand*

"Without hesitation I am endorsing this book. It will be a great addition to atmospheric science."
– **Professor Dr. Hans R. Pruppacher**, *author of Microphysics of Clouds and Precipitation*

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To my parents
and
to Libby, Lawrence and Victor

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Preface

Clouds are magic in the sky. On a perfectly clear day, clouds may suddenly appear from nowhere, literally out of the blue, and soon cover the whole sky with inconceivable rapidity. And they can be gone just as quickly, as you will know if you have ever encountered a sudden rainstorm, sometimes even with lightning and thunder, while hiking in the mountains. When you are scurrying to find a hiding place, the rain suddenly stops, clouds disappear, and the sun shines brightly over the freshly washed cypress trees. Such was my experience when I was a juvenile in Taiwan, a subtropical volcanic island in the Western Pacific where mountains, sunshine, and water vapor are all abundant. The stir-fry of these ingredients is surely an excellent recipe for cloud making.

Ever since I was a child, I have been intrigued by clouds and had wondered where clouds lived and how they can appear mysteriously in the sky and climb up mountain slopes, and how such seemingly solid blocks can stay afloat in air. Nobody seemed to know the answers. Some adults cited an old saying from ancient Chinese literature: “clouds come out from mountains,” but I had never been able to find any “central storage house” of clouds in any mountain in Taiwan.

So one day I was hiking on a mountain and saw a patch of cloud resting on the slope not too far ahead, up the winding path, and I decided to find out what there was in the cloud. I rushed to it as I was afraid it would disappear. But the closer I was, the more it didn’t look like a cloud, but rather like fog. And finally I was very sure I was in it, but I couldn’t see anything tangible. It was even more dilute than many fogs I had experienced before. Later, I read a poem *Reply to the Imperial Inquiry* by the noted Taoist hermit scholar and alchemist Tao Hongjing (AD 456–536) who wrote it to decline the emperor’s invitation to serve in the court:

> What is there in the mountain?
> Over the ranges there are copious white clouds
> But I can only enjoy them by myself
> And am unable to offer them as a gift to you.

Truly, you cannot even hold a piece of cloud in your hand.

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But what intrigued me most are those tall cumulus clouds (towering cumulus). In the summer time of Taiwan, the tropopause is very high and these clouds can easily go above 10 or 12 kilometers. Viewed from a distance, they look like silvery mountain peaks topped with intricate palaces or castles. Old fables maintain that there are immortals living in these palaces. The fable notion fades quickly with age, of course, but one question remained in my mind: How would these tall clouds look if viewed from the top?

In college I majored in meteorology but there was no cloud physics course in the first three years, so I had to satisfy my curiosity by reading Horace Byers' (1965) *Elements of Cloud Physics*, the only textbook dedicated to cloud physics in the library there. Only in my senior year was the first-ever cloud physics course offered. It was a one-semester course but was taught at a rather elementary level. Meanwhile, another cloud physics book, *The Physics of Rainclouds* by N. H. Fletcher (1966), became available in the library.

In 1973 I went to UCLA to pursue my graduate study and was fortunate to be taken into Hans Pruppacher's group. Ken Beard, who later became a Professor at the University of Illinois, was a research associate with Hans at the time. It was Ken who got me involved in some experimental work with aerosol particles that marked the beginning of my career in cloud physics. Hans taught his cloud physics class using his hand-written notes and I was looking for a textbook for additional information. I found a used copy of B. J. Mason's (1971) *The Physics of Clouds* for sale in the UCLA student book store and purchased it. Both this and Fletcher's books were my major references for cloud physics in addition to the lecture notes.

There is an interesting anecdote about this copy of Mason's book. In the summer of 2010 I went to NCAR in Boulder, Colorado to collaborate with Bob Sharman, also a UCLA graduate, on some research on turbulence generated by deep convection. One day Bob lamented that he shouldn't have sold his copy of Mason's book after he finished the cloud physics course. He now felt that he needed to consult the book from time to time. It turned out that the copy he sold is precisely the copy I bought. Of course, I didn't really know Bob at the time. So, some 37 years later I finally discovered the origin of that book.

In 1978, Hans and Jim Klett together published their classic *Microphysics of Clouds and Precipitation* (Pruppacher and Klett, 1978), which was the most comprehensive cloud physics textbook available at the time. Their second revised and enlarged edition came out in 1996 and has remained the standard reference in this field. When I became a faculty member in the University of Wisconsin-Madison in 1980, I began teaching cloud physics using Pruppacher and Klett's book as the textbook.

But for beginners, Pruppacher and Klett's book can be overwhelming, as it covers such a vast amount of information in great detail. Thus I used only parts of the book

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that I deemed necessary for beginners. I re-derived many equations in somewhat different ways. I also added some materials not covered in their book, such as the summary of cloud observational methods. Over time, I developed a set of lecture notes that eventually evolved to become this book.

Coming to Madison has added new perspectives to my vision of cloud physics. First of all, it is here that my childhood dream of "seeing a towering cumulus from above" has been realized. UW-Madison is a hub of satellite meteorology, as it is where Vern Suomi and his team pioneered early satellite meteorology. One cannot but be exposed to chats about satellite observations all the time in such an environment. And what a satellite sees (via the visible channel) in the atmosphere is the top of clouds which, of course, include large towering cumulus and thunderclouds. Viewing clouds from above over the globe certainly gives a different perspective and stimulates new threads of thoughts about them, especially their role in global atmospheric processes.

Wisconsin is in the upper Midwest of the US where "real" thunderstorms occur. When I was in Los Angeles, watching the passage of a frontal system usually amounted to seeing a band of not-particularly-thick clouds moving over the otherwise blue sky. Severe storms usually don't occur in southern California. It is here in the US Midwest that I developed a true appreciation of deep extra-tropical cyclonic systems and the severe weather they spawn that are the textbook cases of the Bergen school of meteorology. Though the present book is not about satellite observations or thunderstorms specifically, I kept these two subjects in mind when writing.

Cloud physics as a branch of atmospheric science started relatively late compared with other branches such as synoptic or dynamic meteorology. Initially, the term "cloud physics" usually meant "cloud microphysics," i.e. the study of the initiation, growth, and dissipation of individual cloud and precipitation particles, and topics such as cloud dynamics and large-scale cloud processes (such as cloud impact on the radiative budget of the atmosphere) were not included. However, the boundaries between these disciplines have become blurred as the resolutions of observations and theoretical models improved, and I now feel a necessity to include at least some brief discussions of such non-traditional topics.

We are just beginning to understand the important impact of clouds on our atmosphere. The strange ability of water substance to switch quickly from invisible vapor to visible clouds, and vice versa, in our atmosphere makes the accurate prediction of atmospheric behavior extremely difficult. Such an ability has a strong impact on the atmospheric optical (hence radiative) properties and atmospheric chemistry. It is now recognized that the cloud factor (especially that related to

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aerosol) is the single largest source of uncertainties in climate model predictions because we just don't have adequate knowledge of how, when, where, how much, and what kind of clouds will form under certain environmental conditions. It is precisely the purpose of cloud physics studies that will address these issues, and I hope this book helps to clarify some of these issues at least to a certain extent.

This book is divided into 15 chapters. Chapter 1 deals with the observation and classification of clouds based largely on the conventional methods, but remote sensing techniques are also discussed. This chapter serves as the introduction. Beginning in Chapter 2 we start to enter the proper realm of cloud microphysics and examine the internal structure of clouds and precipitation – the size, shape, and concentration of cloud and precipitation particles; all are important properties of the cloud as a colloid system. In Chapter 3 we look into the molecular structure of water substance – individual water molecules and their aggregation states of vapor, liquid, and solid. There are some recent discoveries in this area, such as the presence of quasi-liquid layer on an ice crystal surface and the status of cubic ice in tropical tropopause that may be important when assessing the impact of clouds on climate, and they are briefly summarized here.

Chapter 4 reviews the classical bulk thermodynamics of water substance that eventually leads to the well-known Clausius–Clapeyron equation, and the associated phase change phenomena are discussed from the classical point of view. At the end, we point out the inadequacy of such classical bulk systems in explaining cloud particle thermodynamic behavior and this leads to Chapter 5, which expounds on the necessity of including the surface properties of the condensed phase and the effect of solutes on cloud particles. Two major products of these discussions are the Kelvin and Köhler equations.

Up to this point, all discussions are about the thermodynamic equilibrium among different components of cloud particles. In preparation of what will come next, we need to discuss the aerosol particles in the atmosphere, as they play such an important role in cloud formation and they themselves have a great impact on the global climate. This is presented in Chapter 6.

Chapter 7 is about nucleation – the initiation process of condensed phases. Unlike previous chapters, we discuss the kinetics of molecules instead of their equilibrium behavior. Both homogeneous and heterogeneous nucleation processes are discussed in some detail. In addition, recent molecular level imaging techniques has made it possible to visualize the nucleation on the crystal surface and some results are summarized here.

Up to Chapter 7, discussions are about the physics of cloud particles in the static state. But cloud particles are moving relative to air and such motions generate complicated flow fields around the particles and impact the growth of particles and the overall development of clouds. Hence in Chapter 8, we examine the flow

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fields around various hydrometeors falling in air from both the theoretical and experimental aspects. We need the knowledge gained in this chapter to understand the discussions in the next few chapters.

Chapter 9 discusses the diffusion growth, namely the growth of cloud and precipitation particles by the diffusion of water vapor towards the particle surface. This process dominates the early stage of cloud growth and we discuss the cases of water drops and ice crystals separately. But to develop large precipitation particles, diffusion growth is too slow and the collision and coalescence of hydrometeors take over as the dominant mechanism. This is discussed in Chapter 10 where the collision and coalescence between two individual particles are considered. In this chapter, we also examine the related process of break-up of particles, especially the drops, and the melting of ice particles. Chapter 11 examines the population dynamics of cloud drops to illustrate the impact of the stochastic nature of the collision growth process in clouds.

All the above microphysical processes occur in the cloud whose behavior is determined by the joint play of these processes and the environmental dynamic condition. To put the microphysics in a proper perspective, we need to understand some fundamental dynamics of the cloud formation, which is the main subject of Chapter 12. Here we review some basic cloud thermodynamics and convection physics. I include some observations by Lidar on the boundary layer processes prior to the formation of clouds. The mathematical expressions used for illustrating these basic processes are analytical which, while useful, cannot handle the complicated non-linear interactions between microphysics and dynamics. Thus in Chapter 13, I introduce numerical cloud models, which can simulate more realistically the time evolution of clouds if the microphysical processes are represented by suitable parameterizations. Simulation results of a deep convective storm and some thin cirrus clouds are shown to illustrate applications of such cloud models.

Chapter 14 is about the cloud electricity, which announces its existence visibly and audibly during a thunderstorm. This is a field that still needs more research to understand better both qualitatively and quantitatively. Earlier works in this field were rather speculative, but recently substantial progress has been made in both observational and modeling aspects, and I have summarized some of these studies.

The last chapter, Chapter 15, serves to illustrate some aspects of the impact of clouds on the global atmospheric processes. I selected the cloud scavenging of aerosol particles and sulfur dioxide, the radiative impact of cirrus due to cloud microphysics, and the cross-tropopause transport of water substance by deep convective storms as examples. All these phenomena strongly impact the global atmospheric process. Naturally, the discussions presented here are confined to the cloud scale processes.

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This book is not meant to be comprehensive. The topics I selected for inclusion here are what I thought essentials for a coherent but uncomplicated understanding of cloud and precipitation processes in the atmosphere. There are so many beautiful pearls of research in the vast sea of cloud physics literature that I couldn't include here owing to space limitation. Undoubtedly the term "essentials" contains personal bias as others may have different opinions. Similarly, some topics get more detailed treatments and others much less for the same reason.

The main targeted readers of this book are advanced undergraduate and graduate students of atmospheric sciences. The prerequisite is quite general for college students in physical sciences, namely, a solid background in calculus-based general physics with some exposure to partial differential equations. Readers familiar with physical chemistry will find earlier chapters easy to read as they are essentially the chemical thermodynamics of clouds. But the book is sufficiently self-contained and can also serve as a self-reading reference for research scientists who are not specialized in cloud physics but need to gain some familiarity in this area.

The book contains more materials than can be covered in a one-semester cloud physics course. For a one-semester course, the instructor can use Chapters 1–10 at normal pace. By adding Chapters 11–15, and going through derivations step by step, the book can be used for a two-semester or tri-quarter cloud physics course. I have used mostly the same mathematical symbols as in Pruppacher and Klett's book, so readers can easily cross-check the two books for similar subjects. A few mostly simple problems are given at the end of each chapter, which are designed to get readers familiarized with the subjects discussed.

Book writing is also a self-education process. During the writing, I often found something I thought I knew well a long time ago, but in the process of trying to explain it clearly to readers I discovered that my previous understanding of it was rather superficial. The rewriting, re-derivation, and searching for original papers to clarify these subjects have afforded me to understand them more deeply and I have tried to convey these subtleties in my writing. Of course, the readers are the ultimate judge of how successful I am on this point.

Writing this book also caused me to recall the fond memory of my journey into the field of cloud physics and the people who have helped me along the way, and it is a pleasure to acknowledge them here. Foremost, I would like to thank Prof. Dr. Hans R. Pruppacher who took me into his group and got me started in this field. It was a real pleasure and indeed a privilege for me to participate in the Pruppacher Symposium in Mainz, Germany to celebrate Hans's 80th birthday. The hospitality Hans and his wife Monica have shown to me and my wife Libby every time we visit their house is simply unforgettable. Ken Beard introduced me to the experimental aspects of cloud and aerosol physics. Fellow graduate students and colleagues of Hans at the time, among them Bill Hall, John Pflaum, Sol Grover, Subir Mitra, and John Topalian, have

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enriched my study experience of cloud physics as well as my social life in a new country. Sol was also a very patient teacher who tried to improve my English.

My former students in the University of Wisconsin-Madison had worked out some excellent results of fundamental importance to cloud physics that have contributed significantly to the contents of this book. Among them, Jerry Straka single-handedly worked out the 3-D prognostic cloud model that has been used profitably by others to produce many model-derived studies by Dan Johnson and Hsin-Mu Lin. Emily Hui-Chun Liu developed the cirrus model that we used to study the radiative impact of ice microphysics. The radiation code for this cirrus model was graciously provided by Dr. Dave Mitchell of the Desert Research Institute, at Reno, Nevada. Norman Miller, Wusheng Ji, and Mihai Chiruta contributed to the ice scavenging, ice flow fields, and ice capacitance, respectively. My colleague Bob Schlesinger, one of the pioneers in 3-D cloud modeling, has provided much valuable advice to our cloud model studies.

In 1993, I spent half a year in Mainz, Germany under the support of a Senior Research Award bestowed on me by the Alexander von Humboldt Foundation of Germany. During this time and later when I was invited back, I had fruitful exchanges with many scientists in the Department of Atmospheric Physics, University of Mainz, and the Max-Planck Institute for Chemistry, especially Professors Stephan Borrmann, Andrea Flossmann, Paul Crutzen, Ruprecht Jaenicke, Peter Warneck, and many other younger scientists.

I have been also benefited from extensive exchanges with Prof. Franco Prodi and Dr. Vincenzo Levizzani of the Institute of Atmospheric Sciences and Climate, National Research Council, Italy (ISAC-CNR), during my several visits to Bologna. Franco arranged support for my visits to Bologna, Ferrara and Venice. Franco's comment that "a book should deliver a vision" alerted me to re-examine the contents of this book more carefully in that respect. I also met Dr. Martin Setvak of the Czech Institute of Hydrometeorology (CHMI), Prague, Czech Republic, via Vincenzo and we have since had very active collaborations in thunderstorm research.

UW-Madison supported my sabbatical leaves to the Massachusetts Institute of Technology and the National Taiwan University. I was also supported by the National Science Council of Taiwan for several summer visits in Taiwan. This support contributed directly or indirectly to the contents of this book.

My research in cloud physics has been supported for a long time by grants sponsored by US National Science Foundation (NSF) to which I am very grateful. Other federal agencies including EPA, NASA, NOAA and DOE have also contributed substantially. In 1992, the Samuel C. Johnson Foundation of Racine, Wisconsin, conferred upon me a S. C. Johnson Distinguished Fellowship that afforded me additional support for my research.

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I am grateful to the American Meteorological Society and the American Geophysical Union for allowing researchers to reproduce figures and tables from their publications for use with academic books. Many fellow researchers have also generously granted permission for me to reproduce figures from their research and I have acknowledged their courtesy individually in the figure captions.

The publisher Cambridge University Press has played a big role in the production of this book. Although writing a cloud physics textbook had been in my mind for quite a while, it was Dr. Susan Francis of CUP who urged me several times to get it really started. Ms. Laura Clark, Abigail Jones, Kirsten Bot and Mr. Geoff Amor went through various aspects of the book production to make its completion so professionally done. Kai-Yuan Cheng and Dierk Polzin contributed by drawing or redrawing many figures.

Finally, I want to thank my wife Libby for her faithful support, without which the completion of this book could not have been achieved so smoothly.

Pao K. Wang
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