MICROPHYSICS OF CLOUDS AND PRECIPITATION

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HANS R. PRUPPACHER

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JAMES D. KLETT

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HANS R. PRUPPACHER

Department of Atmospheric Sciences, University of California, Los Angeles

and

JAMES D. KLETT

Los Alamos Scientific Laboratory, Los Alamos, New Mexico and Department of Physics, New Mexico Institute of Mining and Technology, Socorro

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PREFACE

Cloud physics has achieved such a voluminous literature over the past few decades that a significant quantitative study of the entire field would prove unwieldy. This book concentrates on one major aspect: *cloud microphysics*, which involves the processes that lead to the formation of individual cloud and precipitation particles.

Common practice has shown that one may distinguish among the following additional major aspects: *cloud dynamics*, which is concerned with the physics responsible for the macroscopic features of clouds; *cloud electricity*, which deals with the electrical structure of clouds and the electrification processes of cloud and precipitation particles; and *cloud optics* and *radar meteorology*, which describe the effects of electromagnetic waves interacting with clouds and precipitation. Another field intimately related to cloud physics is *atmospheric chemistry*, which involves the chemical composition of the atmosphere and the life cycle and characteristics of its gaseous and particulate constituents.

In view of the natural interdependence of the various aspects of cloud physics, the subject of microphysics cannot be discussed very meaningfully out of context. Therefore, we have found it necessary to touch briefly upon a few simple and basic concepts of cloud dynamics and thermodynamics, and to provide an account of the major characteristics of atmospheric aerosol particles. We have also included a separate chapter on some of the effects of electric fields and charges on the precipitation-forming processes.

The present book grew out of a series of lectures given to upper division undergraduate and graduate students at the Department of Atmospheric Sciences of the University of California at Los Angeles (UCLA), and at the Department of Physics of the New Mexico Institute of Mining and Technology at Socorro (New Mexico Tech.). We have made no attempt to be complete in a historical sense, nor to account for all the work which has appeared in the literature on cloud microphysics. Since the subject matter involves a multitude of phenomena from numerous branches of physical science, it is impossible to make such a book truly self-contained. Nevertheless, we have considered it worthwhile to go as far as possible in that direction, hoping thereby to enhance the logical structure and usefulness of the work. In keeping with this goal, our emphasis has been on the basic concepts of the field.

This book is directed primarily to upper division and graduate level students who are interested in cloud physics or aerosol physics. Since no specialized knowledge in meteorology or any other geophysical science is presumed, the material presented should be accessible to any student of physical science who has had the more or less usual undergraduate bill of fare which includes a general background in physics, physical chemistry, and mathematics. We also hope the book will be of value to those engaged in relevant areas of teaching and research; also, we hope it will provide a source of useful information for professionals working in related fields, such as air chemistry, air pollution, and weather modification.

In the preparation of this book we have incurred many debts. One of us (HRP) is extremely grateful to his long time associate Prof. A. E. Hamielec of McMaster University at Hamilton, Canada, whose generous support provided the basis for solving many of the nydrodynamic problems reported in this book. Gratitude is also gladly expressed to the faculty and research associates at the Meteorological Institute of the Johannes Gutenberg University of Mainz and at the Max Planck Institute for Chemistry at Mainz, in particular to Profs. K. Bullrich, C. Junge, and Drs. G. Hänel, F. Herbert, R. Jaenicke, and P. Winkler for the assistance received during two stays at Mainz while on sabbatical leave from UCLA. In addition, sincere thanks are extended to the Alexander von Humboldt Foundation for a U.S. Senior Scientist Award which made possible the second extended visit at Mainz. Also, one of us (JDK) is grateful to Drs. C. S. Chiu, P. C. Chen, and D. T. Gillespie for informative discussions, and to Prof. M. Brook and Dr. S. Barr for providing time away from other duties. Appreciation is expressed also to the National Center for Atmospheric Research (NCAR) for the assistance provided during a summer visit.

A large number of figures and tables presented in this book have been adapted from the literature. The publishers involved have been most considerate in granting us the rights for this adaptation. In all cases, references to sources are made in the captions.

Our own research reported in this book has been supported over the years by the U.S. National Science Foundation. We would like to acknowledge not only this support, but also the courteous, informal, and understanding manner in which the Foundation's Officers, Drs. F. White, P. Wyckoff, E. Bierly, and F. Eden, conducted their official business with us.

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Los Angeles,
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H. R. PRUPPACHER
J. D. KLETT

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CHAPTER 1

HISTORICAL REVIEW

As one studies the meteorological literature, it soon becomes evident that cloud microphysics is a very young science. In fact, most of the quantitative information on clouds and precipitation, and the processes which are involved in producing them, has been obtained since 1940. Nevertheless, the roots of our present knowledge can be traced back much further. Although a complete account of the development of cloud physics is not available, a wealth of information on the history of meteorology in general can be found in the texts of Middleton (1965), Schneider-Carius (1962, 1955), and Humphreys (1942, 1937). Based on these and other sources we shall sketch here some of the more important events in the history of cloud physics. In so doing we shall be primarily concerned with developments between the 17th century and the 1940's, since ideas prior to that time were based more on speculation and philosophical concepts than scientific fact. As our scope here is restricted to west European and American contributions, we emphasize again that no claims for completeness are made.

It was apparently not until the 18th century that efforts were underway in Europe to give names to the characteristic forms of the clouds. Lamarck (1744–1829), who realized that the forms of clouds are not a matter of chance, was probably the first to formulate a simple cloud classification (1802); however, his efforts received little attention during his lifetime. Howard (1772–1864), who lived almost contemporaneously with Lamarck, published a cloud classification (1803) which, in striking contrast to Lamarck's, was well received and became the basis of the present classification. Hildebrandson (1838–1925) was the first to use photography in the study and classification of cloud forms (1879), and may be regarded as the first to introduce the idea of a cloud atlas (an idea beautifully realized much later by the International Cloud Atlas I, II (1956) of the World Meteorological Organization, and by the Cloud Encyclopedia of Scorer (1972), where a full description is given of the major genera, species, and varieties of atmospheric clouds).

Both Lamarck and Howard believed the clouds they studied consisted of water bubbles. The bubble idea was originated in 1672 by von Guericke (1602–1686), who called the small cloud particles he produced in a crude expansion chamber 'bullulae' (bubbles). Although he explicitly named the larger particles in his expansion chamber 'guttulae' (drops), the bubble idea, supported by the Jesuit priest Pardies (1701), prevailed for more than a century until Waller (1816–1870) reported in 1846 that the fog particles he studied did not burst on impact, as bubbles would have. Although this observation was confirmed in 1880 by Dines (1855–1927), it was left to Assmann (1845–1918) to finally end the dispute through the authority of his more comprehensive studies of cloud droplets under the microscope (1884).

The first attempt to measure the size of fog droplets with the aid of a microscope was made by Dines in 1880. Some early measurements of the size of the much larger raindrops were made by ingeniously simple and effective means. For example, in 1895 Wiesner (1838–1916) allowed raindrops to fall on filter paper impregnated with water-soluble dye and measured the resulting stains. A little later, Bentley (1904) described an arrangement in which drops fell into a layer of flour and so produced pellets whose sizes could easily be measured and related to the parent drop sizes.

The elegant geometry of solid cloud particles has no doubt attracted attention from the earliest time. A woodcut done in 1555 by Olaus Magnus, Archbishop of Upsala, represents one very early attempt to depict a snow crystal. Kepler (1571–1630) was also intrigued by the forms of snow crystals and asked the question "Cur autem sexangula?" ("But why are they six-sided?"). Descartes (1596–1650) was perhaps the first to correctly draw the shape of some typical forms of snow crystals (1635). Hooke (1635–1703) first studied the forms of snow crystals under a microscope. Scoresby (1789–1857), in his report on arctic regions (1820), presented the first detailed description of a large number of different snow crystal forms and noticed a dependence of shape on temperature. Further progress was made when Neuhaus (1855–1915) introduced microphotography as an aid in studying snow crystals. These and earlier studies on the shape of snow crystals were summarized and critically discussed by Hellmann (1854–1939). Hellmann also pointed out in 1893 that snow crystals have an internal structure, which he correctly attributed to the presence of capillary air spaces in ice. The most complete collections of snow crystal photomicrographs were gathered by Bentley in the U.S. (published by Humphreys in 1931), and during a life's work by Nakaya in Japan (published in 1954).

It was also realized early that not all ice particles have a six-fold symmetry. However, before the turn of the 18th century, interest in the large and often quite irregular shaped objects we now call hailstones was apparently restricted to their outward appearance only. Volta (1745–1827) was among the first to investigate their structure, and in 1808 he pointed out that hailstones contain a 'little snowy mass' at their center. In 1814 von Buch (1774–1853) advocated the idea that hailstones originate as snowflakes. This concept was further supported by Waller and Harting (1853), who investigated sectioned hailstones under the microscope. In addition to finding that each hailstone has a center which, from its appearance, was assumed to consist of a few closely-packed snowflakes, they discovered that hailstones also have a shell structure with alternating clear and opaque layers, due to the presence of more or less numerous air bubbles.

All known observations of cloud and precipitation particles were made at ground level until 1783, when Charles (1746–1823) undertook the first instrumented balloon flight into the atmosphere. Although frequent balloon flights were made from that time on, they were confined mostly to studies of the pressure, temperature, and humidity of the atmosphere, while clouds were generally ignored. The first comprehensive study of clouds by manned balloon was conducted by Wigand (1882–1932), who described the in-cloud shape of ice crystals and graupel particles (snow pellets or small hail) in 1903.

Attempts to provide quantitative explanations of the processes of cloud particle formation came relatively late, well into the period of detailed observations on individual particles. For example, in 1875 Coulier (1824–1890) carried out the first crude expansion chamber experiment which demonstrated the important role of air-suspended dust particles in the formation of water drops from water vapor. A few years later, Aitken (1839–1919) became the leading advocate of this new concept. He firmly concluded from his experiments with expansion chambers in 1881 that cloud drops form from water vapor only with the help of dust particles which act as *nuclei* to initiate the new phase. He categorically stated that "without the dust particles in the atmosphere there will be no haze, no fog, no clouds and therefore probably no rain." The experiments of Coulier and Aitken also showed that by progressive removal of dust particles by filtration, clouds formed in an expansion chamber became progressively thinner, and that relatively clean air would sustain appreciable vapor supersaturations before water drops appeared. The findings of Coulier and Aitken were put into a more quantitative form by Wilson (1869–1959), who showed in 1897 that moist air purified of all dust particles would sustain a supersaturation of several hundred percent before water drops formed spontaneously. This result, however, was already implicitly contained in the earlier theoretical work of W. Thomson (the later Lord Kelvin, 1824–1907), who showed that the equilibrium vapor pressure over a curved liquid surface may be substantially larger than that over a plane surface of the same liquid (1870).

As soon as experiments established the significant role of dust particles as possible initiators of cloud drops, scientists began to look closer at the nature and origin of these particles. Wilson followed up his early studies with dust-free air and discovered in 1899 that ions promote the condensation process, a result which had been predicted theoretically in 1888 by J. J. Thomson (1856–1940). However, it was soon realized that the supersaturations necessary for water drop formation on such ions were much too large for them to be responsible for the formation of atmospheric clouds. Aitken (1880), Welander (1897), and Lüdeling (1903) suggested that the oceans inject hygroscopic salt particles into the atmosphere, which may then serve as condensation nuclei. The great importance of such particles was also realized by Köhler (1888–   ), who pointed out that the presence of large numbers of hygroscopic particles generally should prevent large supersaturations from occurring in clouds. In addition, Köhler was the first to derive a theoretical expression for the variation of the vapor pressure over the curved surface of an aqueous solution drop (1921, 1922, 1927). His pioneering studies became the foundation of our modern condensation theory.

Although the significance of oceans as a source of condensation nuclei was by now clearly recognized, Wigand's observations (1913, 1930) suggested that the continents, and not the oceans, are the most plentiful source. Wigand's conclusions (1934) were supported by the studies of Landsberg (1906–) and Bossolasco (1903–).

Lüdeling (?) and Linke (1878–1944) were probably the first to determine the concentration of condensation nuclei in the atmosphere (1903, 1904). However, it was Wigand who, during balloon flights from 1911 to 1913, first carried out detailed studies of condensation nuclei concentrations at different levels in the atmosphere as a function of various meteorological parameters. He discovered that their concentration was related to the temperature structure in the atmosphere, and was significantly different inside and outside clouds. On comparing the concentrations of condensation nuclei and cloud drops, Wigand concluded that there are sufficient numbers of condensation nuclei in the atmosphere to account for the number of drops in clouds.

Studies during the same period brought out the fact that dust particles also play an important role in the formation of ice crystals. Thus, those researchers who ascended into clouds with instrumented balloons found ice crystals at temperatures considerably warmer than the temperatures to which Fahrenheit (1686–1736) had supercooled highly purified water in the laboratory. On the other hand, in view of the large number of condensation nuclei found in the atmosphere, they were also surprised to find that often clouds consisted largely of supercooled drops rather than ice crystals, even though they reached heights where the temperature was considerably below 0 °C. This implied that apparently only a small fraction of the dust particles present acted as ice-forming nuclei. Wegener (1880–1931) suggested that water drops form on water-soluble, hygroscopic nuclei while ice crystals form on a selected group of dust particles which must be water-insoluble. From his observations during a Greenland expedition (1912–1913), he concluded that ice crystals form as a result of the direct deposition of water vapor onto the surface of ice-forming nuclei. He therefore termed this special group of dust particles 'sublimation nuclei.' Wegener's mechanism of ice crystal formation by direct vapor deposition was also advocated by Findeisen (1909–1945). On the other hand, Wigand concluded from his balloon flights that ice crystal formation is often preceded by the formation of supercooled water drops, which subsequently freeze as a result of contact with water-insoluble dust particles. Other arguments against a sublimation mechanism for the formation of ice crystals were brought forward by Krastanow in 1936, who demonstrated theoretically that the freezing of supercooled drops is energetically favored over the formation of ice directly from the vapor.

While all these studies provided some answers concerning why and how clouds come into being, they did not provide any clues as to why some clouds precipitate and others do not. One of the first precipitation theories was formulated in 1784 by Hutton (1726–1797). He envisioned that the cloud formation requisite to precipitation is brought about by the mixing of two humid air masses of different temperatures. The microphysical details of the apportioning of the liquid phase created by this cooling process were not considered. The meteorologists Dove (1803–1879) and Fitz Roy (1805–1865) evidently were in favor of his theory, since it seemed to predict the observed location of rain at

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