Cambridge University Press
978-0-521-89910-9 - Physics and Chemistry of Clouds
Dennis Lamb and Johannes Verlinde
Excerpt
More information

Part I

Background

1
Introduction

1.1 Importance of clouds

What would our world be like without clouds? Unimaginable – quite literally – for clouds are essential for our lives on earth. Humans, and for that matter most other land-dwelling species, would simply not exist, let alone thrive in the absence of the fresh water that clouds supply. The favorable climate we have enjoyed for thousands of years might also not exist in the absence of atmospheric water and clouds. A world without clouds would be different indeed.

Clouds contribute to the environment in many ways. Clouds, through a variety of physical processes acting over many spatial scales, provide both liquid and solid forms of precipitation and nature's only significant source of fresh water. Under extreme circumstances, however, clouds and precipitation may not form at all, leading to prolonged droughts in some regions. At other times and places, too much rain or snow falls, giving rise to devastating floods or blizzards. Liquid rain drops bring usable water directly to the surface, while simultaneously carrying many trace chemicals out of the atmosphere and into the ecosystems of the Earth. Chemical wet deposition thereby supplies nutrients (and sometimes toxic compounds) to both terrestrial and aquatic lifeforms, as well as the weak acids responsible for the weathering of the Earth's crust. The solid forms of precipitation contribute in additional ways to the world as we know it. Snow, for instance, forms the winter snowpacks that dramatically affect the radiation balance and climate of high latitudes on a seasonal basis. In mountainous regions, snow simultaneously yields a long-lasting supply of water and lucrative opportunities for human recreation. Snow that accumulates from one year to the next gives rise to glaciers that carve out valleys as they slowly flow downhill under their enormous weight. Atmospheric clouds and the precipitation they yield are responsible for much of the world that we take for granted.

Many aspects of weather revolve around the presence or absence of clouds. The weather systems that routinely pass through the mid-latitudes transform invisible water vapor into sometimes beautiful, sometimes dreary clouds of many sizes and types. These clouds affect the radiation balance of the region and hence the temperature of the air and exposed surfaces. The precipitation they generate removes the water and trace chemicals from the sky, serving simultaneously to dry and cleanse the air. Forecasting the meteorological events of the next day or of the coming season is becoming ever more crucial to our individual lives and to the economy of our society. Being able to anticipate the amount and nature of the clouds with assurance is an important skill of every forecast meteorologist, for which one needs a thorough understanding of the atmosphere and the processes responsible for cloud formation.

Less apparent than the weather we see and feel, but which is nevertheless important to the workings of the atmosphere, are the roles clouds play in the atmospheric energy budget. Clouds reflect incoming solar radiation back to space, thus helping regulate the overall input of solar energy and its distribution around the world. Clouds also intercept infrared radiation emitted from the surface that would otherwise be lost to space; reradiation of infrared radiation by the same clouds helps warm the surface. Energy deposited in the oceans helps evaporate water and provides the primary ingredient for cloud formation, water vapor. The transformation of water vapor into the many liquid and solid particles that compose clouds necessarily results in a warming of the air. This energy consequence of a physical change of phase determines in part the macroscopic shape and behavior of clouds, whether they are convective or stratiform in nature. On a much larger scale, the thermal energy "released" by the phase transformations in the large convective clouds of the tropics becomes an important component of the Earth's energy balance. Major circulation patterns in the atmosphere are thus spawned, helping redistribute the surplus energy from the tropical regions to other parts of the world, where less energy is received from the Sun than is lost to space by thermal infrared radiation.

The composition of the atmosphere, especially regarding its trace gases and particulate matter, is greatly influenced by clouds. The precipitation resulting from clouds serves as a carrier of the material taken up by the cloud and precipitation particles. Cloud and precipitation "scavenging" thus serves as a remarkably efficient mechanism by which the atmosphere is cleansed of the diverse gases and particles continually emitted into the air, thereby preventing the build-up of natural and anthropogenic pollutants. At the same time that air quality is improved by precipitating clouds, the precipitation itself becomes correspondingly fouled, leading to such ecosystem problems as acidic rain, for instance. Even in the absence of precipitation, clouds offer several important opportunities for transforming trace components of the atmosphere into other compounds. In the lower atmosphere, such in-cloud reactions oxidize sulfur and nitrogen compounds, leading to enhanced summertime hazes across industrial regions. In the middle atmosphere, chemical balances may be altered rather profoundly by reactions occurring in or on the surfaces of aerosol and cloud particles, causing ozone to be lost. The chemistry of clouds thus becomes as important as the physics of clouds toward the workings of the atmosphere.

The study of clouds offers rich opportunities for applying our understanding of physics and chemistry to real-world phenomena. Clouds give direct evidence of changes taking place in the atmosphere. By our conventional ways of categorizing the disciplines of science, we would say that some of these changes are physical in nature, some are chemical in nature. Nature, of course, knows no such distinction, so we need to realize that dividing the atmospheric sciences into "physical" and "chemical" domains is largely a matter of convenience. Physics, the science of matter, energy, and their interactions, is the discipline used in traditional cloud physics to understand the fundamentals of cloud and precipitation formation, the microscale structure of clouds, cloud electrification, and the impacts of clouds on climate. The conventional restriction to the physics of clouds, however, ignores several important chemical attributes of clouds. Chemistry, the science of the composition, structure, and properties of substances and their transformations, is needed to understand the very nature of water itself, as well as how water interacts with aerosol particles to permit clouds to form under atmospheric conditions. Chemistry is also needed to understand how those aerosol particles that serve as the sites of condensation came to exist in the first place. The atmospheric phenomena of acidic haze formation, acid rain, stratospheric ozone depletion, and some aspects of the natural biogeochemical cycles and climate can be understood only via the traditional discipline of chemistry. Throughout this book, we will find frequent occasion to jump between physical and chemical concepts, often without mention. It is only important to recognize that the fundamental principles of science guide us aptly as we try to understand atmospheric clouds in their natural, complex setting.

1.2 Observed characteristics of clouds

1.2.1 Overview

Careful observations of the atmosphere reveal much about clouds. Some, "macroscopic" characteristics of clouds are readily seen with the unaided eye, whereas other "microscopic" properties require elegant instrumentation. At all levels, we find it natural and helpful to give names to phenomena, properties, and concepts. The nomenclature and jargon of the science become the means by which we communicate effectively with one another and so must be learned along with the scientific concepts. Some attention is therefore given to the proper use of terminology throughout the text.

Cloud formation requires moisture, aerosol particles, and a process for cooling the air. The abundances of moisture and aerosol particles determine the total mass of condensate and the number concentration, respectively, and they affect the ability of clouds to produce precipitation. These two components also regulate the radiative properties of clouds and how we perceive them visually. The necessary cooling to form a cloud may arise from any one or combination of processes: radiative cooling, turbulent mixing of air across moisture/temperature gradients, or expansion of air during forced ascent or free convection.

The observed characteristics of a cloud depend on how the atmosphere organizes itself to provide these key ingredients. Atmospheric moisture, derived from evaporation of surface water or transpiration of plants, originates at or near the Earth's surface. The fact that most clouds are observed well above the surface suggests that surface moisture must be transported upward by atmospheric motions. The surface is likewise the dominant source for aerosol particles, although these particles may also be formed in the atmosphere through gas-to-particle conversion. The processes responsible for upward moisture transport also results in a cooling of the air, the other requirement for cloud formation. The type of vertical motion is the major determinant of the cloud forms we commonly see. Slow, large-scale ascent results in broad, featureless clouds, whereas rapid ascent of smaller parcels of air result in cloud turrets. The mixing of warm, moist air with cooler air leads to transient clouds of limited spatial extent.

Once formed, a cloud changes in response to the relative rates of the processes responsible for condensate formation and loss. Continued cooling from the net loss of radiation, adiabatic expansion, and/or moisture advection adds condensate; conversely, radiative heating, adiabatic compression, mixing with drier atmospheric air, and precipitation all remove condensate. The radiative heating rates are determined by a combination of the macroscopic (large-scale) and microscopic (small-scale) characteristics of the cloud. The vertical distribution of diabatic heating and cooling plays a further role in changing the atmospheric stability profile, the impact of which is to enhance (suppress) vertical motions.

The vertical velocities in a cloud determine the time an air parcel spends inside the cloud. This in-cloud duration limits the time available for condensate to grow to sizes large enough to fall against the updraft and remove condensate. Spatial variations in vertical velocities induced by turbulence result in spatial variations of microscopic properties, and are responsible for lumpiness in the visually observed cloud outline. Turbulence further serves to mix drier atmospheric air into the cloud, leading to the loss of condensate through evaporation. The interactions between the macroscopic air motions and the microscale processes ultimately determine the characteristics of the clouds we observe.

1.2.2 Macroscopic forms

The sky is rich in information about the state of the atmosphere and the diverse processes that bring about changes. One needs to learn how to read the sky much as one does to read a book. In both cases, we depend on our sense of vision to recognize patterns (the shape of a cloud, or the words on a page) and on our mind to interpret what we see. “Sky reading”, the art of interpreting observed properties of the sky in terms of categories and processes, is practiced by many, amateurs and professionals alike, as a way of understanding atmospheric phenomena and foretelling weather events. By combining the ever-changing visual clues presented by clouds with an understanding of physical processes, much can be gleaned about the current or anticipated weather. We start with basic terminology and categorization before explaining the processes that bring clouds into being and eventually to their demise.

Clouds can be seen at various times from virtually every point on the Earth’s surface, but it is often challenging to know what to call them or how they evolve. Despite difficulties in determining the sizes and altitudes of clouds with precision, level in the atmosphere is good for telling one cloud type from another. We can usually distinguish low-lying clouds from those higher in the atmosphere, for instance. Thus, clouds may be categorized as “low” (up to about 2 km above the surface), “mid-level” (2 to 7 km), or “high” (above 7 km). Clouds confined to distinct levels often take on a “stratiform” appearance, one exhibiting dimensions in the horizontal that are substantially greater than those in the vertical. Stratiform clouds form in air that is thermodynamically stable, meaning that small vertical displacements have little effect on the overall air motions. "Cumuliform" clouds, by contrast, tend to extend farther in the vertical than in horizontal directions. Cumuliform clouds are sometimes said to be convective because they form in air that is locally unstable, meaning that small vertical displacements lead to further displacements and convective overturning of the air. The stability of the air is determined by how rapidly the temperature and humidity change with altitude. Large cumuliform clouds can span all altitude categories, from "low" to "high". The conventional names given to the various cloud forms are derived from visual observations taken at the ground (see Appendix A for a summary).

The observed forms of clouds differ substantially within a given category. Often, the shape of a cloud itself best reveals its type. A few photographic examples illustrate the diverse forms clouds can take in various settings. As Fig. 1.1 shows, the view from the ground often reveals multiple cloud types at one time. The cloud elements near the bottom of the figure are individually cumuliform in nature and indicative of a turbulent, nearly well-mixed boundary layer. Such disconnected clouds are classified as cumulus (Cu). If the edges of the cloud elements were touching, the deck would be classified as stratocumulus (Sc). The particles constituting these clouds are liquid water droplets, the result of vapor condensation at relatively high temperatures. The clouds toward the top of Fig. 1.1 have a fibrous appearance indicative of high cirrus clouds (Ci), perhaps the result of a jet aircraft. The cloud particles are ice crystals, evidence for which is the coloration (bright spots left and right of center) arising from the refraction of sunlight through adjacent facets of the crystal (causing a "circumhorizontal arc" in this case). Another example of cirrus, in this case Ci uncinus, is shown in Fig. 1.2. Such high clouds are made of relatively large

Figure 1.1 Diverse cloud forms over eastern Oregon. The two bright spots in the upper third are from a circumzenithal halo, which forms when sunlight refracts through hexagonal ice crystals. Photo by D. Lamb.

Figure 1.2 Cirrus uncinus clouds over Victoria, British Columbia. Photo by D. Lamb

ice particles that sediment rather rapidly. Ci uncinus in effect, represent snow that never reaches the ground.

Mid-level clouds are often relatively thin and take on a variety of sub-forms. Perhaps the most diverse types occur with altocumulus (Ac). Figure 1.3a shows an example of Ac undulatus, cumuliform elements that formed in a relatively thin layer where moisture accumulated preferentially. A distinctly different form of Ac is shown in Fig. 1.3b. In this case, stable air was forced over an upstream mountain, forming a gravity wave with clouds in the crest. Such a cloud is commonly called a wave cloud, although the scientific designation is Ac lenticularis because of the lens-like shape. Figure 1.3c shows the edge of an altostratus deck (As), a continuous deck of clouds at mid levels. Where precipitation is falling out, the cloud is called nimbostratus (Ns). It is hard to tell if the precipitation is rain or snow here, but any precipitation that evaporates before reaching the ground is termed virga.

Clouds sometimes look tall and vertically extended relative to their horizontal dimension. Such cumuliform clouds arise when moist air rises rapidly in an unstable atmosphere. Examples of cumulus clouds in the trade winds of the Pacific Ocean are shown in Fig. 1.4. The flat bases indicate that each of the clouds was derived from boundary-layer air having common thermodynamic properties. The towering nature of these clouds shows the importance of buoyancy generated by the release of the latent heat of condensation. Particularly impressive cumulus and cumulonimbus clouds (Cb) can develop when air moves upwards rapidly in moist air that it unstable over large depths. The cloud shown in Fig. 1.5, for instance, towered over the Grand Canyon in Arizona and was just about to develop an anvil and begin raining at the time the photograph was taken. Such a cloud with hints of an anvil is called Cb calvus. A fully developed Cb is shown Fig. 1.6. Note the active convection on the upshear (left-hand) side and the extended anvil on the downshear side of

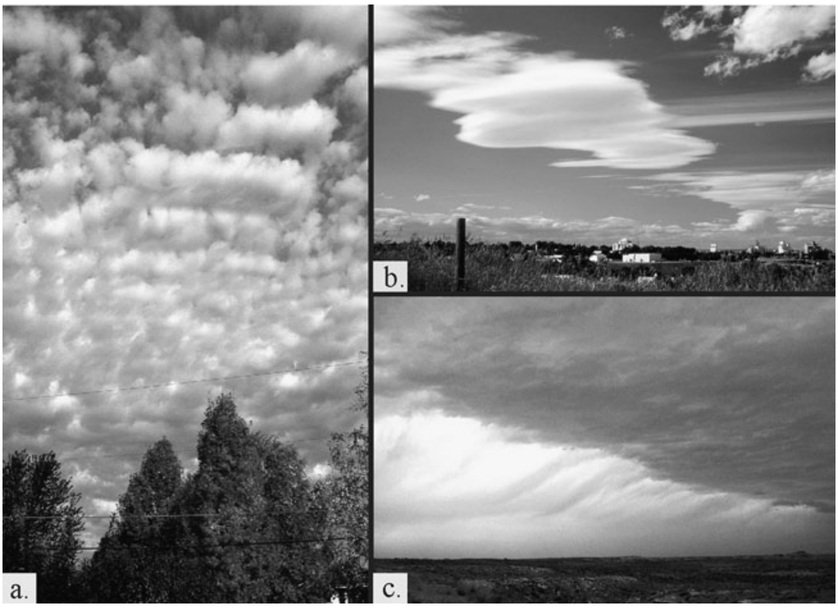

Figure 1.3 Examples of mid-level clouds. a. Altocumulus (Ac) undulatus over Pennsylvania. b. Ac lenticularis over Alberta. c. Nimbostratus (Ns). Photos by D. Lamb.

Figure 1.4 Trade-wind cumuli off the shore of Kauii. Photo by D. Lamb.

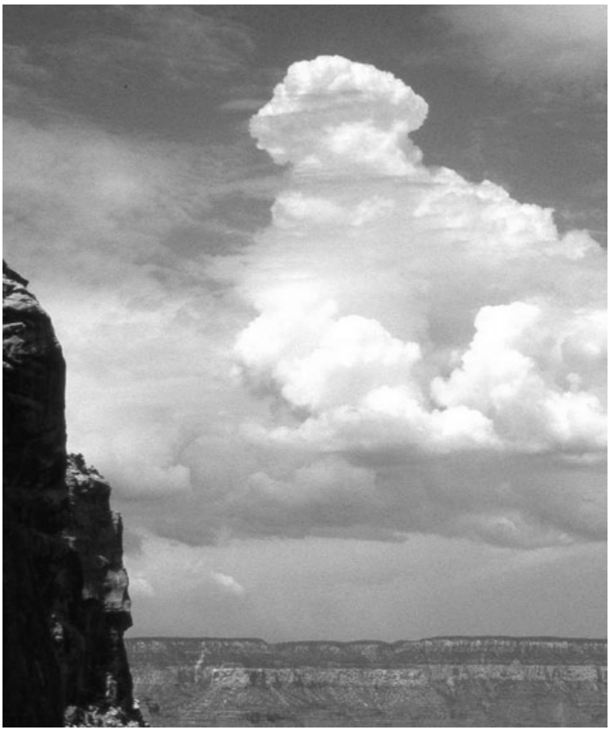

Figure 1.5 Towering cumulus cloud over the Grand Canyon. Photo by D. Lamb.

Figure 1.6 Cumulomnimbus cloud with long anvil along east coast of the United States. Photo by D. Lamb.