Meteorology

JSM Coleman, Ball State University, Muncie, IN, USA
KT Law, Marshall University, Huntington, WV, USA

Atmospheric Science: Meteorology and Climatology

Atmospheric science encompasses the main subfields of meteorology and climatology that are similar in the scientific principles and phenomena being examined, but usually differ by approach, time scale, and application. Meteorology is the study of the atmosphere and motions within the atmosphere on short-time scales (minutes to weeks). Commonly known as 'weather,' meteorology focuses on the atmospheric variables (e.g., temperature, precipitation) related to weather forecasting and current or near-future conditions. Alternatively, climatology is the study of climates or long-term mean atmospheric conditions over a particular place as well as the extremes. Climatology focuses on the processes that create climate patterns and variability. In comparison with meteorology, climatology often has a stronger emphasis on interactions within the earth–atmosphere system that includes the following 'spheres': the atmosphere, the thin envelope of gases surrounding the earth and held by gravitational force; the hydrosphere and cryosphere, all terrestrial and atmospheric water and ice sources; the biosphere and anthrosphere, general living organisms and human beings and their activities; and the lithosphere, the terrestrial crust and upper mantle. Meteorology concentrates on processes within the atmosphere and the energy interactions with the surface that affect those processes.

Weather is essentially the behavior of the atmosphere during the present time and predicting future atmospheric conditions, particularly with reference to human comfort and activities. Temperature, precipitation, relative humidity (RH), cloud cover, wind speed and direction, and atmospheric pressure are all variables commonly used to characterize the weather for a specific place and time period. The temporal distinction between weather and climate is succinctly stated in adages such as "climate is what on average we may expect, weather is what we actually get" (Herbertson, 1908, p. 118), "climate lasts all the time weather only for a few days" (Twain, 1887, p. 934), and other variants. Weather is then often described against climatology or the expected state of the atmosphere based on the record of observation and internationally accepted 30-year averages. For example, a weather statement for a particular location may be framed as the current air temperature outside is 15 °C (59 °F) whereas the climate may be described as mild with an average temperature of 20 °C (68 °F).

A Brief History

The field of meteorology developed from the ancient Greeks that provided some of the earliest known observations and theories on atmospheric processes. Anaximenes of Miletus (c. 525 BCE) proposed that changes in atmospheric conditions, such as clouds and winds, were the results of a thickening of the atmosphere. Paramenides (c. 500 BCE) did one of the earliest global climate classification schemes using relative human comfort level by latitude zones (Moran, 2006). Aristotle (c. 340 BCE) produced *Metetorologica*, the first compendium on atmospheric science knowledge and usage of the word meteorology. Stemming from the Greek *meteoron*, the term meteorology originally referred to the study of objects that originate above the surface, including the atmosphere and extraterrestrial objects (Frisinger, 1983). The philosophical (and erroneous) theories of Aristotle were largely not challenged until over a millennium later with the advent of meteorological instruments and new theories stemming from more objective, quantitative data.

Although the first known rain gauge was developed in India (c. 400 BCE), most significant weather instrumentation was not developed until the sixteenth and seventeenth centuries. One of the earliest modern weather instruments was the mechanical anemometer, a device for measuring relative wind strength, invented by Leon Battista Alberti in 1450. Galileo Galilei invented the thermoscope (c. 1592), a predecessor to the modern thermometer, and determined that the atmosphere was not weightless. Yet, the first uniform temperature scales were not developed until 1714 and 1742 by Gabriel Fahrenheit and Anders Celsius, respectively. In 1643, Evangelista Torricelli, who studied under Galileo, invented the mercury barometer, an instrument for measuring atmospheric pressure (Frisinger, 1983). The hygrometer (a device for measuring humidity) was invented by Guillaume Amontons (1687), an advancement over an earlier version developed by Cardinal Nicholas of Cusa in 1450 (Moran, 2006). Collectively, these

 http://dx.doi.org/10.1016/B978-0-12-409548-9.09492-6

instruments and their subsequent improvements established the first methods from which meteorology moved from a simplistic branch of knowledge to a field of scientific inquiry.

The eighteenth and nineteenth centuries were periods when scientists made observations and developed theories on global atmospheric motion and regional scale meteorological phenomena. In 1735, George Hadley proposed the planetary-scale Hadley circulation with an area of low pressure around the equator and a high pressure around the poles resulting in a single cell circulation system in each hemisphere. However, Hadley did not consider the effects of the Earth's rotation on the planetary wind structure, as shown by Gaspard Gustave de Coriolis in 1835 (Ahrens, 2015). Based on the Coriolis effect, the global circulation has three major circulation cells in each hemisphere (Polar, Ferrell, and Hadley), with the Hadley cell now confined to the low-latitudes.

Major theoretical and technological advancements occurred in the twentieth century. In 1904, Vilhelm Bjerknes founded the so-called Bergen (Norway) School of Meteorology that established modern synoptic meteorology (large-scale weather analysis taken at simultaneous time periods). The Bergen School (including Bjerknes, his son Jacob, Halvor Solberg, and later Tor Bergeron) would eventually formulate the polar front theory on mid-latitude cyclone and front development and extratropical precipitation processes in a series of scientific papers from 1917 through the early 1930s (Friedman, 1989). At the onset of World War II, the technological advances came to the forefront. The development of radar (1935) coupled with increasing upper-air observations from weather balloons and aviation led Carl-Gustav Rossby (1937) to introduce methods for analyzing the upper-level atmospheric wave structures that now bear his name. Based on earlier mathematical atmospheric modeling efforts, John von Newmann and his colleagues in 1950 produced the first computer-generated weather forecasts (Moran, 2006). Weather satellites (1960), Doppler radar (1990), and other technological innovations have continued to shape our understanding and forecasting of atmospheric processes.

Meteorological Variables and Forecasting

Instrumentation provided a quantitative and objective means of describing the current state of the atmosphere, measuring the magnitude of future (and past) changes, and establishing the long-term normal and range of weather conditions (i.e., climatology). Although qualitative descriptions are still common, quantitative measurements and statistical summaries of weather elements are used in television, radio, internet, newspaper, and government reports. Weather elements include variables on temperature, moisture, atmospheric pressure, wind movement, and cloud conditions.

Air temperature is the degree of hotness or coldness of the atmosphere. In physics terms, temperature is the average kinetic energy of the molecules. Faster (slower) moving molecules have higher (lower) temperatures. Standard temperature reports are in degrees Celsius (°C); however, the United States and a few other nations also use the Fahrenheit scale (°F). For scientific purposes and physical laws (e.g., the Stefan–Boltzmann law), the Kelvin (K) scale is generally employed where the Kelvin temperature is obtained by adding 273 to the Celsius temperature. Various temperature derivatives are commonly reported such as hourly temperature, the maximum and minimum temperature within a 24-period, and the daily, monthly, seasonal, and annual average temperature. Lapse rates (the change in temperature with height) are used to determine the stability of the atmosphere or the tendency of air parcels to become buoyant. Strong temperature gradients (a large change in temperature over a relatively small horizontal distance) are indicative of fronts, boundaries between two air mass types with different temperature and/or moisture characteristics.

Numerous moisture variables exist to express humidity or the amount of moisture in the air. The most common measure in media broadcasts is RH, the ratio of actual amount of water vapor in the air to the amount required for saturation at a given temperature and pressure. Usually expressed as a percentage, RH only indicates how close air is to saturation and not the actual moisture content of the air; hence, RH is appropriate for local conditions and not broad geographic comparison. The relationship between RH and air temperature is inversely proportional, meaning as one variable increases the other variable decreases and vice versa. The diurnal temperature cycle tends to promote higher (lower) RH during the morning (afternoon) hours when air temperature is cooler (warmer) and saturation is more (less) likely.

Other moisture variables such as dew point, wet-bulb temperature, specific humidity, and mixing ratio are more used in atmospheric science since moisture content is being directly measured or derived. Dew point (or frost point) indicates the temperature air must be cooled to reach saturation and condensation (or deposition) to occur without changing the pressure or moisture content of the environment. Higher (lower) dew points indicate higher (lower) moisture content. Wet-bulb temperature is the lowest temperature that can be achieved through evaporative cooling, a particularly useful parameter for assessing the likelihood of heat related health hazards (e.g., heat stroke). Two similar variables are specific humidity (q) and mixing ratio (r), that examine the ratio of the mass water vapor to either the total mass of the air parcel or the total mass of dry air, respectively. Specific humidity and mixing ratio are absolute measures of water vapor, meaning the actual proportion of water molecules in the atmosphere is being measured (Ackermann and Knox, 2012). Expressed as grams per kilogram ($g\ kg^{-1}$), the range of specific humidity and mixing ratio values are from $<1\ g\ kg^{-1}$ around the poles to $20\ g\ kg^{-1}$ or more over the tropical oceans.

Atmospheric pressure is the amount of force per unit area of the overlying air. The International System (SI) of measurement for atmospheric pressure is the Newton per square meter ($N\ m^{-2}$) or Pascal (Pa). In practice, meteorologists frequently report pressure in hectopascals (hPa) or millibars (mb), where 100 Pa equals 1 mb or 1 hPa. In the United States, media broadcasts and aviation use inches of Mercury (Hg). Since atmospheric pressure decreases at a decreasing rate with height, station pressure readings are usually adjusted to sea-level to compare locations using a standard height. The average sea-level pressure of the earth is 101 100 Pa or 1011 mb (hPa) or 29.85 in. Hg (Ahrens, 2015). In comparison with these average conditions, relatively high pressure readings usually denote fair skies and calm conditions and are associated with sinking air; whereas low pressure periods are associated with cloudiness, precipitation inclement weather, and rising air. Surface stations also report the pressure tendency or the change in pressure over the past 3 h where rising (falling) pressure indicates the approach of a high (low) pressure system.

Atmospheric pressure differences are the driving force in wind development and movement. The pressure gradient force (PGF) or change in pressure over a distance initiates the movement of air from high to low pressure areas. Stronger (weaker) winds occur over areas with reasonably large (small) pressure differences over short (long) distances. In addition to the PGF and gravity, three other forces can impact winds: (1) the Coriolis effect, the apparent force that arises from the Earth's rotation and deflects winds to the right (left) of their path direction in the Northern (Southern) Hemisphere; (2) the centripetal force, the inward-directed force resulting from an imbalance between the PGF and Coriolis effect around curved flow, such as high and low pressure systems; and (3) the friction force, the resistance to wind movement that slows wind speeds, particularly due to surface drag from uneven terrain. Based on the global distribution of semi-permanent surface pressure features and these forces, winds in tropical and polar latitudes tend to flow from the east whereas mid-latitude locations have winds that flow from the west.

Winds are described by direction, speed and gusts and are measured relative to the Earth's rotation (Ahrens, 2015). Wind direction can be conveyed using cardinal directions around a compass (e.g., northeast) or degrees around a circle moving clockwise beginning and ending with true north. Using meteorological conventions, the principal direction winds are coming from dictates the wind name; hence, a westerly wind (270°) is coming from the west and heading eastward. The prevailing winds (or most common wind conditions during a specified time period) are often plotted on a wind rose that shows wind direction frequencies at a location.

Wind speed is the change in distance over time or relative velocity of the local atmosphere. Before the advent of accurate anemometers, the graduated Beaufort wind scale was used to make a qualitative assessment on wind strength based on sea surface conditions, ranging from 0 (calm) to 12 (hurricanes); the modern Beaufort scale attaches wind speeds to the categorical descriptions in kilometers per hour (Moran, 2006). In addition to standard SI and English units, wind speeds are regularly reported in knots where 1 knot equals 0.51 m per second (or 0.87 miles per hour) (Ahrens, 2015). Wind is a vector with magnitude and direction whose vectors may be separated into horizontal (east–west (u) and north–south components (v)) and vertical components (w). Surface station reports may also include information on wind gusts, a sudden and brief increase in wind speed followed by calmer or average wind conditions.

Clouds, fog, and other atmospheric visibility obstructions (e.g., smog, volcanic ash) have both qualitative and quantitative descriptors. Produced from condensation (or deposition) of water vapor in the atmosphere, clouds are characterized according to their shape, composition (liquid, ice, or supercooled droplets), vertical depth, cloud base height, and temperature. Meteorologists recognize ten fundamental cloud types (see **Figure 1**) with numerous subgroups that are coded using internationally recognized symbols and/or letter abbreviations (Pouncy, 2003). Cloud coverage is reported as the percentage of the sky with clouds from the perspective of the surface location. Fog conditions (i.e., cloud cover at the surface) are the suspension of water droplets that reduce visibility to 1000 m (3250 ft) or less (Moran, 2006) and are reported as the furthest horizontal distance seen by a human observer.

The weather elements are either directly recorded from weather stations or indirectly from remote sensing platforms. Numbering over 11 000 stations worldwide (WMO, 2015), weather stations are usually positioned 1.5–2 m high, the level weather most impacts human beings and agriculture. Traditional meteorological instrument shelters known as Stevenson screens are used to shield instruments from the direct solar radiation and precipitation while allowing free air movement around the instruments. Most surface weather observing stations are now automated using an array of electronic sensors, such as the U.S. Automated Surface Observing System (ASOS) (NOAA, 2015). Sea surface temperatures are recorded using ships and ocean buoys. Satellites, radar, airplanes, radiosondes (radio-equipped instrument packages pulled aloft by weather balloons) and other remote sensing tools provide measurements of weather conditions at the surface and throughout the atmosphere. Additional meteorological data are derived through numerical weather prediction models that interpolate atmospheric conditions between data points and extrapolate or forecast spatiotemporal changes in the weather elements.

Scales of Atmospheric Processes

Meteorological phenomenon are often categorized, examined, and forecasted according to their average horizontal size and life span. Ordered from minimum to maximum spatiotemporal scale, the three major classes of weather systems and processes are microscale, mesoscale, and macroscale. Atmospheric processes may further be subdivided by employing criteria other than spatiotemporal characteristics. For instance, Orlanski (1975) and Thunis and Bornstein (1996) proposed alpha (α), beta (β), gamma (γ) and/or delta (δ) subdivisions based on dynamic motion considerations, particularly the Coriolis parameter relative importance, atmospheric static stability, and system oscillation period (**Table 1**). Generally, the average life span of a weather systems increases with increasing size, however the relationship is not linear and some systems are difficult to categorize.

Microscale weather systems (e.g., small dust devils, thermals, turbulent eddies) occur on very short-time scales, ranging from a few seconds to minutes, with an average diameter between less than a meter to a couple kilometers. The local pressure gradient, centrifugal, and frictional forces are important aspects of microscale dynamics; whereas the Coriolis effect is negligible given the short life span. At the microscale, atmospheric processes are dominated by the underlying surface conditions and energy exchanges

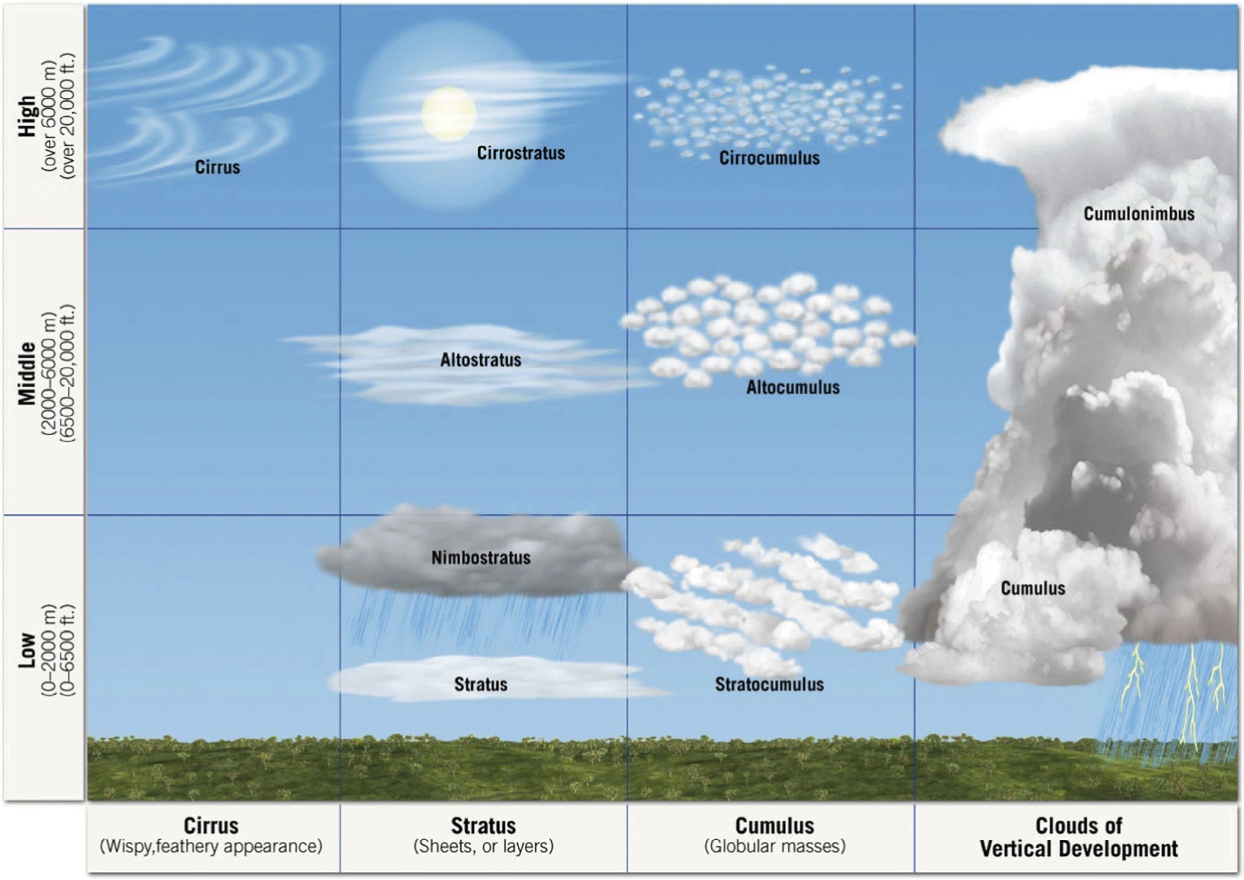

Figure 1 Ten major cloud types. Reproduced from Lutgens et al., 2016. http://www.pearsonhighered.com/bookseller/product/Atmosphere-An-Introduction-to-Meteorology-The-Plus-MasteringMeteorology-with-eText-Access-Card-Package/9780321984425.page

in the lowest portion (<1 km) of the troposphere or planetary boundary layer (PBL). Three main PBL sub-layers exist: (1) the turbulent surface layer, the top layer of the PBL that fluctuates with diurnal fluctuation in small-scale turbulence; (2) the roughness layer, the primary portion of the PBL most influenced by terrain and land cover variability; and (3) the laminar layer, the non-turbulent sector of the PBL that forms a few millimeter thick buffer between the surface and roughness layer (Oke, 1996). Surface friction from obstacles (e.g., urban structures, trees, uneven terrain) and unequal surface heating in the PBL help develop small-scale eddies (spins within the atmosphere) and irregular wind patterns known as turbulence.

Mechanical (friction-induced) and thermal (heating-induced) turbulence create local wind shear conditions or rapid changes in wind speed and/or direction with height. In the PBL, thermals (rising warm air plumes) and short-lived vortices may develop. Dust devils, for example, typically develop in hot arid environments where daytime heating destabilizes the surface air and convection ensues. As the rising wind encounters obstructions, the wind twists into a small rotating column (with diameters typically a few meters) that lifts loose surface debris, including dust. Aloft, mechanical turbulent flow manifests as specialized cloud forms (e.g., lenticular or lens-shaped clouds near mountainous regions) or strong wind velocity gradients in cloudless skies known as clear air turbulence (CAT), a major aircraft hazard.

Lasting several hours to a couple days, mesoscale or middle-sized atmospheric structures (e.g., thunderstorms, sea-land breezes, and squall lines) refers to phenomenon between the microscale and macroscale (about 1–1000 km in diameter). The term mesoscale is often attributed to a radar-based storm observation study conducted by Ligda (1951), referencing large, non-microscale systems that could not be resolved by the current observation network (such as those in the macroscale category). From a dynamic viewpoint, mesoscale phenomenon are motions that are not geostrophic (i.e., the PGF and the Coriolis effect are not balanced) and yet usually meet the criteria for the hydrostatic assumption (the vertical pressure gradient may be approximated by the product of density and gravitational acceleration) (Pielke, 2013). However as the system diameter becomes smaller, the vertical and horizontal scales become more comparable and the hydrostatic approximation is no longer valid such as in mesoscale γ and δ systems (e.g., tornadoes, microbursts).

Mesoscale phenomena result from internal and external forcing mechanisms. Internally forced mesoscale systems generate their structure and circulation from latent heat energy release and dynamic movement stemming from local pressure and temperature gradients. External forcing results in mesoscale features created from other circulation features and processes at the micro and

Table 1 Scales of atmospheric motion (Lin, 2010)

Horizontal Scale	*Lifetime*	*Stull (1988)*	*Pielke (2002)*	*Orlanski (1975)*	*Thunis and Bornstein (1996)*	*Atmospheric phenomena*
	1 month		Synoptic Regional	Macro-α	Macro-α	General circulation, long waves
10 000 km		Macro				
2000 km	1 week			Macro-β	Macro-β	Synoptic cyclones
200 km	1 day			Meso-α	Macro-γ	Fronts, hurricanes, tropical storms, short cyclone waves, mesoscale convective complexes
20 km			Meso	Meso-β	Meso-β	Mesocyclones, mesohighs, supercells, squall lines, inertia-gravity waves, cloud clusters, low-level jets thunderstorm groups, mountain waves, sea breezes
	1 h					
2 km		Meso				
200 m	30 min			Meso-γ	Meso-γ	Thunderstorms, cumulonimbi, clear-air turbulence, heat island, macrobursts
20 m	1 min	Micro		Micro-α	Meso-δ	Cumulus, tornadoes, microbursts, hydraulic jumps
			Micro	Micro-β	Micro-β	Plumes, wakes, waterpouts, dust devils
2 m	1 s			Micro-γ	Micro-γ	Turbulence, sound waves
		Micro δ			Micro-δ	

Adapted from Thunis, P. and Bornstein, R. (1996). Hierarchy of mesoscale flow assumptions and equations. *Journal of Atmospheric Science* **53**, 380–397.

macroscale levels. Mesoscale circulations may be generated from large-scale temperature and vorticity advection, cloud thermodynamic energy transfers, and atmospheric disturbances from surface inhomogeneities, among others (Anthes, 1986; Lin, 2010). For instance, sea breeze circulations are produced from uneven heating between land and water surfaces that yield regional pressure differences and onshore winds.

Macroscale weather phenomena have the largest size (diameter > 1000 km) and longest life span (several days or weeks) of the three classes. Typically, the macroscale category is further subdivided into synoptic or continental scale systems (approximately between 1000 and 10 000 km) and larger planetary-scale features. Synoptic-scale systems encompass larger weather phenomenon from which mesoscale and microscale systems derive, including mid-latitude cyclones, anticyclones, and air masses. Depending on the criteria employed, tropical cyclones, mesoscale convective complexes, and fronts are also classified as a regional, synoptic-scale disturbance (e.g., macro γ in Thunis and Bornstein, 1996).

Stemming from Greek origin, the term synoptic roughly translates to affording a general view of the whole. Synoptic-scale analysis focuses on assimilation of observations over a relatively large geographical area at a given time for weather prediction. Synoptic features have a horizontal scale length several magnitudes larger than their vertical depth and the hydrostatic approximation is considered valid (Lackmann, 2011). Global-scale long waves and the jet stream (a region of high-velocity winds aloft) move synoptic features within them.

Meteorology Subfields and Profession

Meteorology is a broad subject that can be divided into subfields based on different temporal and spatial scales, geographic location, and interdisciplinary specialties. The major scales of atmospheric motion (microscale, mesoscale, and macroscale) are also primary concentration areas with focus on a specific atmospheric phenomenon or application. For example, urban meteorologists examine the effect of city structures and the built environment on local weather conditions and energy fluxes occurring in the PBL.

In addition to the spatiotemporal scale, meteorology can be divided according to geographic area of study. Tropical meteorology focuses on tropical cyclones, monsoon circulations, tropical based teleconnection patterns (e.g., El Niño-Southern Oscillation, Madden-Julian Oscillation) and other equatorial features. Polar meteorology investigates phenomena such as polar cyclones, katabatic (downslope) winds, and sea ice/ocean–atmosphere interactions. Mountain meteorology studies the causes of clouds, precipitation, and wind patterns in mountainous and high-terrain regions as well as the microclimates created by the rapid elevation changes.

Meteorology has a variety of applied specialties that often overlap with other science disciplines. Applied meteorology relates the theory of operational meteorology and forecasting to weather sensitive industries and practices (e.g., agriculture). Fire and forest meteorology focuses on the impacts of weather on wildfire occurrence, fire management and ecosystem health. Biometeorologists investigate how weather affects living organisms and their well-being, such as human health, agricultural yields, and domestic animal performance. Pollution meteorology evaluates the atmospheric chemistry and air quality of not only local sources but also the sources that can contribute to long-range transport of pollutants. Hydrometeorology evaluates methods for observing, modeling, and forecasting processes related to energy and moisture fluxes occurring between the atmosphere and the hydrosphere, crucial aspects for flood control, water management, and drought monitoring. Increasingly, forensic meteorologists are employed by legal firms and insurance adjusters to analyze weather data and given an expert opinion on the extent meteorological conditions were a factor in a contested event (e.g., car accident).

Given the practical applications for general societal concerns and planning, meteorology traditionally has a strong focus on short-term and long-term weather forecasting, including improvements in theory, technology, and communication. Weather forecasts employ numerical weather models which use fundamental equations of motion and heat studied in dynamic and thermodynamic meteorology, respectively. The numerical models use observational input data which are then processed to forecast the future state of the atmospheric conditions. Satellite and radar meteorology use remote sensing technology to monitor and forecast weather system movement and development. Radar meteorology is the field that studies the principles of radar technology for examining precipitation intensity and type, storm relative motion and specialized features (e.g., tornados). Satellite meteorology focuses on improving satellite sensors, algorithms, and interpretation methods. Satellite imagery is used to help determine the development and movement of cloud types, storm systems, wind flow patterns, and moisture content at the macroscale. Information from numerical models and other weather forecasting tools is rather complex and must be simplified and communicated to the general public in a clear, concise manner. The field of broadcast meteorology combines the fields of meteorology and broadcast journalism by stressing the need to effectively communicate sophisticated weather information through television, radio, and other media outlets.

References

Ackermann SA and Knox JA (2012) *Meteorology: understanding the atmosphere*, 3rd edn. Sudbury, MA: Jones and Bartlett Learning.
Ahrens CD (2015) *Essentials of meteorology: an invitation to the atmosphere*, 7th edn. Stamford, CT: Cengage Learning.
Anthes RA (1986) The general question of predictability. In: Ray PS (ed.) *Mesoscale meteorology and forecasting*, Boston, MA: American Meteorological Society, pp. 636–656.

Friedman RM (1989) *Appropriating the weather: Vilhelm Bjerknes and the construction of modern meteorology*. Ithaca, NY: Cornell University Press.
Frisinger HH (1983) *History of meteorology to 1800*. Boston, MA: American Meteorological Society.
Herbertson AJ (1908) *Outlines of physiography: an introduction to the study of the Earth*, 3rd edn. New York: The Century Company.
Lackmann G (2011) *Midlatitude synoptic meteorology: dynamics, analysis and forecasting*. Boston, MA: American Meteorological Society.
Ligda MGH (1951) Radar storm observations. In: *Compendium of meteorology*, Boston, MA: American Meteorological Society, pp. 1265–1282.
Lin Y (2010) *Mesoscale dynamics*. Cambridge, UK: Cambridge University Press.
Lutgens FK, Tarbuck EJ, and Tasa DG (2016) *The atmosphere: an introduction to meteorology*, 13th edn. New York: Prentice Hall.
Moran JM (2006) *Weather studies: introduction to atmospheric science*, 3rd edn. Boston, MA: American Meteorological Society.
National Oceanic and Atmospheric Administration (NOAA). Automated Surface Observing System (ASOS). https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-surface-observing-system-asos (accessed 2015).
Oke TR (1996) *Boundary layer climates*, 2nd edn. New York: Routledge.
Orlanski I (1975) A rational subdivision of scales of atmospheric processes. *Bulletin of the American Meteorological Society* 56: 527–530.
Pouncy FJ (2003) A history of cloud codes and symbols. *Weather* 58: 69–80.
Pielke RA Sr (2013) *Mesoscale meteorological modeling*, 3rd edn. Waltham, MA: Academic Press (2nd edn., 2002).
Stull R (1988) *An introduction to boundary layer meteorology*. Norwell, MA: Kluwer Academic Press.
Thunis P and Bornstein R (1996) Hierarchy of mesoscale flow assumptions and equations. *Journal of Atmospheric Science* 53: 380–397.
Twain M (1887) English as she is taught. *The Century Magazine* 33: 932–934.
World Meteorological Organization (WMO). Climate observation networks and systems. http://www.wmo.int/pages/themes/climate/climate_observation_networks_systems.php (accessed 2015).

Further Reading

Burt S (2012) *The weather observer's handbook*. New York: Cambridge University Press.
Carlson TN (1998) *Mid-latitude weather systems*. Boston, MA: American Meteorological Society.
Petty GW (2008) *A first course in atmospheric thermodynamics*. Danvers, MA: Sundog Publishing.
Stull RB (2000) *Meteorology today for scientists and engineers*, 2nd edn. Pacific Grove, CA: Brooks/Cole Publishing.
Wallace JM and Hobbs PV (2006) *Atmospheric science: an introductory survey*, 2nd edn. Burlington, MA: Academic Press.
Williams J (2009) *The AMS weather book: the ultimate guide to America's weather*. Boston, MA: American Meteorological Society.

Relevant Websites

http://glossary.ametsoc.org/wiki/Main_Page – American Meteorological Society.
http://www.srh.noaa.gov/jetstream/index.htm – National Weather Service (NWS).
https://www.meted.ucar.edu/ – The University Corporation for Atmospheric Research (UCAR).