Chapter 17
Climate Classifications

Abstract   There are different criteria used to classify climates. The most common classification is the Köppen-Geiger classification that recognizes five major climatic zones: Tropical, Dry, Moderate (or Temperate), Continental, and Polar with sub-zones under each. Classifications of climate systems include those based on their origin or those based on their effects. The Bergeron classification is based on areas of origin for air masses. Thornthwaite devised a climate classification built on the physical interactions between local moisture and temperature. Disruption of climate and of the Jet Stream in the Northern Hemisphere due to arctic warming and sea ice melting is a concern.

Keywords Climate • Classification • Köppen • Biome • Bergeron • Polar • Taiga • Continental • Geiger • Thornthwaite • Steppe • Humid • Desert • Cyclones • Synoptic • Subarctic • Rainforest • Tundra • Boreal • Savanna • Stream • Jet • Sea • Ice • Geosphere • Atmosphere • Moist • Tropical

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Köppen-Geiger classification	Thornthwaite classification
World climate zones	Polar
Jet Stream	Bergeron classification
Spatial synoptic classification	Rainforest
Tropical savanna	Alexander von Humboldt
Biome	Humid subtropical
Cyclones	Mediterranean climate
Steppe	Subarctic
Oceanic climate	Tundra
Taiga climate	Geosphere
Boreal climate	Sea ice
Precipitation effectiveness	Thermal classifications

17.1   An Introduction to Climate Classification

The definition of climate includes the weather of an area but it is not the same as weather, as has been discussed earlier. The climate is different in the Sahara than it is in Florida and the weather patterns are also different. The weather is what is happening now and may include a prediction such as "a 10% chance of rain tomorrow" or "it will be chilly tomorrow with a high of 50°," or "the chance of snow is 20%"; "the wind will be 15 mph out of the southwest" or it was like that yesterday or last week. Weather is short-term, climate is long-term. One can generalize about climate and state that it is milder near the tropics, harsher as one goes toward the poles. The mild climate near the equator may be interrupted by hurricanes or monsoons or other storms, but in the mid-latitudes there is little letup.

There is concern about the effect of climate change on weather in many parts of the world. Inhabitants of the Northern Hemisphere in particular are already seeing a disruption of "normal" weather patterns and as the climate continues to change, weather patterns will continue to be impacted.

A major concern among climate scientists is the future of the Jet Stream and its effect on weather in the Northern Hemisphere. The Jet Stream is a major air current of high-altitude air circling the globe in the Northern Hemisphere. This current has a major influence on climate as it meanders across the Northern Hemisphere continents and ocean basins. It separates warm air in the south from cold air in the north. The extent of the northern ice cap is decreasing rapidly due to global warming. As the ice recedes, more sunlight is absorbed by ocean waters and the Jet Stream is affected as the warming Arctic gives up more heat to the atmosphere. This causes the Jet Stream to slow and develop a widely meandering path when looked upon from above. The result is more warm air moving north and more cold air moving south.
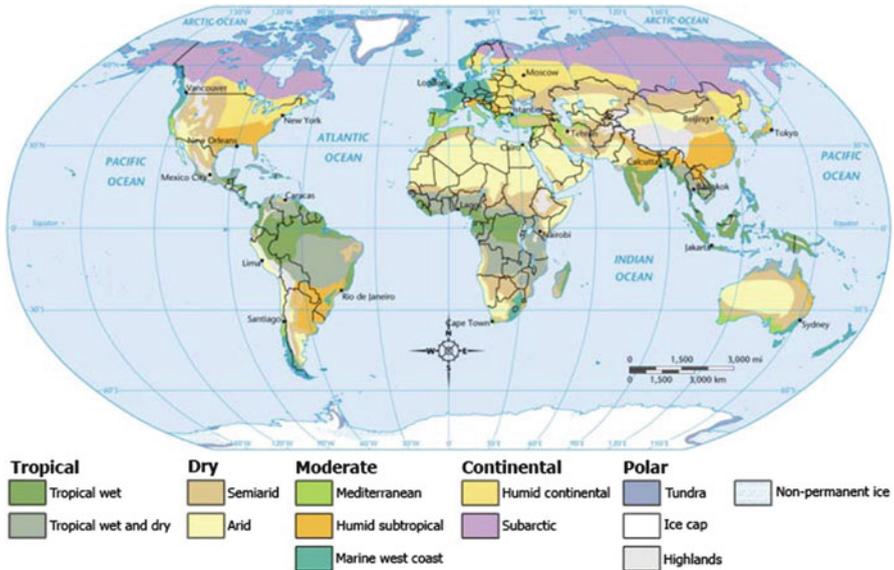
Fig. 17.1   The world's major climate zones

The result, in combination with more energy in the atmosphere, is greater instability in the Northern Hemisphere and a greater chance of severe storm activity.

The climate system is part of the Earth system and consists of the following spheres of influence: atmosphere, hydrosphere, cryosphere, geosphere, and biosphere. These spheres interact and the result is a complex climate system with a great many variables. However, it is possible to classify different aspects of the climate system and examine different types of climate throughout the globe.

The most common global climate classification used today is the Köppen-Geiger classification, usually referred to as the Köppen (often misspelled as "Koeppen") climate classification, which consists of five different climates designated Tropical, Dry, Moderate, Continental, and Polar (as seen in Fig. 17.1). Modern climate classifications fall into two groups: those that are based on origin (genetic) and those based on effects (empiric).

The original Greek word *klima*, from which the word climate is derived, was used to refer to the Sun's radiation angle of incidence with the Earth. The seasonal variation of this inclination depends on latitude and the Earth's position relative to the Sun. Early naturalists (Egyptian, Roman, and Greek) were aware of the profound effect of latitude on climate. In 1817 Alexander von Humboldt, a German naturalist, drew annual-mean temperatures on a world map. Wladimir Köppen (1846–1940) refined von Humboldt's map and plotted seasonal temperature ranges leading to his climate classification. Köppen's classification followed that

of plants with major categories subdivided, and then subcategories divided again, etc. In fact Köppen had initially studied botany and completed a Ph.D. at Heidelberg, Germany on the effect of temperature on plant growth. At the highest level his system is based on five sets of temperature limits. These were developed from his categorization of thermal zones suited to various kinds of vegetation.

Köppen deduced geological climates in support of the continental drift theory formalized by his son-in-law, Alfred Wegener. He also became associated with Rudolf Geiger (1894–1981) and collaborated with him in producing a system of climate classification. Geiger was later responsible for further revisions. Geiger also established the discipline of microclimatology.

17.2   Air Masses

The atmosphere consists of air masses or bodies of air that have a set of characteristics such as temperature and moisture. These characteristics vary from one air mass to another. Air masses often show a fairly homogeneous temperature lapse rate (vertical temperature decrease with altitude) above the influence of the surface layer. At any given time, an estimated 50 distinct air masses are scattered across the face of the planet. Some are newly born and reflect their origin. Others are older and have only the smallest indication of their place of origin.

Different air masses are separated by narrow transition zones that analysts or meteorologists distinguish by drawing weather fronts, such as warm, cold, stationary and occluded fronts, between them. Sometimes these fronts indicate subtle transitions, perhaps only a shift in wind direction and they are hardly noticed as they pass. Others are vigorous where conflicts between warm and cold air masses produce strong weather systems such as severe thunderstorms, tornadoes, or heavy snowfalls. Often, the difference between air masses is so great that large cyclonic weather systems develop along the frontal boundary to cause the surface beneath to have high winds, rapidly changing temperatures, and heavy precipitation.

The differences among air masses was likely first recognized when humans realized that major changes in weather had recognizable, repeatable patterns such as cold, dry conditions coming from the north; hot and dry or hot and humid weather coming from the south.

Before the seventeenth century, early meteorologists used their senses to distinguish difference between air masses. In the seventeenth century, the invention of instruments such as the thermometer, barometer, and hygrometer allowed observers to objectively measure properties of the air. With the advent of regular weather observations across large regions of the continents and weather and climate records from locations around the globe, meteorologists began to see repeatable patterns that showed large bodies of air that could be distinguished by their degrees of temperature and humidity.

The first formal and widely disseminated theory of the impact of air mass differences came out of the famed Bergen School of Meteorology in Norway during the

early decades of the 1900s. The Norwegian research group, which included Tor Bergeron, laid the foundation for modern weather analysis and forecasting. The group developed the concepts of frontal analysis, wave cyclone formation, and air mass analysis to name but a few of their achievements. Bergeron confirmed that certain characteristics of air masses did not substantially change for long periods of time as the air mass flowed over oceans and continents. Therefore, Bergeron concluded that knowledge of these characteristics was fundamentally important to improving weather forecasts.

Bergeron saw air masses as being of four types based on their area of origin: Equatorial, Tropical, Polar and Arctic (or Antarctic). From this, he developed a classification scheme that included distinguishing properties of temperature, humidity and aerosol content. With slight modifications, his classification system remains a viable concept today in weather analysis and forecasting.

Approximately 50 distinct air masses can be identified in the lower atmosphere near the surface of Earth at any one time. Most cover thousands of square kilometers and extend several kilometers vertically. Each one bears the mark of the region in which it was formed. Some of the 50 are young and fresh. Others are old and greatly transformed. Some are moving across the planet at speeds covering several hundred kilometers each day, others are nearly stationary.

Air masses acquire their characteristic temperature and moisture (or absolute humidity) signature from the source regions over which they are born. The ideal source region is one with light winds, particularly in the upper atmosphere so that the air mass remains in place long enough to acquire the temperature and moisture properties of the underlying surface throughout the air mass. Therefore, middle latitude regions where the weather systems move quickly across their surface, driven by fast-moving upper level air currents such as the Jet Stream are not good air mass breeding grounds.

Areas dominated by extensive areas of high pressure and light winds are the ideal breeding grounds for air masses. There are several such areas of extensive, semi-permanent high pressure around the globe in particular, two latitude belts in each hemisphere; one in the Polar Regions and the other in the subtropics.

Bergeron's classification system categorizes a place according to the frequencies with which it experiences various kinds of air mass. Each air mass is labeled in terms of the latitude at which its temperature had been determined previously, and the kind of surface there, either marine or continental (Figs. 17.2 and 17.3).

In the U.S., Warren Thornthwaite (1892–1963) developed a hierarchical classification based on the annual pattern of soil-moisture conditions. These were regarded as depending in a complicated manner on the monthly input as rain, and implicitly on the output as evaporation, indicated by temperature. Studies in New Zealand, for example, showed that Thornthwaite's classification made more sense than Köppen's, except at low latitudes. Later, the connection to soil moisture was made more explicit in Thornthwaite's landmark approach toward a more rational classification of climate. However, it involved an empirical formula for estimating evaporation, which was superseded the same year by the physics-based formula of Howard Penman (1909–1984) in England.
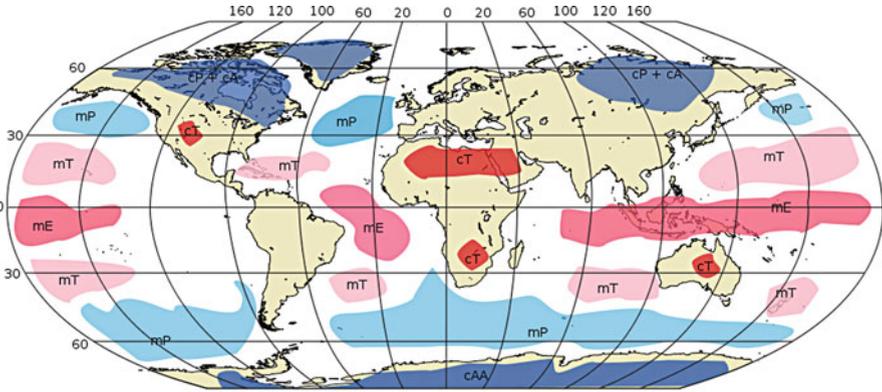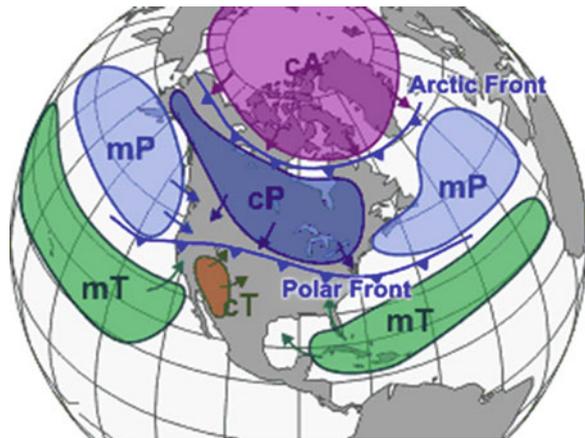
Fig. 17.2 Source regions of global air masses. (NASA, Public Domain)

Fig. 17.3 Source regions of
common air masses (NOAA,
Public Domain)

All these classification systems differ from what has been done since, in solving
practical problems. Now climatologists use complex statistical procedures to group
the climates of places and to define areas of similar climates.

Climate in a narrow sense is usually defined as the description in terms of the mean
and variability of relevant quantities (e.g., temperature and precipitation) over a period
of time ranging from months to thousands or millions of years. The usually accepted
period for accepted climate data is 30 years, as defined by the World Meteorological
Organization (WMO). These quantities are most often surface variables such as tem-
perature, precipitation, and wind. Climate in a wider sense is the variation, including
a statistical description, of the climate system in an area or region.

Over geological time spans there are a number of nearly constant variables that determine climate including latitude, altitude, proportion of land to water, and proximity to oceans and mountains. These change only over spans of millions of years due to processes such as plate tectonics, continental drift, and mountain building. Other climate determinants are more dynamic; for example, the thermohaline circulation of the ocean leads to a 5°C (9°F) warming of the northern Atlantic Ocean compared to other ocean basins. Other ocean currents redistribute heat between land and water on a more regional scale. The density and type of vegetation coverage affects solar heat absorption, water retention, and rainfall on a regional level. Changes in the concentration of atmospheric greenhouse gases determine the amount of solar energy retained by the planet, leading to global warming or global cooling. The variables which determine climates are numerous and their interactions complex, but there is general agreement that the broad outlines are understood, at least as for the determinants of historical climate change are concerned.

17.3   Modern Climate Classification

Modern climate classification methods can be broadly divided, into (a) generic methods which focus on the causes of climate, and (b) empiric (or empirical) methods, which focus on the effects of climate. Examples of generic classification include methods based on the relative frequency of different air mass types or locations within synoptic (i.e., relating to or showing simultaneous weather conditions over a large area) weather disturbances. Examples of empiric classifications include climate zones defined by plant hardiness, evapotranspiration, or more generally the Köppen-Geiger climate classification which was originally designed to identify the climates associated with certain biomes (see Fig. 17.1). A common shortcoming of these classification schemes is that they produce distinct boundaries between the zones they define, rather than the gradual transition of climate properties as seen in nature.

17.3.1   The Bergeron Climate Classification

The most generic classification is that involving the concept of air masses. The Bergeron classification is the most widely accepted form of air mass classification. Air mass classification involves three letters (Figs. 17.2 and 17.3). The first letter describes its moisture properties, with c used for continental air masses (dry) and m for maritime air masses (moist). The second letter describes the thermal characteristic of its source region: T for tropical, P for polar, A for Arctic or Antarctic, M for monsoon, E for equatorial, and S for superior air (dry air formed by significant downward motion in the atmosphere). The third letter is used to designate the stability of the atmosphere. If the air mass is colder than the ground below it, it is

labeled k. If the air mass is warmer than the ground below it, it is labeled w. While air mass identification was originally used in weather forecasting during the 1950s, climatologists began to establish synoptic (i.e., general) descriptions based on this idea in 1973.

The Spatial Synoptic Classification System (SSC) is based on the Bergeron classification scheme. There are six categories within the SSC scheme: (1) Dry Polar (similar to continental polar), (2) Dry Moderate (similar to maritime superior), (3) Dry Tropical (similar to continental tropical), (4) Moist Polar (similar to maritime polar), (5) Moist Moderate (a hybrid between maritime polar and maritime tropical), and (6) Moist Tropical (similar to maritime tropical, maritime monsoon, or maritime equatorial).

17.4   The Köppen-Geiger Classification

The Köppen-Geiger classification depends on average monthly values of temperature and precipitation (Fig. 17.4). The most commonly used form of the Köppen-Geiger classification has five primary types labelled A through E. These primary types are A, tropical; B, dry; C, mild mid-latitude; D, cold mid-latitude; and E, polar. The five primary classifications can be further divided into secondary classifications such as rain forest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic climate, Mediterranean climate, steppe, subarctic climate, tundra, polar ice cap, and desert.

17.4.1   Group A Climates

Tropical climates (A) are characterized by high temperatures at sea level and lower elevations all year (12 months). Their temperatures average 18°C (64°F) or higher.

Tropical rain forests (Af) are characterized by high rainfall, with definitions setting minimum normal annual rainfall between 1,750 mm (69 in.) and 2,000 mm (79 in.). Mean monthly temperatures exceed 18°C (64°F) during all months of the year. Examples are Hilo, Hawaii and Singapore.

A tropical monsoon (Am) climate is a seasonal prevailing wind which lasts for several months, ushering in a region's rainy season. Regions within North America (Miami, Florida), South America, Sub-Saharan Africa, Queensland, Australia, and East Asia are monsoon regimes.

A tropical savanna (Aw) is a grassland biome located in semi-arid to semi-humid climate regions of subtropical and tropical latitudes, with average temperatures remain at or above 18°C (64°F) year round and rainfall between 750 mm (30 in.) and 1,270 mm (50 in.) a year. They are widespread on Africa, and are also found in India, the northern parts of South America (Rio de Janeiro, Brazil), Malaysia, and Australia (Darwin, Northern Territory).
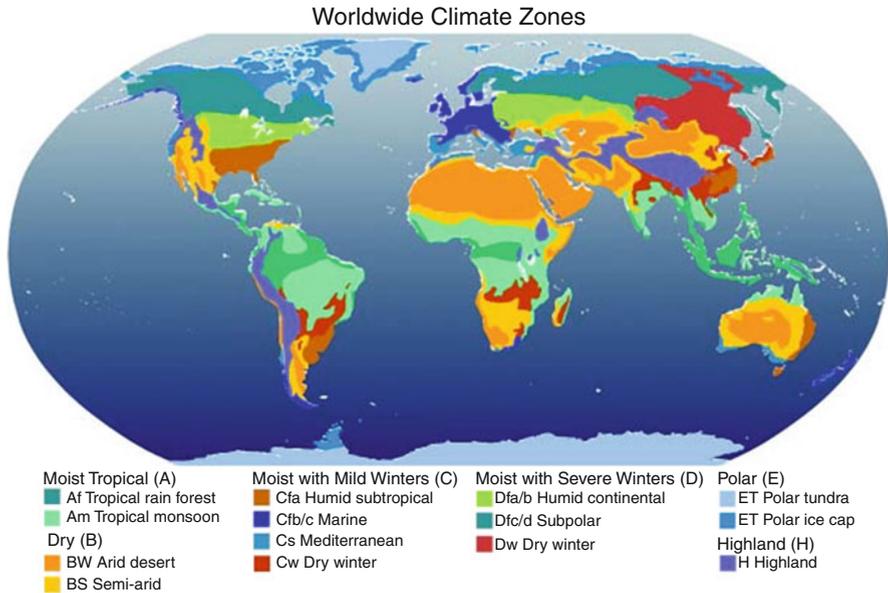
Worldwide Climate Zones

Moist Tropical (A)	Moist with Mild Winters (C)	Moist with Severe Winters (D)	Polar (E)
■ Af Tropical rain forest	■ Cfa Humid subtropical	■ Dfa/b Humid continental	■ ET Polar tundra
■ Am Tropical monsoon	■ Cfb/c Marine	■ Dfc/d Subpolar	■ ET Polar ice cap
Dry (B)	■ Cs Mediterranean	■ Dw Dry winter	Highland (H)
■ BW Arid desert	■ Cw Dry winter		■ H Highland
■ BS Semi-arid			

Fig. 17.4 World map of the Köppen-Geiger climate classification (From UCAR/NOAA, The COMET Program, Public Domain)

17.4.2   Group B Climates

Group B climates are dry, arid and semiarid climates. Precipitation is less than evaporation. BW is a desert climate and Bs is a steppe climate. A third letter can be used to indicate temperature, e.g., Yuma, Arizona (BWh).

A steppe is a dry grassland with an annual temperature range in the summer of up to 40°C (104°F) and during the winter down to −40°C (−40°F). Steppes are usually characterized by a semi-arid and continental climate. Extremes can be recorded in the summer of up to 40°C (104°F) and in winter, –40°C (–40°F). Besides this huge difference between summer and winter, the differences between day and night are also great. In the highlands of Mongolia, 30°C (86°F) can be reached during the day with sub-zero °C (sub 32°F) readings at night.

The mid-latitude steppes can be summarized by hot summers and cold winters, averaging 250–500 mm (10–20 in.) of precipitation per year. Precipitation level alone is not what defines a steppe climate. Potential evapotranspiration must also be taken into account. Prairies are steppe climates such as the central U.S. and western Canada.

17.4.3   Group C Climates

Group C climates are those temperate climates with an average temperature above 10°C (50°F) in their warmest months and a coldest month average between −3°C (27°F) and 18°C (64°F).

Mediterranean climates are dry-summer subtropical climates. They occur on the western side of continents between latitudes of 30° and 45°. Summers are hot and dry. Athens, Greece, Tel Aviv, Israel, Cape Town, South Africa, Los Angeles, California are examples.

The Mediterranean climate regime resembles the climate of the lands in the Mediterranean Basin, parts of western North America, parts of Western and South Australia, in south-western South Africa and in parts of central Chile. The climate is characterized by hot, dry summers and cool, wet winters.

An oceanic climate is typically found along the west coasts at the middle latitudes of all the world's continents, and in south-eastern Australia, and is accompanied by plentiful precipitation year round. London, England, Bilbao, Spain, Melbourne, Australia, Vancouver, British Columbia, Canada are examples.

The humid subtropical climate zone (Cfa, Cwa) is where winter rainfall (and sometimes snowfall) is associated with large storms that the westerlies steer from west to east. Most summer rainfall occurs during thunderstorms and from occasional tropical cyclones. Humid subtropical climates lie on the east side of continents, roughly between latitudes 20° and 40° away from the Equator.

17.4.4   *Group D Climates*

These are continental climates and they have an average temperature above 10°C (50°F) in their warmest months, and a coldest month average below −3°C (or 0°C). These climates usually occur in the interiors of continents, or on their east coasts, north of 40° North latitude. In the Southern Hemisphere, Group D climates are extremely rare due to the smaller land masses in the middle latitudes and the almost complete absence of land between 40° and 60° south latitude, existing only in some highland locations.

A subarctic climate has little precipitation, and monthly temperatures which are above 10°C (50°F) for 1–3 months of the year, with permafrost in large parts of the area due to the cold winters. Winters within subarctic climates usually include up to 6 months of temperatures averaging below 0°C (32°F). Chicago, Illinois, Cleveland, Ohio, Toronto, Ontario, Canada, Beijing, China, Bucharest, Romania are examples.

A humid continental climate (Dfa) is marked by variable weather patterns and a large seasonal temperature variance (Fig. 17.5). Places with more than 3 months of average daily temperatures above 10°C (50°F) and a coldest month temperature below −3°C (26.6°F) and which do not meet the criteria for an arid or semiarid climate, are classified as continental.

The taiga or boreal forest exists as a nearly continuous belt of coniferous trees across North America and Eurasia (Fig. 17.6). Overlying formerly glaciated areas and areas of patchy permafrost on both continents, the forest is a mosaic of successional and subclimax plant communities sensitive to varying environmental conditions. Taiga is the Russian name for this forest which covers so much of that country. However, the term is used in North America as well (Fig. 17.6).

Fig. 17.5 Humid continental climates throughout the world outlined in blue (Public Domain)
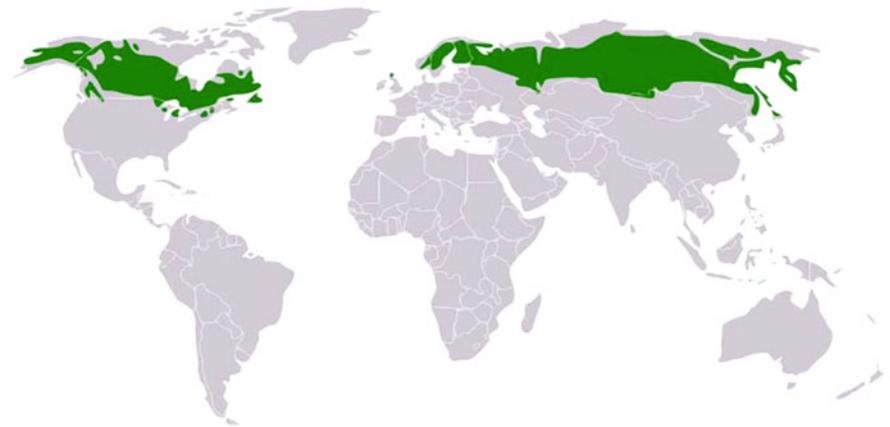

Fig. 17.6 Distribution of the taiga belt (Public Domain)

17.4.5   Group E Climates

Group E climates are characterized by average temperatures below 10°C (50°F) in all 12 months of the year.

Tundra occurs in the far Northern Hemisphere, north of the taiga belt, including vast areas of northern Russia and Canada (Fig. 17.7). Barrow, Alaska is an example.

A polar ice cap, or polar ice sheet, is a high-latitude region of a planet or moon that is covered in ice. Ice caps form because high-latitude regions receive less energy in the form of solar radiation from the Sun than equatorial regions, resulting in lower surface temperatures.

A desert is a landscape form or region that receives very little precipitation (Fig. 17.8). Deserts usually have a large diurnal and seasonal temperature range, with high daytime temperatures (in summer up to 45°C or 113°F), and low night-time

Fig. 17.7 Arctic tundra (Public Domain)

Fig. 17.8 Larger non-polar deserts of the world (NASA, Public Domain)

temperatures (in winter down to 0°C; 32°F) due to extremely low humidity. Many deserts are formed by rain shadows, as mountains cause moist air to rise and condense and block the path of moisture and precipitation to the desert. Rainfall will occur on the windward side of the mountain and dry air swoops down the leeward side.

17.5   The Thornthwaite Climate Classification

The Thornthwaite Climate Classification system is built on the physical interactions between local moisture and temperature rather than only the precipitation and temperature data. It represents a sophisticated and precise scheme of classification based on local surface water balances. Thornthwaite devised a number of specific indices to quantify necessary climatic components, including the moisture index (MI) and the potential evapotranspiration (PE) rate for a location.

Thornthwaite also derived a Thermal Efficiency Index (T/ET) of the ratio of temperature (T) to a calculated evapotranspiration (ET) value, and a Dryness Index (DI) and Humidity Index (HI) to identify the times of the year with water deficit or surplus.

The Thornthwaite climate classification requires monitoring the soil water budget using the concept of evapotranspiration. It requires monitoring the portion of total precipitation used to nourish vegetation over a certain area. It uses indices such as a humidity index and an aridity index to determine an area's moisture regime based upon its average temperature, average rainfall, and average vegetation type. The lower the value of the index in any given area, the drier the area is.

The moisture classification includes climatic classes with descriptors such as hyper-humid, humid, subhumid, subarid, semi-arid (values of −20 to −40), and arid (values below −40). Humid regions experience more precipitation than evaporation each year, while arid regions experience greater evaporation than precipitation on an annual basis. A total of 33% of the Earth's landmass is considered either arid of semi-arid, including southwestern North America, southwestern South America, most of northern and a small part of southern Africa, southwest and portions of eastern Asia, as well as much of Australia. Studies suggest that precipitation effectiveness (PE) within the Thornthwaite moisture index is overestimated in the summer and underestimated in the winter. This index can be effectively used to determine the number of herbivore and mammal species numbers within a given area. The index is also used in studies of climate change.

Thermal classifications within the Thornthwaite scheme include microthermal, mesothermal, and megathermal regimes. A microthermal climate is one of low annual mean temperatures, generally between 0°C (32°F) and 14°C (57°F) which experiences short summers and has a potential evaporation between 14 cm (5.5 in.) and 43 cm (17 in.). A mesothermal climate lacks persistent heat or persistent cold, with potential evaporation between 57 cm (22 in.) and 114 cm (45 in.). A megathermal climate is one with persistent high temperatures and abundant rainfall, with potential annual evaporation in excess of 114 cm (45 in.).

Additional Readings

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