1 Clouds: Definitions and Significance

Clouds are visible clusters of small water drops and ice particles. Being a widespread atmospheric phenomenon, clouds are part of most processes occurring in the atmosphere. To a great extent, they govern solar radiation and energy fluxes reaching Earth, and have a strong effect on the hydrological cycle and freshwater distribution over the globe. Clouds are the energy source for different mesoscale phenomena, including dangerous ones such as tornadoes and hurricanes. All this determines the vital impact that clouds exert on all forms of life on the planet, human life included. Studies of clouds and cloud-related phenomena are an integral part of modern meteorology, providing data to be directly applied in weather forecasting, agriculture, environment control, air traffic control, and many other spheres of human activity.

1.1 The Importance of Clouds

The Sun is the major source of energy for Earth's oceans, atmosphere, land, and biosphere. The flux of about 342 J/s of shortwave solar radiation falls upon every square meter of Earth. The difference between the total amount of energy that Earth receives from the Sun and the total amount of energy that Earth reflects and emits back into space in the form of infrared radiation determines our planet's energy budget. Earth's climate system tends toward eventually reaching a *radiation balance* between the incoming solar energy and the outgoing thermal energy. If more solar energy comes in, Earth warms up and emits more heat into space to restore the radiation balance.

Figure 1.1.1 shows the composition of the annual mean global energy balance for the decade 2000–2010. The average top-of-atmosphere (TOA) imbalance is $0.6 = 340.2 - 239.7 - 99.9$ Wm^{-2}. This small imbalance is more than two orders of magnitude smaller than each of the individual balance components. Covering a substantial portion of Earth's surface, clouds significantly influence the TOA balance. The main impact factor is a so-called cloud *albedo* effect, which is a measure of cloud reflectivity and is defined as the ratio of the reflected radiation to the incident radiation. It varies within a vast range from less than 10% to more than 90% and depends on several factors, such as liquid water content and ice content, sizes of drops and ice particles, cloud thickness, the Sun's zenith angle, etc. The smaller the drops and the

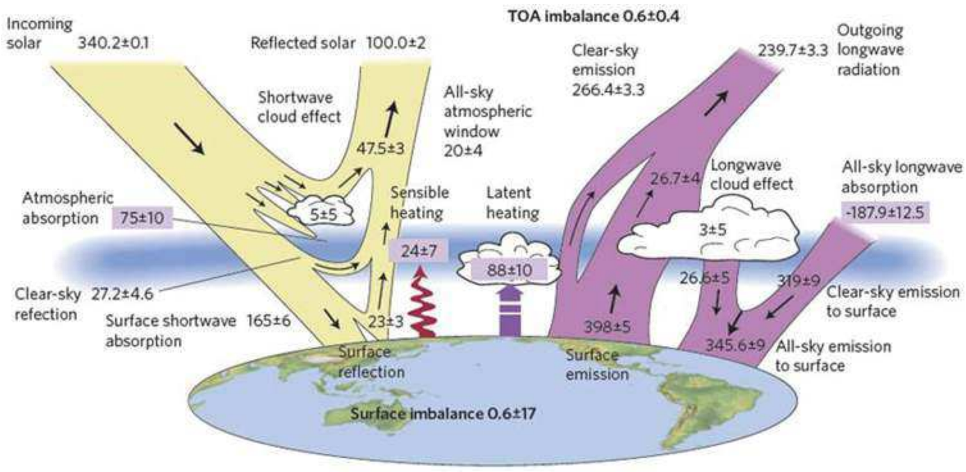

Figure 1.1.1 The annual mean global energy budget of Earth for the period 2000–2010. All the fluxes are in Wm^{-2}. The solar fluxes are marked yellow and the infrared fluxes are marked pink. The four flux quantities in the purple-shaded boxes represent the principal components of the atmospheric energy balance (from Graeme et al., 2012; reprinted with permission from Macmillan Publishers Ltd.).

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larger the liquid water content, the higher the cloud albedo is, all other factors being equal. The overall reflectance of planet Earth is about 30%, meaning that about 30% of the incoming shortwave solar radiation is reflected back into space. If, hypothetically, all clouds were removed, the global albedo would decrease to about 15%. Figure 1.1.1 shows that the cloud albedo effect decreases the radiative influx by $47.5 \pm 3\ \mathrm{Wm}^{-2}$.

At the same time, in comparison to the clear-sky case, clouds reduce the outgoing long-wave radiation flux by approximately $26.4 \pm 4\ \mathrm{Wm}^{-2}$ (Figure 1.1.1), creating a phenomenon known as the *greenhouse effect*. The global cloud albedo effect is significantly larger than the greenhouse effect. The net cloud-induced loss of radiation from Earth can be estimated as $21.1 \pm 5\ \mathrm{Wm}^{-2}$. This accounts for a net cooling effect that clouds have on Earth's climate, as illustrated in **Figure 1.1.2**. The scatter diagram of the global air temperature vs. the total cloud cover clearly demonstrates the inverse dependence between the temperature and the cloud cover with the correlation coefficient of about 0.5. A simple linear fit model suggests that an increase in the global cloud cover by 1% corresponds to a global temperature decrease of about 0.07°C. The diagram also shows that the cloud impact strongly depends on the cloud cover, which varies in the range of 63–70%.

Different types of clouds play different roles in the radiation balance. *Cirrus clouds* transmit most of the incoming shortwave radiation but trap some of the outgoing long-wave radiation. Their cloud greenhouse forcing is greater than their cloud albedo forcing, resulting in net warming of Earth. *Stratocumulus clouds* reflect much of the incoming shortwave radiation but also reemit large amounts of long-wave radiation. Their cloud albedo forcing is larger than their cloud greenhouse forcing, causing a net cooling of Earth. *Deep convective clouds* emit little long-wave radiation at the top but much of it at the bottom, and reflect much of the incoming shortwave radiation. Their cloud greenhouse and albedo forcing are both high, but are nearly in balance, causing neither warming nor cooling.

Since the atmosphere is nearly in energetic equilibrium, the net effect of different factors is substantially smaller than the value of any individual factor (or component) and smaller than errors in estimations of each individual factor. This fact indicates an almost precise radiation and energetic balance and complicates predictions of climate change, because changes result from small differences between large components of the balance. Variation of the cloud cover is one of the most important factors affecting the radiation balance. Even comparatively small changes in cloud cover may substantially affect the climate and affect climatic changes. Hence the great attention paid today to factors that can change the reflectivity properties of clouds and of the cloud cover (Rosenfeld et al., 2006).

Another important factor affecting the radiation balance is the aerosol effect on clouds. Rain and drizzle formation have a high impact, as well. Human activity can also affect the cloud cover and cloud radiation properties, thus creating anthropogenic climate changes (Ramanathan et al., 2001).

Clouds are an important component of the global *hydrological cycle* schematically shown in **Figure 1.1.3.**

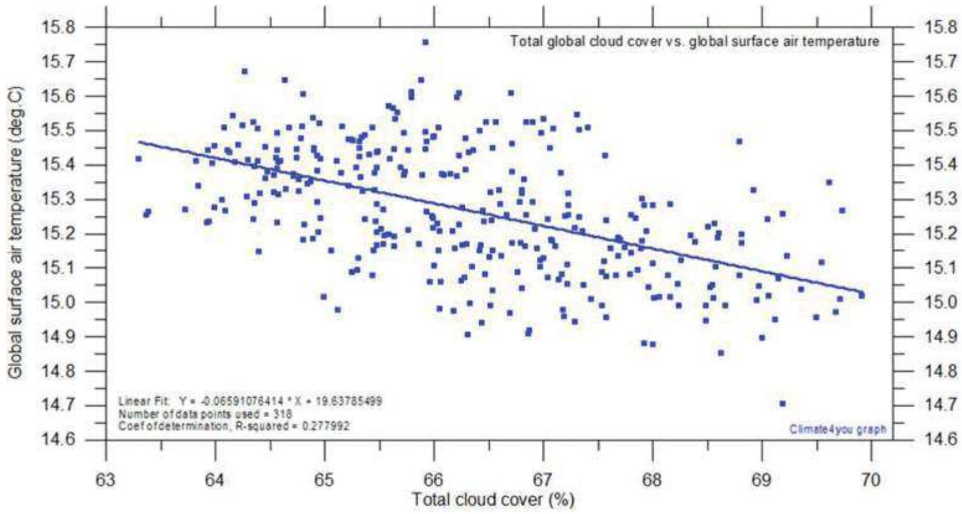

Figure 1.1.2 Scatter diagram showing the total monthly global cloud cover plotted versus the monthly global surface air temperature (diagram of Dr. Ole Humlum; published with permission of the author).

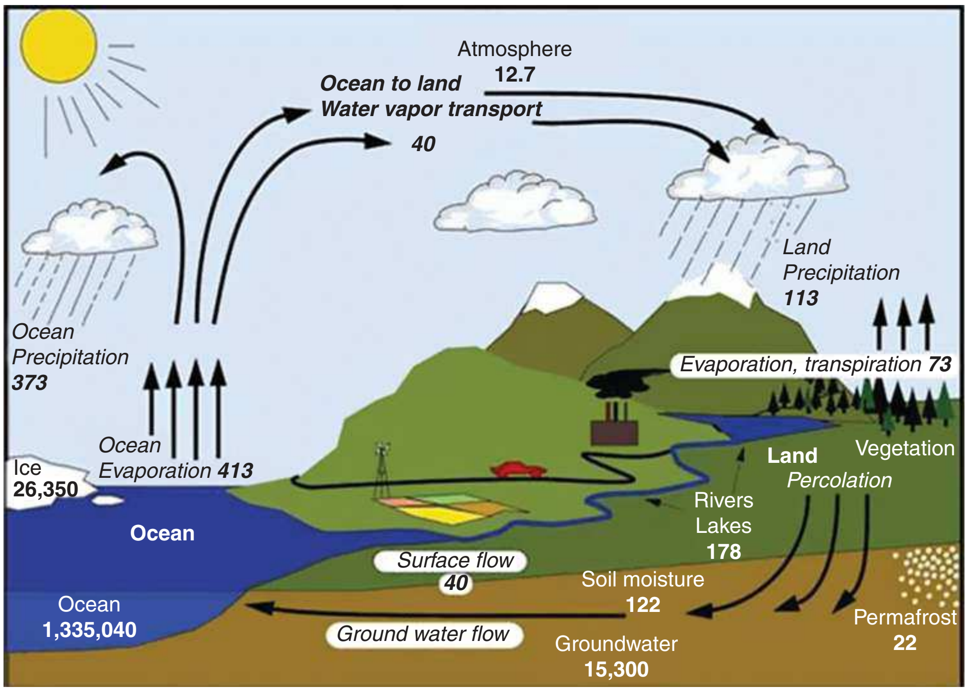

Figure 1.1.3 Scheme of the global hydrological cycle. Units: 1,000 cubic km for storage and 1,000 cubic km/year for exchanges (from Trenberth et al., 2007; courtesy of © American Meteorological Society. Used with permission).

Water vapor evaporated from Earth's surface – mostly from the ocean surface – is transported by atmospheric motions sometimes over hundreds or thousands of kilometers and then ascends. The temperature in the ascending air volumes decreases and the air becomes saturated or oversaturated. This process leads to formation of clouds containing droplets formed on small aerosol particles. Droplets grow, decreasing the amount of water vapor in the air. At freezing temperatures, ice particles form and grow, producing different types of ice hydrometeors: ice crystals, aggregates (snow), graupel, and hail. The growth of ice particles also decreases the air humidity. Thus, clouds are responsible for the amount of water vapor in the atmosphere. Collisions of cloud particles lead to formation of large drops and precipitation. The rate and type of precipitation (liquid vs. solid) depends on a cloud type and environment conditions (temperature and humidity). Water reaching the surface as precipitation may seep underground or get into rivers, where it travels large distances before evaporating. The combination of evaporation, precipitation, and transport of liquid water into (or beneath) soil and along rivers and ocean streams creates the complicated global hydrological cycle.

Since water vapor and clouds play a crucial role in the atmospheric energy balance, there is a close relationship between the climate and the hydrological cycle. The hydrological cycle is also essential in shaping Earth's environment, the availability of water being a critical factor for life as well as for many chemical reactions and transformations affecting the physical environment. Describing various components of the hydrological cycle and analyzing the mechanisms responsible for the exchange of water between different reservoirs are thus important elements of climatology.

The role of clouds is not limited to their effect on radiation and the hydrological cycle. The latent heat released during condensation of water vapor is a dominant energy source of atmospheric motions of different scales. The release of the latent heat in clouds is the main source of kinetic energy of global circulation of the atmosphere. The kinetic energy of clouds and related phenomena, such as thunderstorms, tropical cyclones, etc., is largely determined by the latent heat release in clouds. Clouds are an important energetic source of turbulent motions. The latent heat in clouds is released during condensational growth of liquid droplets and ice particles as well as during freezing of liquid droplets and melting of ice. These processes take place at microscales, the sizes of cloud particles ranging from about 1 μm to 1,000 μm, and in rare cases up to 1 cm.

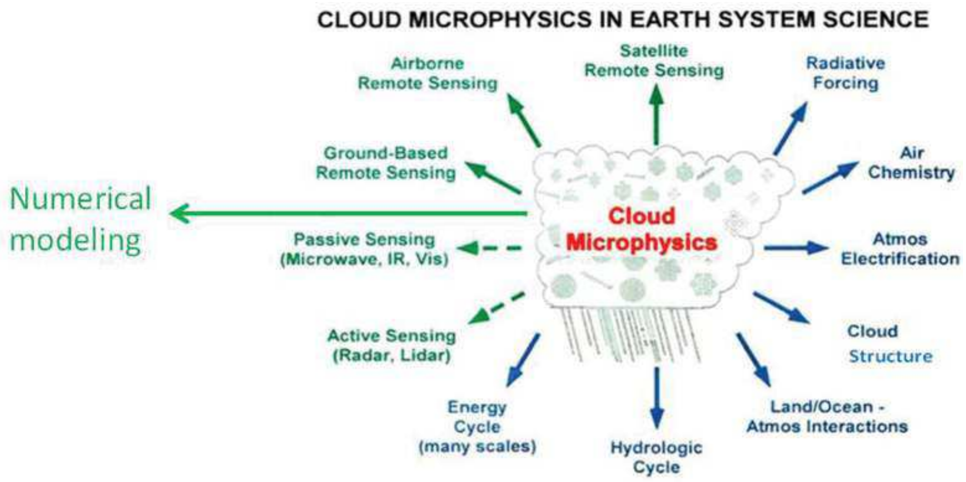

Figure 1.1.4 Links between cloud microphysics and other fields of atmospheric and earth sciences and methods of cloud investigation (from Tao and Moncrieff, 2009 with changes; courtesy of © Willey and Sons Ltd.).

Thus, atmospheric motions within a wide range from centimeters to global scales are affected by microscale processes taking place in clouds.

Cloud effects depend on cloud type, height, cloud age, cloud thickness, etc. *Cloud physics* represents a special branch of *earth science*. *Cloud microphysics* studies formation, growth, transition, conversion, and sedimentation of cloud particles (drops, ice particles, and aerosol particles). The cloud microphysical processes determine the microstructure of clouds that include the spatial-temporal field of masses and concentrations of cloud particles (hydrometeors), as well as size distributions of cloud particles belonging to different hydrometeor types. Cloud microphysics is related to many areas of earth science: atmospheric radiation (radiation forcing), hydrology, atmospheric electrification, aerosol science, and atmospheric chemistry. These links are illustrated in **Figure 1.1.4**.

1.2 Clouds and Cloud-Related Phenomena

1.2.1 Typology of Clouds

Clouds can be classified according to their geometrical (morphological) structure and (roughly) assigned to two large classes. Clouds belonging to the first class have horizontal scales far exceeding their thickness. These clouds are stratiform-like clouds. The word "stratus" comes from the Latin prefix *strato-*, meaning "layer." Stratiform-like clouds are further separated into subclasses according to the altitudes of their cloud base as low-, middle-, or high-level clouds. Each subclass is, in turn, separated into different types according to cloud forms and structures determined by their dynamical and microphysical properties. The second class includes clouds of vertical development (convective clouds) whose thickness is of the same order or even larger than their horizontal size and whose base is typically located in the boundary layer (BL). Convective clouds are driven by atmospheric instability and buoyancy forces. The class of convective clouds is separated into subclasses according to altitudes of their tops. The main subclasses of clouds are shown in **Figure 1.2.1**. Next, we briefly describe the main specific phenomenological properties of cloud types shown in Figure 1.2.1. A more detailed description and classification can be found on Cloud Atlas (www.clouds-online.com/)

Stratiform-Like Clouds

Subclasses of low-level stratiform-like clouds include four cloud types: stratus (St), stratus fractus (St fr.), stratocumulus clouds (Sc), and nimbostratus (Ns). Horizontal sizes of *St* exceed the cloud depth by several orders of magnitude. They are homogeneous in the horizontal direction and often cover the entire sky. The height of cloud base of *St* typically ranges from 0.1 to 0.7 km, and the thickness of the cloud layer ranges from 0.2 to 0.8 km. They sometimes produce drizzle, freezing drizzle, or snow (aggregates), depending on temperature. *St* form due to turbulent mixing of air in the BL, or in a manner similar to that of fog formation when the ambient air temperature decreases, thus increasing the relative humidity. Once the temperature drops below the dew point, a stratus cloud forms. *St* are essentially aboveground fog formed either through

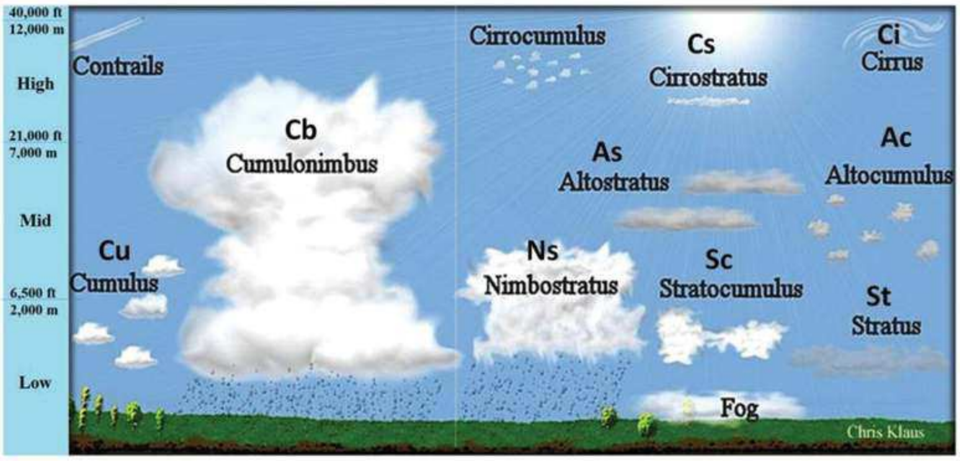

Figure 1.2.1 Classification of clouds. Clouds of vertical development (convective) are depicted on the left side of the panel; stratiform-like clouds are depicted on the right side of the panel (*The Scheme*, by Christopher Klaus, published with changes; with permission of the author).

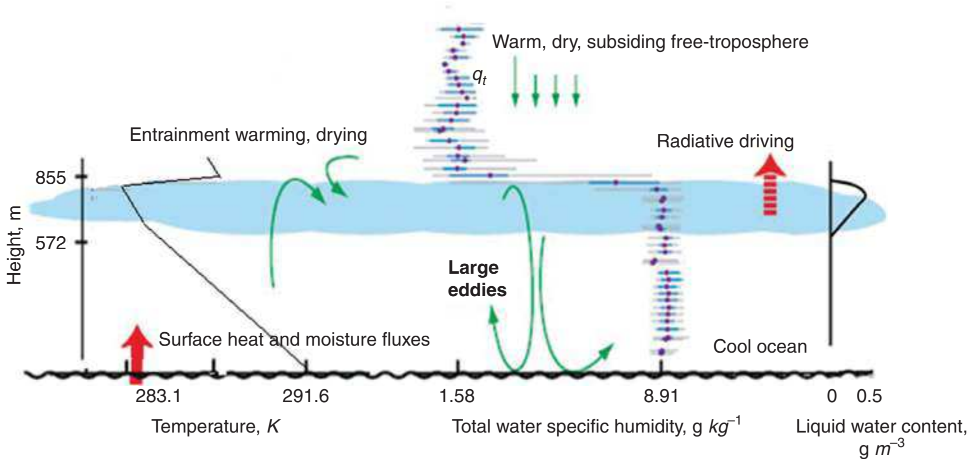

Figure 1.2.2 Conceptual scheme of a well-mixed boundary layer covered by a non-precipitating maritime *Sc* over the cool, eastern subtropical oceans (research flight near 30°N, 120°W) (with changes) (courtesy of Bjorn Stevens).

lifting of morning fog or through cold air moving at low altitudes over a region. Sometimes *St* are called “high fog.” They can be composed of water droplets, supercooled water droplets, or ice crystals, depending upon the ambient temperature. *St fr.* clouds look like separate shreds with broken edges.

***Stratocumulus clouds* (*Sc*)** is a basic cloud type of low-level stratiform-like clouds. *Sc* contain elements of *Cu* that are embedded into zones of stratiform clouds. Cloud tops of *Sc* is typically less than 2.5 km. The vertical velocities are usually caused by convective cells in the BL and reach 1–2 m/s. The maximum vertical velocities often take place near the cloud base.

A conceptual scheme of a well-mixed boundary layer covered by a non-precipitating maritime *Sc* is shown in **Figure 1.2.2**.

Liquid Sc clouds develop within a neutral or slightly unstable BL, typically over relatively cool ocean surfaces. The BL is well mixed and limited from above by the stable inversion layer in which the temperature increases with height. Figure 1.2.2 shows the vertical profiles of temperature and total specific humidity q_t, i.e., the total amount of water including water vapor and liquid per kg of air.

Mixing in the vertical direction leads to linearly decreases in the temperature from the surface upward

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Figure 1.2.3 Typical stratocumulus cloud (credit: dszc/Getty Images).

Figure 1.2.4 A raining nimbostratus cloud (from https://pixabay.com/en/mongolia-steppe-rain-clouds-487112/).

with a gradient of 9.8 K km^{-1} and to nearly constant values of q_t within the mixing layer of the BL below the inversion level. Sharp increase in T and decrease in q_t take place within the inversion layer. The inversion is typically supported by large-scale subsidence of dry and warm air. The depth of *Sc* is a few hundred meters. Humidity and temperature in the BL are determined to a large extent by surface fluxes. Radiative fluxes from the upper boundary of Sc lead to cooling of the upper boundary and favor the vertical mixing within the BL. Mixing in the BL is due to large eddies arising within it. In non-precipitating *Sc*, cloud droplets are smaller than 20 μm in radius. When the cloud depth is larger and exceeds about 0.3 km, and the air humidity in the BL is high, liquid water content exceeds the critical value, and drizzle (drops of about 100 μm in radius) forms and falls down. Formation of drizzle dramatically changes the cloud structure and cover and, as a result, the radiative characteristics of *Sc*. A typical *Sc* in the BL is shown in **Figure 1.2.3**.

Nimbostratus **(*Ns*)** is a low-to-middle troposphere stratiform cloud that has considerable vertical extent (2–5 km) and horizontal extent (tens to hundred kms) and produces precipitation over a large area. *Nimbo* comes from the Latin word *nimbus*, meaning "precipitation." *Ns* is a major source of precipitation. They usually have a darker color than stratus clouds due to their high moisture content. A typical *Ns* is shown in **Figure 1.2.4.** They form along a warm front or an occluded front within zones of weak updrafts. Often, *Ns* form from an altostratus cloud when it thickens and descends into lower altitudes.

Altostratus **(*As*)** ***and Altocumulus*** **(*Ac*)** are stratiform-like clouds of middle level. *Alto* comes from the Latin word *altus*, meaning "high." *As* look like a sheet or a layer and are generally uniform gray to bluish-green in color (**Figure 1.2.5**). *As* are lighter in color than *Ns*, but darker than cirrostratus. *As* are transparent and the sun can be seen through thin ones. They can produce light precipitation that evaporates, not reaching the surface. If the precipitation increases in persistence and intensity, the *As* may thicken into *Ns*, as previously mentioned. They most often take the form of a featureless sheet; however, they can also be fragmented. The appearance of *As* is often a sign of an upper-level warm front approaching. They may be composed of ice crystals whose sizes increase as the altitude decreases. Near cloud top, the ice crystals are largely hexagonal plates, becoming more conglomerated as the cloud descends.

Altocumulus **(*Ac*)** may appear as parallel bands (**Figure 1.2.6**) or rounded masses. Typically, a portion of an *Ac* is shaded, which distinguishes them from the high-level cirrocumulus. They usually form by convection in unstable layers at the upper levels. The presence of *Ac* during a humid summer morning is a sign of thunderstorms that may occur later in the day.

Cirrostratus **(*Cs*)** ***and Cirrus*** **(*Ci*)** are stratiform-like clouds of the upper level. The word *cirrus* is the Latin word for "curl". These clouds arise due to slow large-scale updrafts at the updraft velocity of the order of 1 to few cm/s in zones of atmospheric fronts. *Cs* are ice crystals stratiform clouds of high location that can appear as a striated sheet in the sky. They are transparent, so the sun or the moon are always clearly visible

Figure 1.2.5 Altostratus (credit: Wallace Garrison/Getty Images).

Figure 1.2.6 Typical *Ac* clouds (from https://pixabay.com/en/mongolia-steppe-rain-clouds-487112/).

Figure 1.2.7 A Cs (from https://pixabay.com/en/cirrostratus-skyscape-sky-cloud-246294/).

through them. A photo of a Cs cloud is shown in **Figure 1.2.7.** *Ci* consist of ice crystals of different types, the fraction of a particular type depending on the temperature. The dominating crystal types in such clouds are thick hexagonal plates and short, solid hexagonal columns.

Clouds of Vertical Development (Convective Clouds)

A specific feature of convective clouds is that they form as a result of a thermal instability in the atmosphere. Their updrafts are caused largely by the buoyancy force, which explains the term "convective clouds." The friction force in the BL leads to formation of zones of convergence and divergence. The vertical velocities arising in the convergence zone foster formation of convective clouds. The subclasses of convective clouds include cumulus (*Cu*), cumulus congestus (*TCu*) and cumulonimbus (*Cb*). The word *cumulus* comes from the Latin word meaning "heap" or "pile." Vertical sizes of *Cu* and *Cb* are of the same order as their horizontal sizes.

Cumulus clouds **(*Cu*)** are often described as "puffy," "cotton like," or "fluffy"; their bases look flat. They are low-level clouds with altitudes generally less than 1,000 m, characterized by an unstable BL capped from above by a stable inversion layer. Sometimes single *Cu* may form, but usually they are organized into 2D rolls or 3D convective cells. The vertical velocities in *Cu*, determined by the magnitude of the BL instability, are of the order of few m/s. Typical *Cu* are shown in **Figure 1.2.8.** They contain only liquid droplets, i.e., they are liquid clouds. The microphysical processes in *Cu* are called warm microphysical processes.

Figure 1.2.8 Fair-weather cumulus clouds (from https://pixabay.com/en/cloud-blue-white-cloudscape-sky-1044223/).

Figure 1.2.9 TCu, developing into a cumulonimbus near Key Biscayne, Florida. The clear-contrast cloud boundaries indicate the liquid phase. Smoothed cloud boundaries indicate ice particles (from Houze's Cloud Atlas, http://www.atmos.washington.edu/Atlas/oro.html; courtesy of R. Houze).

***Cumulus congestus* (*TCu*).** If the atmosphere is unstable within a layer of several kilometers deep, *Cu* can further develop in the vertical direction and become *TCu*. More rarely, Sc can transform into *TCu*. The vertical velocity in *TCu* is typically of several m/s. High vertical velocities are caused by the buoyancy force, while the cloud top height is about 6 km. They contain both liquid and ice particles, thus being mixed-phase clouds (**Figure 1.2.9**). *TCu* are capable of producing severe turbulence and showers of moderate-to-heavy intensity.

***Cumulonimbus clouds* (*Cb*)** are thunderstorm clouds that form if *TCu* clouds continue to grow vertically, sometimes up to the tropopause level (12–16 km). The vertical velocity in *Cb* sometimes reaches 40–50 m/s. A single-cell *Cb* at its mature stage is shown in **Figure 1.2.10**. The *Cb* has a well-defined anvil consisting of ice crystals. The existence of the cloud anvil indicates the presence of a stable layer above the cloud, so the anvil appears in the zone of air detrainment within the cloud. *Cb* are mixed-phase clouds usually producing heavy rains, thunderstorms, hailstorms, and often lightning. The precipitation rates can reach several cm/hour and even tens of cm per hour. Hailstones may reach 5 cm in diameter.

Figure 1.2.10 Single-cell cumulonimbus (from https://pixabay.com/en/cumulus-nimbus-cloud-white-large-491106/).

Crude schemes of the microphysical structures of developing and decaying convective clouds are shown in **Figure 1.2.11.** At the developing stage, aerosols known as *cloud condensational nuclei* ascend in updrafts. The vertical motions can be caused by gravitational waves, orography, temperature inhomogeneity of the underlying surface and other factors. Clouds form due to air cooling in updrafts when the relative humidity exceeds 100%. As the relative humidity exceeds a certain critical value, part of atmospheric aerosols turns into cloud droplets (droplet nucleation). The droplets ascend, growing by condensation of water vapor. The latent heat release increases the vertical velocity. When droplets reach about 20 μm in radius, intense collisions start leading to formation of raindrops, and small raindrops ascend and freeze. In order to freeze, a raindrop should either have an immersion aerosol inside or collide with ice particles. Frozen raindrops give rise to hail particles. At cold temperatures, ice crystals are activated on insoluble aerosol particles. Other mechanisms of ice crystal nucleation also exist, e.g., ice crystals can grow by deposition of water vapor. Collisions between ice crystals lead to formation of aggregates called snow or snowflakes. When the

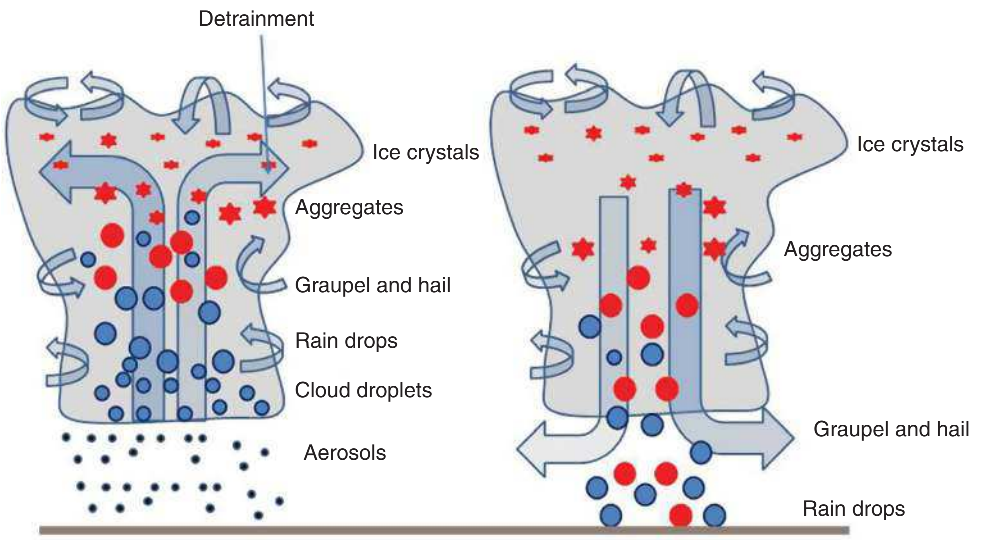

Figure 1.2.11 Schemes of the microphysical structure of a developing (left) and a decaying (right) mixed-phase convective cloud.

Figure 1.2.12 A photo of orographic clouds (from http://213.239.206.108/Bilder/HTML/dig1410_01.html; courtesy of photographer, Dr. Bernhard Mühr).

aggregates accrete a significant amount of cloud droplets, their density increases and they become graupel. Graupel and hail are the main high-density precipitating hydrometeors in *Cb*.

At the decaying stage, the cloud updrafts decrease or may even be replaced by downdrafts. Raindrops, graupel, and hail fall down. Depending on the environmental conditions, some (or all) graupel and hail melt. The largest particles that do not fully melt reach the surface.

There are clouds that typically develop in zones of air updrafts caused by hills and mountains. As the air mass ascends, temperature decreases and the relative humidity rises to 100%, creating clouds and frequent precipitation. Such clouds are called *orographic clouds* (*OC*) (**Figure 1.2.12**). Being linked to the topography,

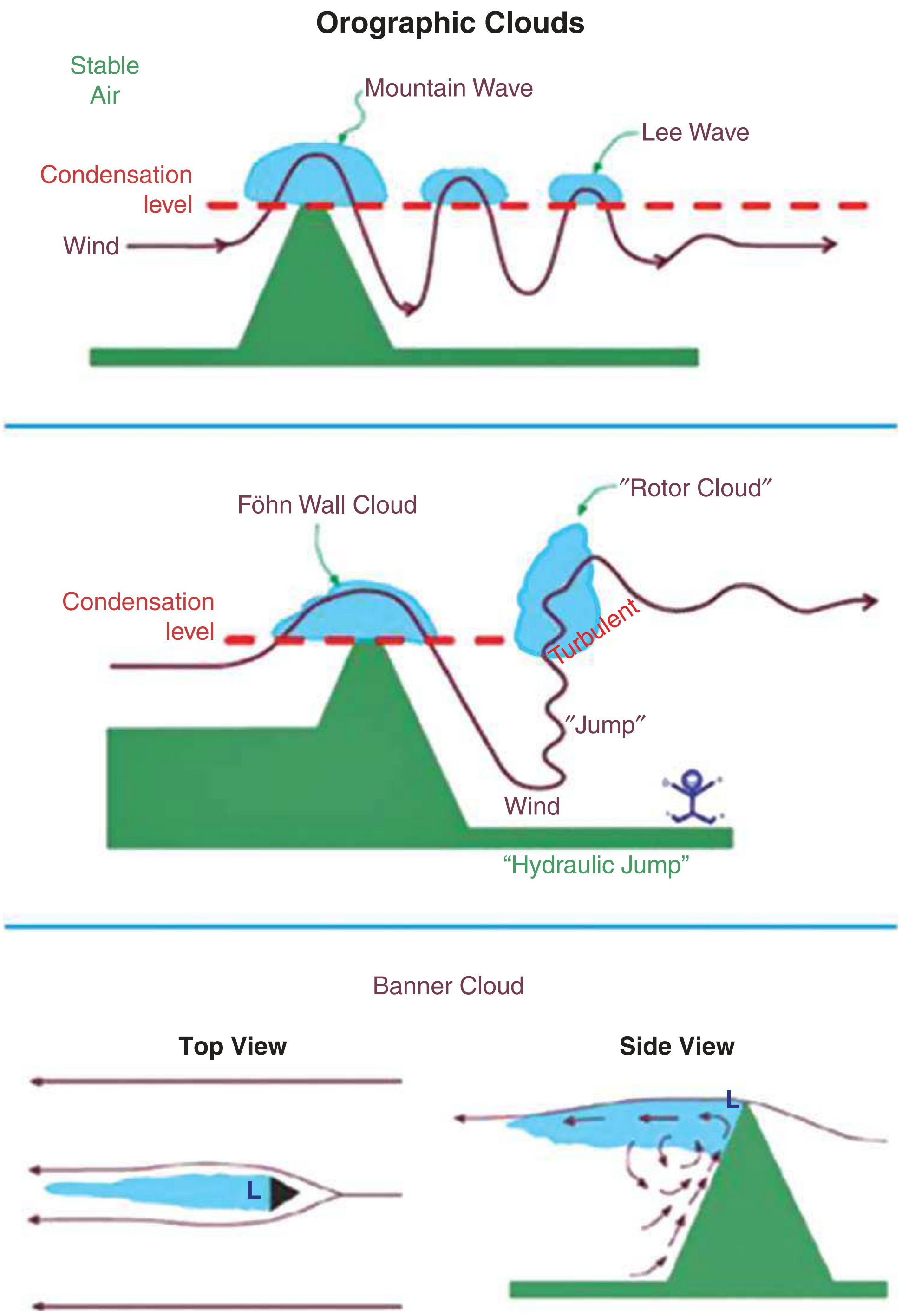

Figure 1.2.13 Structure of wind flows and related cloudiness arising over mountains (from Houze's Cloud Atlas, www.atmos.washington.edu/Atlas/oro.html; courtesy of R. Houze).

OC are usually standing clouds, even if the winds at the same height are very strong. As a result, mountains form local precipitation regimes. Typically, more precipitation falls over the upwind slope of a mountain region while precipitation amount decreases on the downwind side since precipitation on the windward side removes water from the air. Depending on stability conditions, *OC* can be both stratiform like