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Roger G. Barry and Eileen A. Hall-McKim
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Introduction

Automatic weather station in the Apennine Hills near Madigliana, Romagna, Italy.

WE BEGIN by defining climate and weather and then explaining their significance in everyday life. This helps clarify the scope and importance of climatology and its place in environmental sciences. Following a brief introduction to climatic data and frequently used statistics, we review the history of world climatology over the last two centuries. Finally, we examine the contribution of weather satellites to the study of weather and climate beginning in the 1960s.

1.1 Climate and weather

The word *climate* is derived from the Greek word "klima," meaning slope, and was linked to temperature gradients from Equator to Pole. It entered the English language from French in the thirteenth century. Its modern meaning evolved in the sixteenth century.

Climate is the sum total (or composite) of the weather conditions that generally prevail at a place or over a region. It encompasses the statistics (means, variability, and extremes) of temperature, humidity, atmospheric pressure, wind velocity, cloud cover, precipitation, and other meteorological variables over a long period of time. In contrast, weather is the condition of these same elements and their variations over time intervals of a few days. Conventionally, weather extends out to about 10–15 days – the limit of numerical weather prediction – while longer intervals, typically a month, are considered as part of climate. The "standard" interval used to define climatic characteristics by the World Meteorological Organization (WMO) is 30 years, and these data are called "normals." This term was first used for 1901–1930; the current normal is 1961–1990 or 1981–2010, depending on data availability. However, world weather records were earlier published for 1881–1920. The 30 years must be consecutive and the averages are unweighted. The normals are updated by national climate organizations and the WMO each decade.

Another, much broader definition, that recognizes the complexity of climate, was proposed by the US Committee for the Global Atmospheric Research Program in 1975. It refers to the climatic state as "the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric, and cryospheric variables over a specified period of time (monthly, seasonal, annual, decadal) in a specified domain of the earth–atmosphere system." Hydrospheric variables refer to all components of the global water cycle, while cryospheric variables refer to all forms of snow and ice. An updated version of this would also include the biospheric variables on land and in the ocean that affect transfers of energy, water, momentum, and gases between the surface and the atmosphere. The complexity of the climate system is illustrated in Figure 1.1, showing the atmosphere, oceans, hydrosphere, biosphere, and cryosphere. These components, their changes, and their interactions are the subject of this book. Hence, climate is a key element of the global and local environments that has enormous influence on most aspects of our daily lives, whether we live in rural or urban areas. It determines what crops can be grown, how much water is available for drinking and irrigation, and what kinds of shelter and clothing we need.

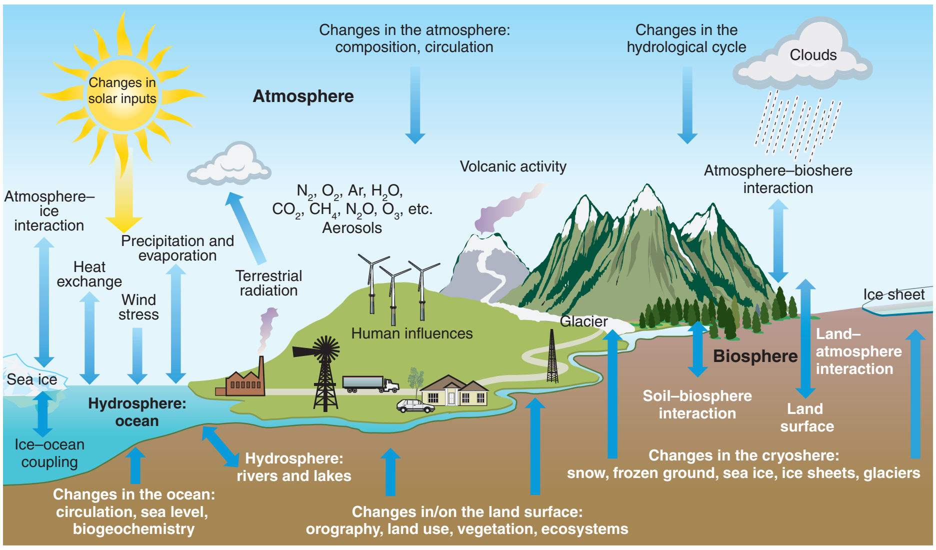

Figure 1.1 The climate system (from Solomon *et al*. 2007, p. 767, Fig. 10.9).

1.2 Why climate matters

Weather affects our day-to-day life and decisions – whether we need an overcoat, umbrella, snow boots, or sunscreen and, in the case of severe weather like thunderstorms or tornadoes, when and where to take shelter. Weather also has major effects on all forms of transportation on land, at sea, and in the air. Climate influences what kind of house we build or buy, whether it has air conditioning or double-glazed windows, and whether it has a flat or sloping roof. It also determines the nature of the local vegetation and agriculture, whether irrigation is needed or not, and the character of the water supply.

Until the mid twentieth century it was considered that climate was essentially constant, but in the 1950s it became widely recognized that as well as ice age events in the distant past, there were important fluctuations on decadal to centennial time scales. We examine changes on these various time scales in Chapter 10. It is also now known that human activities are largely responsible for global warming that began in the late nineteenth or early twentieth centuries and has accelerated over the last few decades. There has been an increasing incidence of heat waves and droughts, as well as floods in other areas. The use of refrigerants (chlorofluorocarbons, or CFCs) led to the formation of the ozone hole in the Antarctic stratosphere, above 15 km, that allows dangerous levels of ultraviolet radiation from the sun to reach the surface in southern South America and Antarctica. While the Montreal Protocol, adopted by most nations of the world

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in 1987, regulated substances thought to destroy stratospheric ozone, there is still no similar international agreement to regulate gases and pollutants in the atmosphere that cause global warming. Apart from the immediate climatic effects, warming is causing glaciers to shrink and disappear, with consequences for water supplies and global sea level; Arctic sea ice is retreating and thinning; the Greenland and Antarctic ice sheets are losing mass; and plant and animal species, including pests and diseases, are shifting to new areas. For all these reasons, knowledge and understanding of climate and climatic processes are key aspects of environmental science.

1.3 Climate statistics

The standard statistics that are used in climatology are the arithmetic mean (or average) and a measure of the variability such as the standard deviation (see Box 1A.1). For example, temperature values that vary widely from day to day have

Box 1A.1 **Climatological statistics**

We provide here a brief summary of the principal statistical measures that are used in climatology.

The arithmetic mean ($\bar{x}$) is the sum of the values, x_i, divided by the number of observations (N):

$$\bar{x}_i = \sum x_i / N.$$

The variability of a record is usually specified by the standard deviation, which is the square root of the average sum of squares of the departures of the individual values from the mean (S_N):

$$S_N = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x}_i)^2}.$$

One simple measure of variation is the range – the difference between the maximum and minimum values, either averages or absolute extremes; thus there is a daily range, a monthly range, and an annual range. Another measure is the interquartile range – the difference between the 75th and 25th percentiles in a ranked sequence of the values.

The coefficient of variation (CV) is given by the standard deviation divided by the mean, sometimes expressed as a percentage. This provides a relative measure of variability. It is only suitable for ratio data, such as rainfall amounts (not interval data such as temperature), and it is unreliable if the mean is close to zero, or the distribution of values is not roughly normal. Values of the CV of annual rainfall in western Europe are typically 10–20 percent.

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a high standard deviation, whereas those that vary little have a low standard deviation. These values are acceptable for variables such as radiation, temperature, pressure, and moisture content, which are more or less normally distributed (i.e., they cluster around the mean value), but are unsuitable for elements like precipitation and wind speed, which are bounded by a lower value of zero, or cloud amounts that have lower and upper bounds (clear skies and overcast). In such cases the median (central 50 percent value of a numerically ranked distribution) and quartile (25 and 75 percent) values may be appropriate measures of the average value and the range of variation. A further measure of average is the most frequent value – the mode. This is obtained by grouping frequency values into classes that are separated by equal intervals (e.g., 0–5, 6–10, 11–15, etc.) and determining by inspection the class with the highest frequency.

To highlight the point made above, an illustration of the characteristic frequency distributions of common meteorological variables is shown in Figure 1.2. A frequency distribution is a plot of the absolute or percentage frequencies of a data set on the vertical axis against equal-sized groups of the values on the horizontal axis. It should be noted that frequency distributions change shape as the averaging period changes. Thus, for example, hourly precipitation amounts are highly negatively skewed (toward zero), whereas annual totals are closer to a bell-shaped normal (also called Gaussian) distribution. In a normal distribution 95.4 percent of values lie within ± 2 standard deviations of the mean and 99.7 percent lie within ± 3 standard deviations. To isolate outliers, which may be erroneous, in a data set a threshold of four standard deviations is sometimes adopted to screen the data for closer examination. In a normal distribution the mean, median, and mode are equal.

The data that go into climatic "normals" may be hourly values for daily averages, daily values for monthly averages, and monthly values for annual averages. In the case of daily averages, these may be based on 24 hourly values, four six-hourly values, or the average of the daily maximum and minimum readings. Each of these will give a different mean daily value. It should be noted that the basis for such determinations has often changed over time and so a careful check of the station information (or metadata) describing such practices is needed before processing averages for long-term data sets. Missing data can be treated by substituting long-term average values, which does not bias the mean, or by various interpolation or extrapolation approaches using, respectively, data from the station in question, or data from surrounding stations.

A further consideration is the spatial averaging of climatological data. Station data are irregularly distributed in space, whereas model output and satellite data are usually gridded. Station data need to be interpolated to produce spatial maps; this can be accomplished manually by a skilled analyst or by employing a numerical smoothing routine. Such interpolation and mapping is relatively

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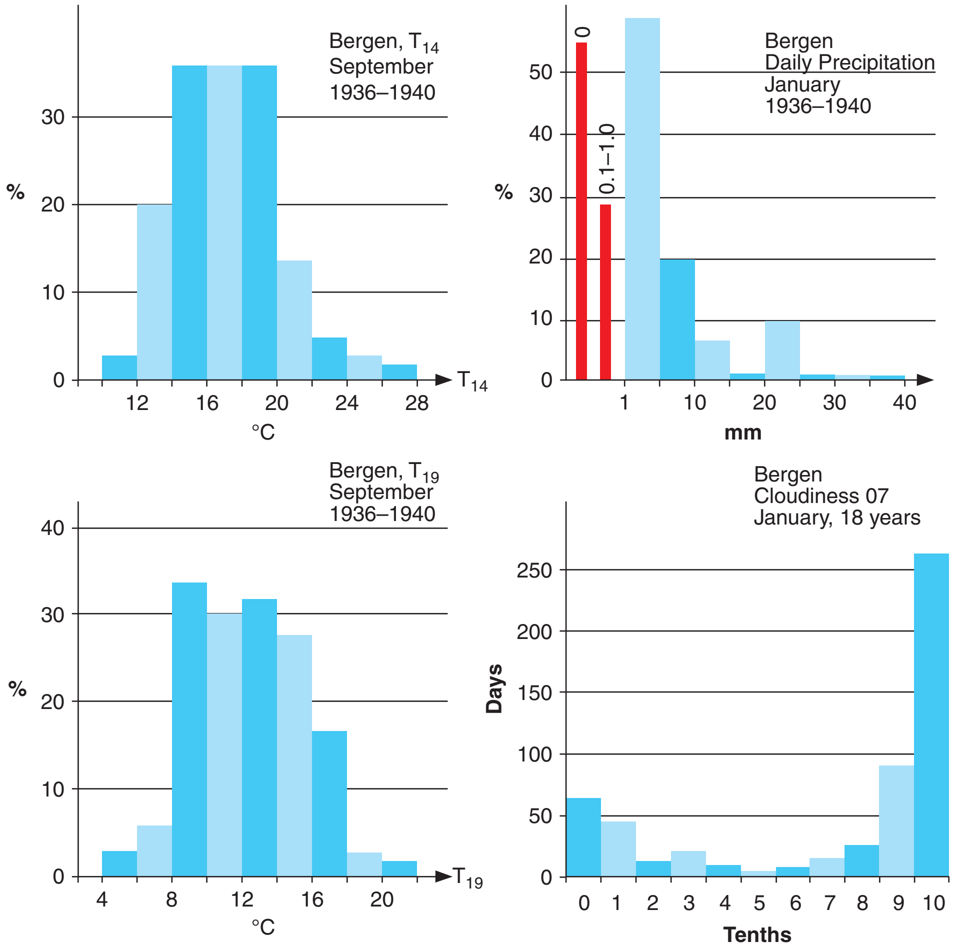

Figure 1.2 Typical frequency distributions of selected meteorological variables at Bergen, Norway (air temperature at 14:00 and 19:00 hours, daily precipitation totals, and cloud amount) (source: after Godske 1966).

straightforward in lowland or plateau areas, but much more difficult in complex and mountainous terrain where the vertical gradients of climatic elements vary according to the variable under consideration, as discussed extensively by Barry in *Mountain Weather and Climate* (2008).

1.4 History of world climatology

Scientific studies of meteorology began when instruments were invented to measure weather elements, notably pressure (the barometer) and temperature (the

Box 1B.1 **Earliest meteorological network**

The earliest meteorological station network was organized in Bavaria in 1780 by the Societas Meteorologica Palatina, based at the Mannheim Academy of Sciences. It operated until 1795, collecting records annually and publishing them over 1781–1792. At its greatest extent there were simultaneous records at 31 stations. For at least one year there were 37 stations, stretching from the Urals, through Europe, to eastern North America.

The instruments and data were standardized. The system anticipated the state networks that developed some 60 years later.

thermometer). The mercury barometer was invented by E. Torricelli in 1643. The mercury thermometer with a scale was invented by D. G. Fahrenheit in 1724. These instruments evolved during the seventeenth and eighteenth centuries, respectively, mainly in Europe. The earliest daily barometric pressure readings were made in Pisa, Italy, in 1657–1658. The earliest temperature readings were made in Uppsala, Sweden, beginning in 1722, with calibrated readings (using the Celsius scale) in use from 1739. Rainfall is reported to have been measured in Greece in 500 BC and in India a century later, but the first records, starting from 1725, were assembled in Britain in 1870 by G. J. Symons. A useful overview of meteorological observations and instruments and their characteristics is provided by Strangeways in his book *Measuring the Natural Environment*. The earliest network of weather stations was set up in the late eighteenth century (see Box 1B.1). Standards for instruments and their exposure were agreed internationally in the late nineteenth century when weather data began to be exchanged via the telegraphic networks, which enabled the collection of weather reports to nearly keep pace with the weather.

Knowledge of world climate also evolved from the late seventeenth to nineteenth centuries. In 1686, British scientist Edmond Halley published a map of the trade winds in the tropical oceans, based on a voyage to the Southern Hemisphere. In 1817, the famous German geographer Alexander von Humboldt published the first map of annual mean temperature in the Northern Hemisphere showing isotherms (lines of equal temperature). In 1832 it was debated at the annual meeting of the British Association for the Advancement of Science whether pressure was the same over the globe. However, a decade later latitudinal differences of air pressure were being reported and discussed.

The term climatology, meaning the science of climatic zones or regions, first came into use in the 1850s. Scientific study of world climatology began in the mid-nineteenth century when sufficient meteorological observations became available

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to construct world maps of selected variables – pressure, winds, and temperature being among the first. In Germany in 1848, Heinrich Dove produced world maps of monthly mean temperature. In Great Britain in 1860, Robert FitzRoy used telegraphic weather reports to produce the first synoptic weather maps. A *synoptic weather map* is a generalized view of the weather conditions over a region at a fixed time. It shows lines of pressure, winds, temperature values, clouds, and weather conditions. The winds of the Northern Hemisphere were analyzed in 1853 by J. H. Coffin, who went on to carry out a global analysis two decades later. In the 1860s, A. Buchan surveyed the mean global pressure distribution and the prevailing winds on a monthly basis. In 1882, E. Loomis prepared the first map of global precipitation and in 1886 Teisserenc de Bort published the first world maps of monthly and annual cloudiness. In 1897–1899, J. Bartholomew published an atlas of meteorology containing world maps of:

- mean annual temperature and monthly temperatures;
- anomalies, extremes, and ranges of temperature;
- isobars (lines) of mean annual pressure, and mean monthly pressure and winds;
- monthly isonephs (lines of cloudiness);
- monthly isohyets (lines of rainfall);
- monthly storm tracks and frequency;
- annual frequency of thunderstorms;
- average typhoon tracks.

In addition, the atlas contained numerous continental and regional charts.

A further step was taken when *climatic classifications* were developed, notably by Vladimir Köppen around 1900 (see Box 1B.2). His first complete version was published in 1918. The classification combines thermal and moisture categories in a globally applicable scheme that takes account of seasonal characteristics. The boundaries between categories were obtained by determining temperature and moisture values that closely corresponded with vegetation boundaries, such as the Arctic tree line with a July mean temperature of 10 °C. A new version of the Köppen world map is presented in Figure 1.3. The authors also provide maps for each continent.

The five major categories of climate are:

A equatorial climates
B arid climates
C warm temperate climates
D snow climates
E polar climates.

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Box 1B.2 **Vladimir Köppen**

Köppen was born of German descent in St. Petersburg, Russia, in 1846. After studying in Russia he spent most of his life in Germany and Austria. In 1875–1879 he was the chief of the new Division of Marine Meteorology at the German naval observatory (Deutsche Seewarte) based in Hamburg. There, he was responsible for establishing a weather forecasting service for the northwestern part of Germany and the adjacent sea areas. He then moved to a career in research and began working on the relationships between climate factors and vegetation types in the 1880s. He published a first version of his classification of world climate in 1900 and the final version in 1936. In 1924 he and his son-in-law Alfred Wegener published a paper on the climates of the geological past, providing crucial support to the newly published Milanković h theory on Ice Ages, although this was not accepted until the 1960s (see Chapter 10). He died in Graz, Austria in 1940.

The five categories are each subdivided according to the precipitation seasonality (s = dry summer, w = dry winter, f = no dry season). In the equatorial category there is also a monsoon subdivision. The arid climates are subdivided according to degree of aridity into desert (BW) and steppe (BS). The polar climates are subdivided based on temperature into tundra (ET) and frost climate (EF). The characteristics of the climatic types are described in Chapter 9.

A major synthesis of *The Climates of the Continents* was prepared by W. C. Kendrew in 1922 in Great Britain, and appeared in a fifth edition in 1961. In Germany, similar works were published by Köppen in 1923 and Köppen and Geiger in 1930. More recently, the *World Survey of Climatology*, in 16 volumes, was edited by Helmut Landsberg. This includes climatic information about all regions of the world and information about the physical processes of the climate system. The first study of microclimates – Rudolf Geiger's *Climate near the Ground* – appeared in German in 1927; a sixth, English, edition was published in 2003. The first text on physical climatology was published by W. Sellers in 1965 with a more recent work by D. Hartmann in 1994. The first textbook on synoptic climatology – the study of climate as described by airflow and circulation patterns – was written by R. G. Barry and A. H. Perry in 1973. Twenty years later, B. Yarnal wrote a primer on synoptic climatology and, in 2001, Barry and A. M. Carleton published *Synoptic and Dynamic Climatology*, dealing with the mechanisms of global climate and atmospheric circulation, and its spatial and temporal variations. *A Climate Modeling Primer* was published by A. Henderson-Sellers and K. McGuffie in 1987, with a third edition in 2005.

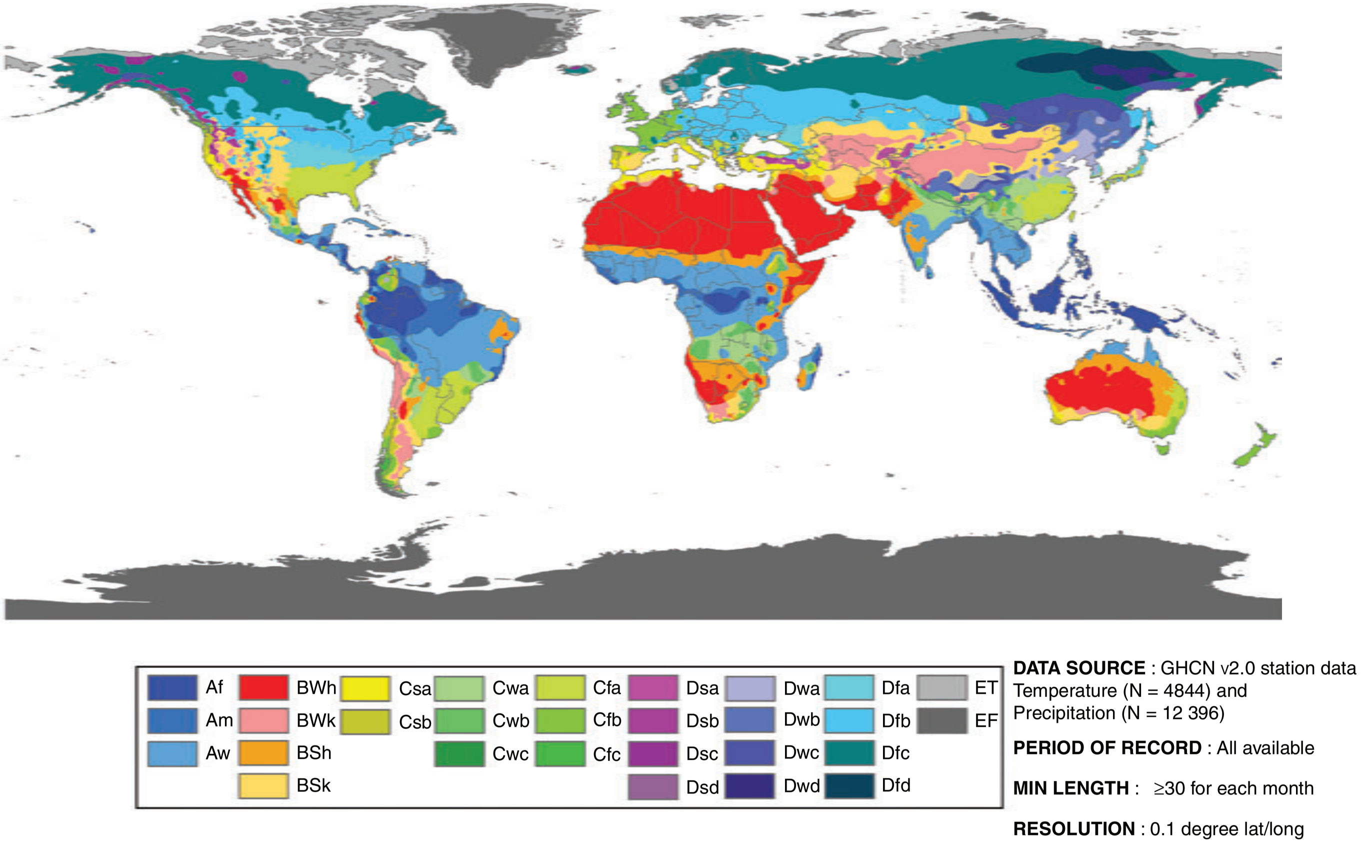

Figure 1.3 World map of the Köppen–Geiger climate classification updated (Peel *et al*. 2007). The map is based on data from the Global Historical Climatology Network (GHCN) that are most representative of the period from 1909 to 1991 for precipitation and 1923 to 1993 for temperature (Source: Peel *et al*. 2007)