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978-1-107-01603-3 — Thermodynamics, Kinetics, and Microphysics of Clouds
Vitaly I. Khvorostyanov , Judith A. Curry
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Introduction

1.1. Relations among Thermodynamics, Kinetics, and Cloud Microphysics

The most distinctive feature of the Earth when viewed from space is the presence of clouds covering approximately 60% of its surface area. Clouds are a major factor in determining the Earth's radiation budget, by reflecting shortwave radiation and emitting longwave radiation. Through their ability to precipitate, clouds provide virtually all of the fresh water on Earth. Clouds are associated with some of the most damaging weather in the world: torrential rains, severe winds and tornadoes, hail, thunder and lightning, and snowstorms. The latent heat released in clouds is an important source of energy for scales of motion ranging from the global atmospheric circulation, to hurricanes and mid-latitude cyclones, to individual storms. Clouds are also important in atmospheric chemistry because they play an active role in many chemical reactions and transport chemicals through updrafts and scavenging associated with precipitation.

A major challenge in understanding and modeling clouds is the broad range of spatial scales involved. The scales range from the micron scale of individual cloud drops, to the scale of an individual cloud (kilometers), up to the scale of the largest cloud systems (1000 km). Our present computational capability allows only a small range of spatial scales to be simulated explicitly in a single model; processes on the other scales are either specified or parameterized.

Cloud microphysics addresses processes at the smallest of these scales associated with the initiation, growth, and dissipation of cloud and precipitation particles. Some of the most challenging issues in cloud microphysics are associated with interactions between aerosol particles and cloud particles. These interactions include heterogeneous nucleation of liquid and ice particles, homogeneous ice nucleation, rates of water adsorption onto growing particles, the number concentration and size distribution of a population of cloud particles, and the likelihood that the cloud will form precipitation-sized particles. The influence of aerosols on cloud processes moulds cloud optical properties directly through determination of the size and phase of cloud particles, and they indirectly influence radiative transfer through determination of whether or not the cloud precipitates, and thereby determines cloud lifetime. Cloud microphysical processes are intimately connected with cloud dynamical processes associated with air motions on a range of scales, and through latent heat release and precipitation-induced downdrafts, cloud microphysical processes influence cloud dynamics. An understanding of cloud–aerosol interactions and ice nucleation has a direct application to weather modification through cloud seeding.

This book focuses on cloud microphysics processes in the context of providing a systematic and unified theoretical treatment of the thermodynamics and kinetics of cloud microphysical processes. Thermodynamics is a branch of theoretical physics that studies the properties of thermodynamic systems in states of thermodynamic equilibrium and during transitions from one equilibrium state to the other.

Physical kinetics is a branch of theoretical physics that considers the processes in systems that are brought to a non-equilibrium state by external forces. One of the major premises of physical kinetics is an assumption that local thermodynamic equilibrium is reached sufficiently fast in small subdomains of the system (even though they contain a large number of particles), while the overall system is in a non-equilibrium state. The microscopic method in physical kinetics describes the processes in non-equilibrium states using distribution functions for various variables and solving kinetic equations for them. The first kinetic equation was formulated by Ludwig Boltzmann in 1872 for the kinetic theory of gases, which has served as a prototype for other numerous kinetic equations for various processes, including the kinetic equations of coagulation and diffusion particles growth that are considered in this book.

A cloud consisting of many drops and/or crystals surrounded by water vapor and other gases comprises a thermodynamic system. Some microphysical processes in this system have small relaxation times for adjustment to an equilibrium state, and these subsystems can be considered in thermodynamic equilibrium. For example, the vapor and temperature fields around a growing or evaporating particle adjust almost instantaneously to the equilibrium state; nucleation of drops and crystals usually occurs at conditions close to thermodynamic equilibrium. Thus, the properties of nucleating particles can be evaluated from thermodynamic equilibrium equations.

Other microphysical processes (e.g., the diffusion and coagulation growth of drops and crystals) have longer durations, the systems remain in non-equilibrium, and the evolution of their microphysical properties can be considered using kinetic equations for drops and crystals distribution functions. Thus, microphysical processes in clouds can be considered to be a combination of thermodynamic equilibrium processes and kinetic non-equilibrium processes, depending on the system state.

1.2. The Correspondence Principle

There are many different parameterizations of various cloud microphysical processes and properties used in atmospheric models: deliquescence of cloud condensation nuclei (CCN) and hygroscopic growth; the activation of CCN into drops; homogeneous and heterogeneous ice nucleation; critical humidities for ice nucleation; terminal velocities; the size spectra of drops and crystals (e.g., gamma or exponential distributions) and their moments; and so on. Most of these parameterizations are based on fits to experimental data, and their parameters may depend on specific observations, air mass, or aerosol samples. Some of these empirical parameterizations extend and develop previous empirical parameterizations, but many suggest newer expressions or newer parameter values. The correspondence between the new and old parameterizations is often unclear. This creates uncertainty in the choice of the optimum parameterizations for atmospheric models, which may lead to uncertainty in the model simulation results. These uncertainties could be diminished if these parameterizations could be derived from the theory and their parameters expressed via the atmospheric and aerosol properties.

A framework for pursuing this strategy is the *correspondence principle*, which is one of the major principles in physics. The correspondence principle was formulated by Niels Bohr between 1913 and 1920 while developing his model of the atom and was later generalized in order to explain the correspondence to, and remove the contradictions between, the new quantum mechanics and the old classical physics. Subsequently, the correspondence principle has been generalized over several decades and extended to other phenomena in physics and other sciences. The correspondence

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principle states that a new theory or parameterization should not reject the previous correct theory or parameterization but rather generalize them, so that the old (previous) theory becomes a particular case of the new theory. The new theory or parameterization contains a new parameter absent in the previous theory; when its value tends to some limiting value, the new theory transforms into the old theory. While the formulation of the correspondence principle is simple, it is nevertheless a very powerful methodological tool in understanding natural phenomena and developing correct generalizations of the existing theories and parameterizations. An important consequence of the correspondence principle is that a newer theory should be able to express the empirical parameters of the previous theories or parameterizations via the physical constants. The historical applications of the correspondence principle are beyond the scope of this book. Here, we emphasize that: When developing a new theory or parameterization, one should attempt to generalize previous theories and express the empirical parameters via physical quantities. One of the major goals of this book is to describe and develop further the theories that derive and generalize the known parameterizations of cloud microphysics, and to express the empirical parameters via the parameters of the theory and fundamental atmospheric constants. The correspondence principle provides an integrating framework for this book, and many examples of correspondence between the older and newer theories and parameterizations are described.

1.3. Structure of the Book

Chapter 2 is devoted to the general description of the global cloudiness and its major properties. Cloud microphysical properties are defined and their characteristics are given. Mathematical formulations are reviewed for various size spectra and their moments used for parameterization of cloud and aerosol microphysical and optical properties: inverse power laws, generalized and ordinary gamma distributions, lognormal distributions and their equivalent—algebraic distributions. Analytical methods for evaluation of the moments of the distributions are described. A brief review is given of cloud optical properties, as well as various parameterizations of their dependence on cloud microstructure. Methods for evaluation of the extinction, scattering, and absorption coefficients are described for polydisperse ensembles of drops and crystals.

Chapter 3 is devoted to the general description of the thermodynamic potentials and relations that are used in the subsequent chapters. Five statistical energy distributions are described: the Gibbs distribution, and its four particular cases—the Maxwell, Boltzmann, Bose–Einstein, and Fermi–Dirac distributions. Phase rules are formulated for bulk phases including systems with curved interfaces. The equations of state for ideal and non-ideal gases are derived. Basic thermodynamic characteristics of solutions are introduced, and their thermodynamic relations are described. A general equilibrium equation (entropy equation) is derived, which serves as a basis for derivation of the following equations: the Clausius–Clapeyron equation for various interface systems (liquid and ice in bulk, water drop and vapor, ice crystal and vapor), the Kelvin equation, and the Köhler equation.

The following thermodynamic properties of gas mixtures and solutions are derived: partial gas pressures in a mixture of gases; equilibrium of two bulk phases around a phase transition point; Raoult's law; freezing point depression and boiling point elevation, and the relation of water activity and freezing point depression. Equations are developed for dry and wet adiabatic processes that serve as a platform for constructing Lagrangian parcel and Eulerian multidimensional cloud models.

The properties of water and aqueous solutions, and their parameterizations, are considered in Chapter 4. Various forms of water are described, including those that form at very low temperatures and high pressures (liquid water, crystalline ices, and amorphous forms of water and ice), along with possible transitions among them. Modern theories of water are reviewed, including stability limit conjecture, singularity free theory, and the theories based on a hypothesis of the second critical point. The temperature and pressure ranges in the clouds of Earth and on other planets of our solar system are described. The equivalence of pressure and solution effects in aqueous solutions is also discussed. A compact review is given of existing parameterizations of some basic water and ice thermodynamic properties (saturated vapor pressures, surface tensions, heat capacities, heats of phase transitions, etc.).

Various equations of state for ice and liquid water are reviewed, including the Einstein-Debye thermodynamic equations of state for ice, modern equations of van der Waals type, equations of state for ice based on the Gibbs function and for fluid water based on the Helmholtz function and based on the concept of the second critical point.

In Chapter 5, the diffusion and coagulation growth of drops and crystals is examined. The equations for the growth rates of individual drops and of crystals are derived. The equations account for the effective diffusion coefficients, kinetic corrections, psychrometric corrections due to latent heat release, and ventilation corrections, and are formulated in a convenient factorized form as a product of the terms describing these factors and are valid in a wide range of diffusion growth rates from diffusion to kinetic limits.

Calculations of drop and crystal diffusion growth require supersaturation equations. A detailed derivation of the general equations for the fractional water and ice supersaturations is given from the heat and vapor balance equations. The supersaturation absorption or relaxation times for drops and crystals are introduced, which are the major scaling times of supersaturation absorption at condensation in clouds or the supersaturation release at evaporation. General mathematical expressions are derived for the relaxation times, including their diffusion and kinetic limits. The supersaturation equations are presented in various forms that can be convenient for various models or parameterizations. In particular, the quasi-equilibrium supersaturations over water and ice are obtained for mixed-phase, liquid, and crystalline clouds that can be used in many cases in the models of all scales instead of the saturation adjustment method. Kinetic equations of condensation and deposition in the adiabatic process are derived, their analytical solutions in terms of the integral supersaturation are obtained for arbitrary values of the condensation coefficients in the wide range of particle growth rates, and the diffusion and kinetic limits of the solutions are found.

Chapter 6 examines aerosol hygroscopic growth and drop activation from cloud condensation nuclei (CCN). Reviews are given of the existing empirical and semi-empirical parameterizations of these processes and of the Köhler theory and its subsequent modifications. Hygroscopic growth of mixed aerosol particles and activation of CCN are considered based on a modification of the Köhler theory without the assumption of a dilute solution in CCN and using a newer parameterization of a soluble CCN fraction that can be proportional to the volume or surface of CCN. New analytical expressions are derived for the equilibrium radius of the wet aerosol in a cloudless atmosphere, and in clouds, and for the critical radii and supersaturations for CCN activation. These expressions generalize the known equations of the Köhler theory and are valid not only for diluted solutions but for arbitrary insoluble fractions and for both volume-distributed soluble fractions and soluble shells

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on the surface of an insoluble core (e.g., mineral dust particle). The accuracy and the regions of applicability of the classical expressions are clarified by the new solutions. Based on these new expressions for the wet radii, a general but simple method is derived for calculation of the wet aerosol size spectrum from the dry aerosol size spectrum. A general method is developed for transformation of the CCN size spectra into differential CCN activity spectra by supersaturations using the equations for the critical radii. Droplet concentrations are calculated by integration over supersaturations of the differential CCN activity spectra. A generalized power law for droplet concentration is derived that includes Twomey's power law as a limiting case, provides physically based expressions for Twomey's parameters, and ensures finite drop concentrations limited by CCN concentration at any large supersaturation.

The kinetics of drop formation in clouds is considered in Chapter 7. To study the kinetics of drop nucleation in clouds, the integro-differential equation for integral water supersaturation in a cloud is derived and analyzed. Solving the supersaturation equation using the algebraic form of the cloud condensation nuclei (CCN) activity spectrum yields analytical expressions for the time of the CCN activation process, the maximum supersaturation, and droplet concentration. All three quantities are expressed as functions of the vertical velocity and characteristics of the CCN size spectra (mean geometric radius, dispersion, and parameters of solubility). Analytical expressions for droplet concentration are found as algebraic functions of maximum supersaturation and as a generalized quasi-power law, and are limited by the total CCN concentration at high supersaturations.

The kinetics of drop activation and the effects of aerosol properties and dynamics on drop concentration are studied using two new methods based on numerical and analytical solutions. In the numerical method, a simple and fast numerical algorithm and solution were developed that allow users to obtain all these characteristics rapidly without running of extensive simulations using parcel models. Analytical expressions are obtained for the time of CCN activation, maximum supersaturation, and the concentration of activated droplets. Solutions are found for these parameters that are the products of power laws by 6 variables: CCN concentration, mean radius, soluble fraction, vertical velocities, surface tension, and condensation coefficient. The solution includes 4 limits: one is a generalization of Twomey's power law, and the other 3 limits are new.

In Chapter 8, the homogeneous nucleation of drops and crystals is considered. Using the concept of metastable states, the Fokker–Planck and Frenkel–Zeldovich kinetic equations are derived for the size distribution function of the germs of a new phase. Based on thermodynamic principles and extending further classical nucleation theory, general equations for the critical germ radius, free energy, and the nucleation rates are derived for homogeneous ice nucleation that express these properties as functions of temperature, water saturation ratio, pressure, and the finite size of freezing particles simultaneously. It is shown that the new expressions generalize and unify previously derived equations and empirical parameterizations, and include them as particular cases.

Using these equations of extended classical nucleation theory, critical freezing and melting temperatures of homogeneous freezing are derived as functions of saturation ratio, and critical saturation ratios over water and ice are derived as a function of temperature. These equations explain, generalize and unify existing empirical parameterizations, express their parameters via the atmospheric and aerosol properties, and outline the limits of their applicability. A simple nonlinear equation is obtained for the liquidus curves, and an analytical relation is found between the freezing and melting point depressions. A simple quantitative expression is derived that establishes equivalence of the

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solution and pressure effects on freezing, that is in good agreement with observed relations. The empirical water activity shift method is derived from the classical theory and its limitations are studied. The kinetics of homogeneous ice nucleation is evaluated at various temperatures, aerosol concentrations, and vertical velocities using parcel model simulations and the new equations for the critical energies and nucleation rates. Simultaneous account for the temperature and supersaturation effects on the nucleation rates produces very strong negative feedback that allows nucleation into crystals of only a very small fraction of deliquescent haze particles.

A new parameterization of homogeneous ice nucleation for the models is developed based on extended classical nucleation theory, whereby the critical energies and nucleation rates are presented in a separable form as a product of the functions of temperature, supersaturation, and vertical velocities. Limits of these equations are found for the diffusion and kinetic regimes of crystal growth, which allows its application for pure and polluted clouds.

Chapter 9 is devoted to heterogeneous nucleation of drops and ice crystals. Nucleation of drops by vapor deposition on water-insoluble particles is considered; the critical radii, energies, and nucleation rates are derived; and the shape factor is introduced. The four basic modes of heterogeneous ice nucleation on ice nuclei (deposition, deliquescence-freezing, immersion, and contact) are described, along with the properties of ice nuclei (IN). A review is given of existing empirical and semi-empirical parameterizations of heterogeneous ice nucleation. Nucleation of crystals in the deposition mode on water-insoluble particles is considered in detail. The major focus of this chapter is on the deliquescence-freezing and immersion-freezing modes. Through further developing classical nucleation theory, equations are derived for the ice germ critical radius, energy and nucleation rate of ice crystals as functions of temperature, water saturation ratio, droplet radius, external pressure, and misfit strain between ice and insoluble substrate crystalline lattices. These equations generalize and unify the previous expressions found for the critical germ radius and energy. The expressions for the critical energy and nucleation rate are presented in the separable form as a product of the function depending on temperature and supersaturation. This unification and separable representation of the temperature and supersaturation dependencies provide a physical basis for existing empirical parameterizations of crystal concentrations as functions of temperature or supersaturation or combined parameterizations and allow further a rigorous theoretical derivation of the combined parameterization.

The equations are derived from classical nucleation theory for the critical freezing and melting temperature as a function of saturation ratio, drops size, pressure, misfit strain, and active sites. Derivation is given for the cases of volume heterogeneous freezing, surface quasi-heterogeneous freezing, and surface quasi-heterogeneous melting. It is found that a simple nonlinear equation for liquidus curves, which describes the freezing and melting point depressions, is a particular limiting case of these equations for the infinitesimally small nucleation rates. Critical saturation ratios or water activities of heterogeneous freezing are derived as functions of temperature, drops size, pressure, misfit strain, and active sites, and the empirical water activity shift method for heterogeneous nucleation is derived from classical nucleation theory. The derived critical energies and nucleation rates of heterogeneous nucleation are applied and verified in parcel model simulation of a mixed-phase cloud in a wide range of temperatures, aerosol concentrations, and vertical velocities. The kinetics of ice nucleation and cloud glaciation are studied in detail. A semi-empirical parameterization of the final concentrations of nucleated crystals is found as a function of temperature and vertical velocities. The simulation results are compared with analogous simulations of homogeneous freezing described in Chapter 8, which reveal the similarities and differences between heterogeneous and homogeneous nucleation. The thermodynamic constrains on the empirical parameterizations are considered.

In Chapter 10, parameterizations of heterogeneous ice nucleation suitable for use in cloud and climate models with large time and space steps are derived from extended classical nucleation theory. Considering heterogeneous freezing of haze particles and drops, the critical energies and nucleation rates are presented in a separable form as a product of the functions of temperature, supersaturation, active site parameter, and vertical velocity. Integrating this nucleation rate over time and solving the integral supersaturation equation yields a new equation for the crystal concentrations as the function of temperature, critical or maximum supersaturation, vertical velocity, and a few fundamental constants. It is shown that the new equations generalize and unify several previous empirical and semi-empirical parameterizations, reduce them in some particular cases, and express their empirically determined parameters via the atmospheric and aerosol properties and fundamental constants. The limits of these equations are found for the diffusion and kinetic regimes of crystal growth, which allows its application for pure and polluted clouds. These parameterizations of heterogeneous freezing are compared with the analogous parameterizations of homogeneous freezing, and the differences are described quantitatively. Similar parameterizations are developed for deposition ice nucleation and for immersion drop freezing near water saturation. Contact ice nucleation is described: its general properties, the three major mechanisms of aerosol scavenging by drops that may lead to contact nucleation (Brownian diffusion, thermophoresis, and diffusiophoresis), the collection rates, probabilities of freezing, and scavenging in polydisperse ensembles of drops and aerosols.

Chapter 11 considers the phenomena of deliquescence and efflorescence in atmospheric aerosols. The general properties of these processes are described, and previous theories and models of deliquescence and efflorescence are reviewed. New models of deliquescence and efflorescence are developed based on extensions of classical nucleation theory that are applied to salt crystallization in solutions. Using the general equilibrium equation, expressions are derived for the critical radii, energies, and nucleation rates of liquid germs on the surface of a particle at deliquescence, and the critical radii, energies, and nucleation rates of the salt crystallization germs in supersaturated solutions. These models are applied to analytical derivations and calculations of the temperature dependencies of the dissolution heat and solubility, and to the temperature dependence of the deliquescence relative humidity. The results are compared with experimental data and good agreement is found. Application of the efflorescence model to salt crystallization, along with the ice nucleation model, allows calculation of the location of the eutectic point in solution and the right branch with salt crystallization on the phase diagram of solutions. These calculations are combined with calculations of the freezing temperatures and a unified phase diagram of solutions is plotted, where all four branches (deliquescence, efflorescence, freezing, and melting curves) are calculated based on a unified basis using extended classical nucleation theory.

Chapter 12 presents a unified treatment of cloud particle fall velocities for both liquid and crystalline cloud particles over the wide size range observed in the atmosphere. A review is given of previous theories and parameterizations of particle fall velocities. The representation in this book is formulated in terms of the Best (or Davies) number, X, and the Reynolds number, Re. The fall velocities are represented as generalized power laws. The coefficients of the power laws for the

Re-X relation and for the fall velocities are found as the continuous analytical functions of X or particle diameter over the entire hydrometeor size range, which makes this method convenient in applications. The turbulent corrections for the drag coefficients and terminal velocities are derived. Analytical asymptotic solutions are obtained for the coefficients of generalized power laws for the two regimes that represent large and small particles and correspond to potential and aerodynamic flows, respectively. The analytical temperature and pressure corrections for the wide size ranges are derived and compared with previous parameterizations. The expressions for Re-X relation and drag coefficients are applied to spherical and non-spherical drops, as well as several crystal habits, with special attention paid to the turbulent corrections.

Chapter 13 considers stochastic condensation in clouds and formation of the broad size spectra of drops and crystals. An extended review is given of various mechanisms that were suggested to explain existence of the broad size spectra in clouds at all stages of their development. A new version of the kinetic equation for stochastic condensation for the small-size fraction of drops and crystals spectra is derived that is valid for arbitrary relative values of Lagrangian turbulent time and supersaturation relaxation time. Analytical solutions are obtained under a number of assumptions. For this purpose, a model of the condensation process in a turbulent cloud (stochastic condensation) is developed and the Reynolds procedure is applied to the regular and fluctuation parts of all the quantities yielding an equation in terms of covariances, which are incorporated into a kinetic equation to yield the final kinetic equation of stochastic condensation. Particular cases of low-frequency and high-frequency approximations are examined.

Using a few basic assumptions and simplifications, various analytical solutions are obtained for the small-size fraction. Neglecting the diffusional growth of larger particles, solutions have the form similar to the gamma distributions. Their indices that determine the breadth of the spectra and the rates of coagulation and precipitation formation are expressed via atmospheric properties and fundamental constants. Other solutions are obtained in the form of the generalized gamma distributions for the cases, including the diffusional growth of large particles, sedimentation, and coagulation with the large fraction when these processes are important. Finally, based on the integral Chapman–Kolmogorov equation for stochastic processes, a general integral stochastic kinetic equation is formulated. Using this equation, the differential Fokker–Planck equation for stochastic condensation is derived, and various versions of the kinetic equations considered in this chapter are shown to be particular cases of this Fokker–Planck equation.

Chapter 14 is devoted to analytical solutions to the stochastic kinetic equation of coagulation and formation of the large-size fractions of the drop and crystal size spectra for precipitating clouds. The kinetic equation of coagulation in approximation of continuous collection is derived from the general coagulation equation, and the corresponding assumptions are discussed. Then, the basic stochastic integral kinetic equation is simplified and reduced to a differential equation. The analytical solutions to this equation are obtained for various cases in various forms that are similar to the gamma distributions, exponential Marshal–Palmer and inverse power law size spectra that have been determined empirically. Finally, it is shown that the coagulation equation represents a particular case of the integral Chapman–Kolmogorov equation and can be presented also as the differential Fokker–Planck equation. Possible ways of generalization of the kinetic equations are outlined.

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Clouds and Their Properties

2.1. Cloud Classification

Clouds represent the large visible ensembles of drops or crystals suspended in the gaseous atmosphere. Clouds in the Earth's atmosphere result from the condensation or deposition of water vapor. Clouds on other planets may result from the condensation of the other gases. For example, clouds on Venus may consist of sulfuric acid drops, some clouds on Mars may consist of CO_2 ice crystals, and the clouds on Jupiter may consist of H_2O–NH_3 drops and CH_3 ice crystals (e.g., Curry and Webster, 1999). Hereafter, we consider the Earth's water clouds, although most of the equations in this book can be applied with appropriate modifications to the clouds of other substances on other planets.

Numerous studies of the condensation process have shown that condensation occurs when the water vapor pressure slightly exceeds the saturated vapor pressure, or is *supersaturated*—i.e., the relative humidity slightly exceeds 100%. At the same time, it is known that the relative humidity near the ground is most often 40–80%, decreases upward, and is 2–3 times smaller at the level of the tropopause. Therefore, cloud formation requires a mechanism that increases the relative humidity to ≈100%. Cloud formation mechanisms include cooling due to vertical uplift (*convection*) or radiative cooling, horizontal transport (*advection*) of heat and moisture, or the mixing of air masses. There is a great variety of conditions and motions in the atmosphere that lead to cloud formation, which results in a diversity of cloud properties and appearances.

Various classifications of clouds are used in meteorological literature. *Classification by levels* is based on sorting clouds by the heights of their locations in the troposphere, and clouds are classified as upper-, middle-, and low-layer clouds, and clouds of vertical development that have significant vertical extension. *Classification by temperature* defines a cloud as warm if the entire cloud is warmer than 0 °C; otherwise, the cloud is classified as cold. The similar *classification by phase state* characterizes clouds as liquid, mixed-phase, or ice clouds.

The most commonly used cloud classification is based on the morphology of the cloud as defined by its appearance as seen by a ground-based observer. This classification is adopted in the International Atlas of Clouds developed and published by the World Meteorological Organization (WMO, 1975, 1987). This classification is tree-like (branched), similar to biological classifications of animals and plants, and classifies the clouds using Latin names. The classification defines ten main groups called *genera*, which are subdivided into *species* determined by the cloud shapes or internal structure, and in turn, are subdivided into varieties determined by some specific features within a species—e.g., the transparency or shapes of the boundaries.

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Upper-level clouds are often called *cirriform clouds*. These clouds form at very low temperatures, generally below −40 °C, are mostly pure crystalline, and contain ice crystals of numerous forms. Cirriform clouds often form in the front upper parts of atmospheric fronts just below the tropopause when a warm air mass lifts above the cold air mass. Therefore, cirriform clouds often serve as indicators of changing weather or approaching storms. Three of the 10 genera defined in the International Atlas of Clouds as cirriform clouds are:

***Cirrus* (*Ci*)**—Detached clouds in the form of white, delicate filaments, or white or mostly white patches or narrow bands. These clouds have a fibrous (hairlike) appearance, or a silky sheen, or both. The height of cirrus cloud bases is typically 7–10 km in the midlatitudes, and reaches 18 km in the tropics. Precipitation from these clouds forms bands of small crystals but they do not reach the ground.

***Cirrocumulus* (*Cc*)**—Thin white patches, sheets, or layers of cloud without shading, composed of very small elements in the form of grains or ripples, merged or separate, and more or less regularly arranged. The cloud base is 6–8 km in the midlatitudes, and the cloud thickness is typically 0.2–0.4 km.

***Cirrostratus* (*Cs*)**—Transparent whitish cloud veils with a fibrous (hair-like) or smooth appearance that totally or partially cover the sky, and generally produce a halo phenomena. The cloud base is 6–8 km in the midlatitudes, and can be much lower in the polar regions; the cloud thickness ranges from 0.1 to 3 km. Their precipitation usually does not reach the ground.

A detailed description of various properties of cirriform clouds is given in Cirrus (2002).

The two genera classified as **middle-level clouds** are:

Altocumulus (***Ac***)—White or grey, or both white and grey, patches, sheets, or layers of cloud, generally with shading, and composed of laminae, rounded masses, or rolls, which are sometimes partially fibrous or diffuse and which may or may not be merged. The cloud base is 2–6 km in the midlatitudes, and the cloud thickness ranges from 0.2–0.7 km. Its precipitation may reach the ground as raindrops or snow crystals. There are 2 species of Ac: wave-like (*Ac undulatus, Ac und*) and convective-like (*Ac cumuliformis*, *Ac cu*).

Altostratus (***As***)—Greyish or bluish cloud sheet or layer with a striated, fibrous, or uniform appearance, totally or partially covering the sky, and having parts thin enough to reveal the sun at least dimly, as if through ground glass. The slightly fibrous structure may be caused by the bands of precipitation. Altostratus does not produce halos. The cloud base is 3–5 km in the midlatitudes, and the cloud thickness is about 1 km. Its precipitation often may reach the ground. Types of As include the fog-like cloud *As nebulosus*, *As neb*, and the wave-like *As undulatus, As und*.

A recent review of the properties of mid-level clouds is given by Sassen and Wang (2012).

Low-level clouds include the following genera:

Stratocumulus (***Sc***)—Grey or whitish, or both grey and whitish, patches, sheets, or layers of cloud which almost always have dark parts, composed of crenellations, rounded masses, or rolls, which are nonfibrous (except when virga-inclined trails of precipitation are present)