CLIMATOLOGY

FOURTH EDITION

ROBERT V. ROHLI
ANTHONY J. VEGA

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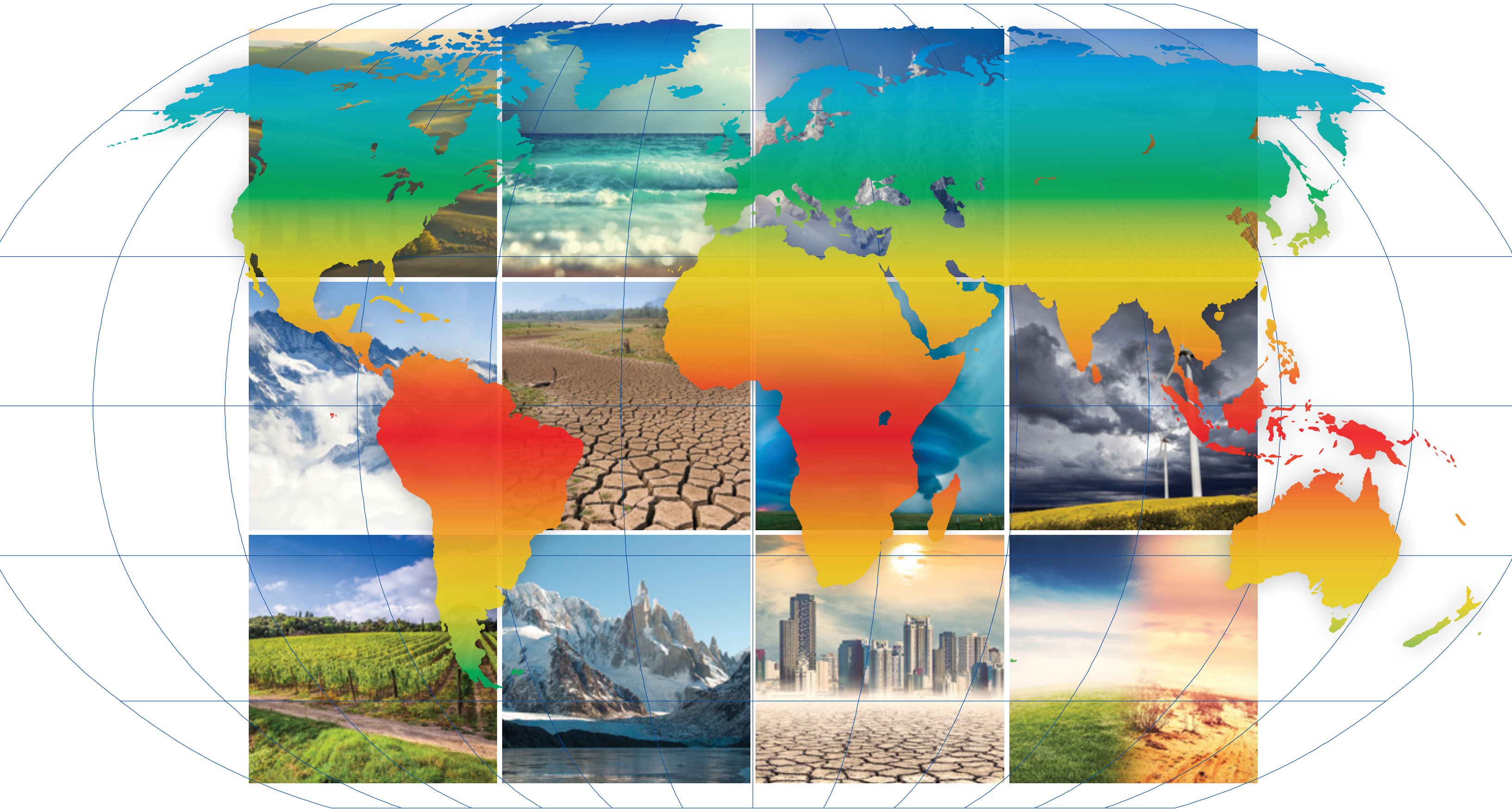

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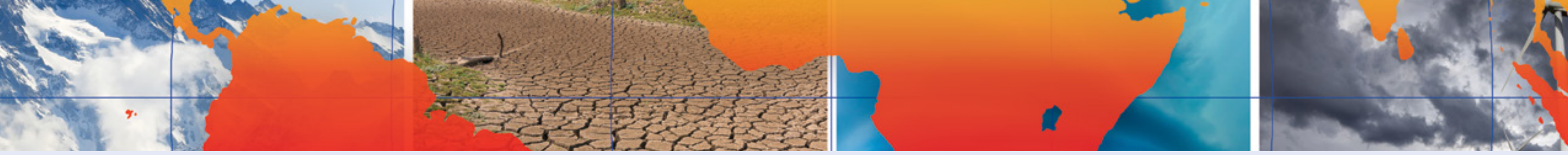
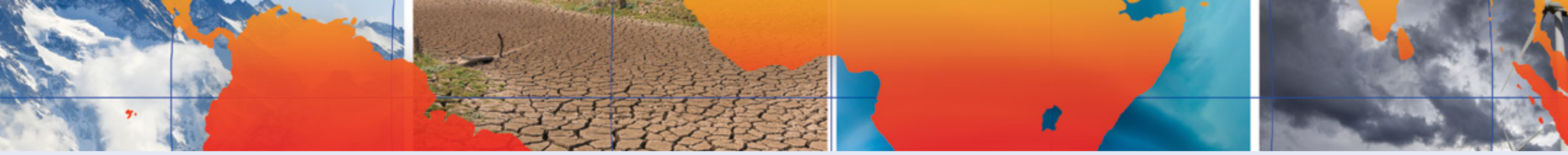
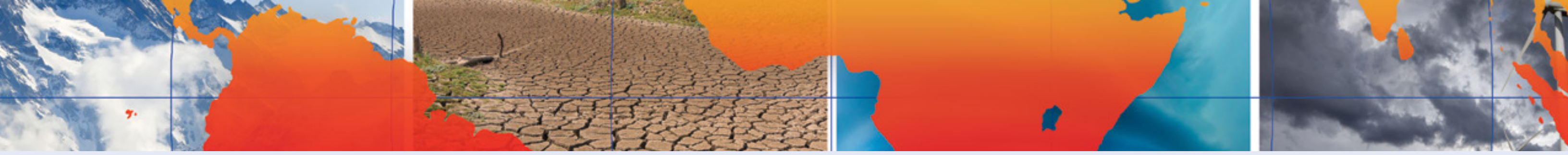


Brief Contents



Contents



Preface

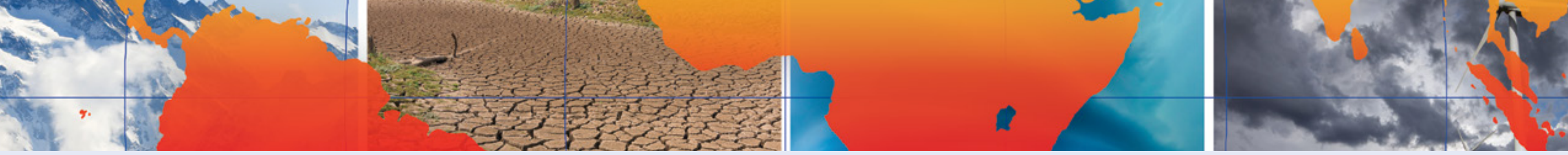
Welcome to an exciting journey to learn more about one of the most widely discussed sciences today. It would be rare to browse newsfeeds in any form for more than a few minutes without a story that pertains in some way to climate. Congratulations on taking the responsibility for being a well-informed citizen on some of the most important environmental issues of our time.

We remain indebted to our family, friends, colleagues, and especially our students who have provided constructive comments to prepare us for undertaking this *Fourth Edition*. We collected those comments and made substantial content-related changes to this edition in nearly every chapter. Some changes involved merely updating data on graphs and maps, whereas others amounted to a complete revision or addition of a chapter section. Some additions reflect the emergence of new prevailing thought as it relates to issues already discussed in previous editions, such as the 2016 survey of global warming opinions among professional atmospheric scientists (Chapter 12). Other additions, such as the notion of climate vulnerability, broaden the scope of the book in parallel to the broadening scope of climatology. We remain invigorated by the rapid developments in our chosen field, but at the same time we feel frustrated that these developments mean that *Climatology* is never quite complete!

The comments we heard motivated us to retain the format and level of the *Third Edition*. This text continues to serve the upper-level undergraduate or introductory-level graduate student. We are aware that users come from a wide array of topical backgrounds. For students lacking a background in basic atmospheric science, the fundamentals are covered in Chapters 1 ("Introduction to Climatology"), 2 ("Atmospheric Structure and Composition"), 3 ("Controls on the Climate System"), and 4 ("Atmospheric Interactions with the Other 'Spheres'"). More experienced readers will be challenged by the "Questions for Thought" at the end of each chapter and by the level of detail of some topics, particularly those in the later chapters. Clarity of explanations, breadth and depth of content, flexibility in instructor-determined chapter assignments, suitability for wide audiences, and timeliness of topical coverage continue to be the principles upon which this book is based.

Although all chapters can be covered in a 3-hour-per-week, semester-length course, some chapters (particularly Chapters 5, 13, and 14) remain self-contained; skipping them would result in little loss of the book's main message. However, these chapters, which cover the basics of boundary layer climatology, climate modeling, and applied climatology, respectively, also form the building blocks for a deeper level of understanding that is expected in more specialized advanced courses and in graduate-level research.

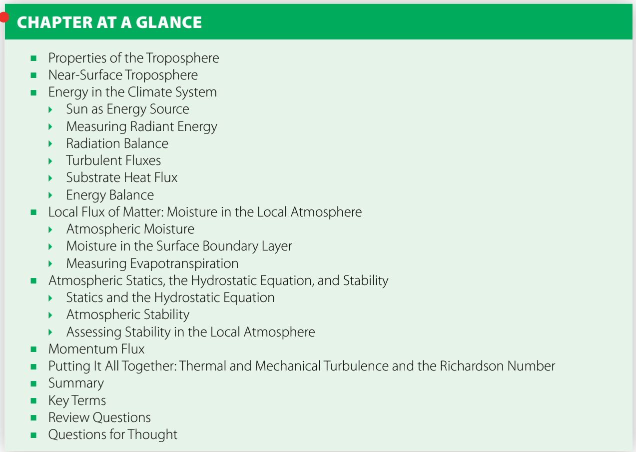
We believe that an improved understanding of the climate system should contribute to a student's development toward improvements in three core outcomes in their education: (1) critical-thinking ability, (2) communication skills, and (3) sense of social responsibility. We hope that the *Fourth Edition* remains true to these goals to an even greater extent than the previous editions.



The Student Experience

Beginning a new course in climatology can be a daunting experience for many students. *Climatology, Fourth Edition*, therefore, incorporates several pedagogical elements to help with comprehension and retention while also generating enthusiasm about the topic. The pedagogical aids that appear in every chapter include the following:

Chapter at a Glance provides instructors and students with a snapshot of the key concepts they will encounter in each chapter and serves as a checklist to help guide and focus study.



CHAPTER AT A GLANCE

- Properties of the Troposphere
- Near-Surface Troposphere
- Energy in the Climate System
    - Sun as Energy Source
    - Measuring Radiant Energy
    - Radiation Balance
    - Turbulent Fluxes
    - Substrate Heat Flux
    - Energy Balance
- Local Flux of Matter: Moisture in the Local Atmosphere
    - Atmospheric Moisture
    - Moisture in the Surface Boundary Layer
    - Measuring Evapotranspiration
- Atmospheric Statics, the Hydrostatic Equation, and Stability
    - Statics and the Hydrostatic Equation
    - Atmospheric Stability
    - Assessing Stability in the Local Atmosphere
- Momentum Flux
- Putting It All Together: Thermal and Mechanical Turbulence and the Richardson Number
- Summary
- Key Terms
- Review Questions
- Questions for Thought

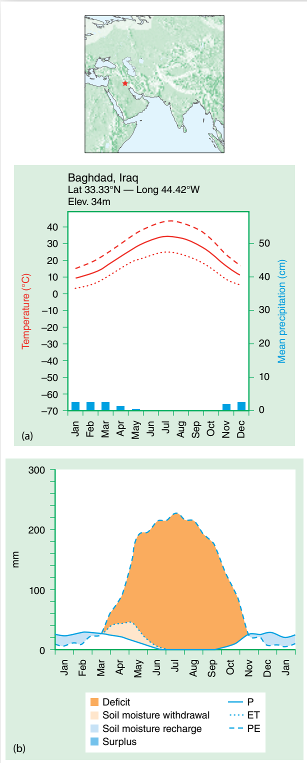


FIGURE 9.14 (a) Climograph for Baghdad, Iraq (BSh climate). Average annual temperature is 22.3°C (72.2°F) and average annual precipitation is 15.7 cm (6.2 in). (b) Water balance diagram for Baghdad, Iraq.

(a) Data from National Centers for Environmental Information. (b) Modified with permission using Web/WIMP version 1.01 implemented by K. Matsuura, C. Willmott, and D. Legates at the University of Delaware, 2003.

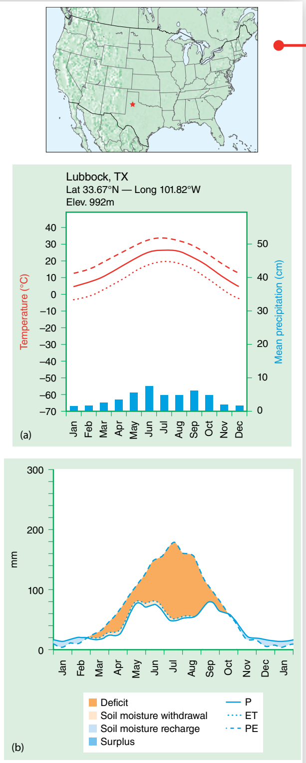


FIGURE 9.15 (a) Climograph for Lubbock, Texas (BSk climate). Average annual temperature is 15.4°C (59.7°F) and average annual precipitation is 47.5 cm (18.7 in). (b) Water balance diagram for Lubbock, Texas.

(a) Data from National Centers for Environmental Information. (b) Modified with permission using Web/WIMP version 1.01 implemented by K. Matsuura, C. Willmott, and D. Legates at the University of Delaware, 2003.

The completely **revised art program**, in full color for the first time, offers enhanced clarity and gradation of all maps, climographs, and images to better illustrate and help students fully understand the diversity of climate within varying climate types.

Key Terms listed at the end of each chapter and bolded throughout aid in students' review of the material. For further help with learning the vocabulary, students are encouraged to use the **Glossary** at the end of the book, as well as the interactive glossary, animated flashcards, and crossword puzzles on the Navigate Companion Website.

Key Terms

Absolute zero
Adret slope
Advection
Aerosol
Antarctic Circle
Anticyclone
Aphelion
Arctic Circle
Attenuation
Autumnal equinox
Axial tilt
Backing
Beam spreading
Centrifugal acceleration (CA)
Circle of illumination
Continentality
Convection
Coriolis effect (CE)
Cyclone
December solstice
Downdraft
Ekman spiral
Equation of state
Evaporation
Flux
Free atmosphere
Friction
Geostrophic balance
Geostrophic wind
Gulf Stream
Heat index
Hydrostatic equilibrium
Ideal gas law
Inertia
Inertial period
Insolation
Isobar
Isotherm
Joule
June solstice
Kelvin temperature scale
Kinetic energy
Lake effect snow
Latent energy
Latitude
Leeward
Longitude
March equinox
Maritime effect
Midlatitude (frontal) wave cyclone
Millibar (mb)
Momentum
National Weather Service
Navier-Stokes equations of motion
Newton (N)
Newton's laws of motion
North Atlantic Drift
Orographic effect
Parallelism
Pascal (Pa)
Path length
Perihelion
Plane of the ecliptic
Pressure
Pressure gradient force (PGF)
Prime meridian
Radiant energy
Refraction
Revolution
Rotation
Second law of thermodynamics
Sensible energy
September equinox
Solar declination
Solar noon
Specific heat
Summer solstice
Thermohaline circulation
Time zone
Tropic of Cancer
Tropic of Capricorn
Tropical cyclone
Troposphere
Ubac slope
Updraft
Upwelling
Urban heat island
Veering
Vernal equinox
Wind
Windward
Winter solstice

Terms in italics have appeared in at least one previous chapter.

Review Questions

1. Explain how Earth and its atmosphere formed.
2. How is today's atmosphere similar to and different from early Earth's atmosphere?
3. Describe how oxygen came to comprise almost 21% of the atmosphere today.
4. Given that solar output has increased over the past 4.6 billion years, how have Earth's temperatures remained fairly constant over that same time?
5. What is residence time and why is it important?
6. What is the carbon cycle and how does it operate?
7. Describe the thermal structure of the atmosphere.
8. What causes the thermal characteristics associated with each thermal layer of the atmosphere?
9. Compare and contrast the heterosphere and the homosphere.
10. Why is there no defined top to the atmosphere?

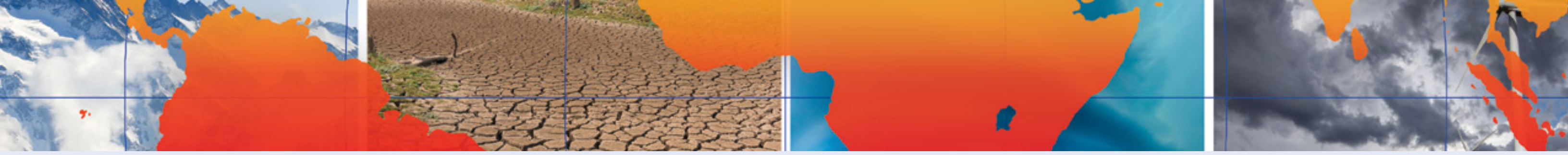
Review Questions ensure that students have assimilated the most important concepts of the chapter. These questions challenge students to describe, discuss, explain, compare, and contrast the material they just read. Answers to the even-numbered review questions can be found on the Navigate Companion Website.

Questions for Thought take learning a step further, asking students to think critically and apply theory to reality. These questions can be used for independent study, in homework assignments, or to stimulate class discussion.

Questions for Thought

1. After studying the chapters discussing climates around the world, discuss the climatic accuracies and inaccuracies portrayed in three popular movies. Would the plot of the movie have changed if the climates had been portrayed more accurately?
2. Assume that a 7000-m (23,000-ft) mountain suddenly appears at your current location. Using the normal environmental lapse rate, calculate the vertical average temperature from your current elevation to the mountain peak. Based on that temperature, calculate which climatic zones would appear on the mountain, and where they would be located both vertically and horizontally (assuming shading influences, etc.).

Additional Online Resources are available for students and instructors, including practice quizzes, an interactive glossary, answers to even-numbered review questions, and flashcards.



Teaching Tools

A variety of Teaching Tools are available for qualified instructors to assist with preparing for and teaching their courses. These resources are accessible via digital download and multiple other formats.

The **Image Bank in PowerPoint format** contains all of the illustrations, photographs, and tables (for which Jones & Bartlett Learning holds the copyright or has permission to reproduce electronically). These images are not for sale or distribution but may be used to enhance your existing slides, tests, and quizzes or other classroom material.

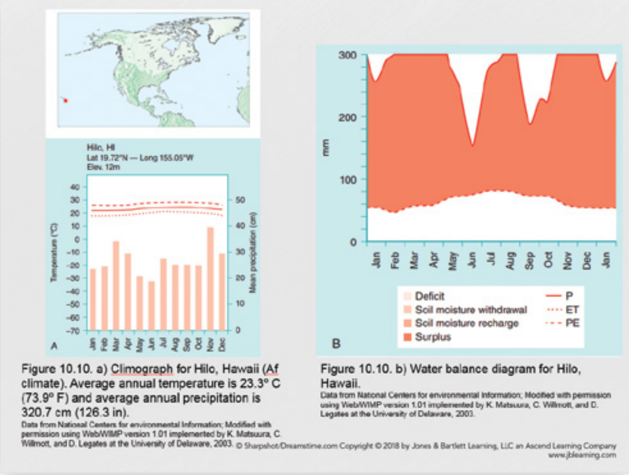


Figure 10.10. a) Climograph for Hilo, Hawaii (Af climate). Average annual temperature is 23.3° C (73.9° F) and average annual precipitation is 320.7 cm (126.3 in).
Data from National Centers for environmental Information; Modified with permission using WebWIMP version 1.01 implemented by K. Matsuura, C. Willmott, and D. Legates at the University of Delaware, 2003.

Figure 10.10. b) Water balance diagram for Hilo, Hawaii.
Data from National Centers for environmental Information; Modified with permission using WebWIMP version 1.01 implemented by K. Matsuura, C. Willmott, and D. Legates at the University of Delaware, 2003.

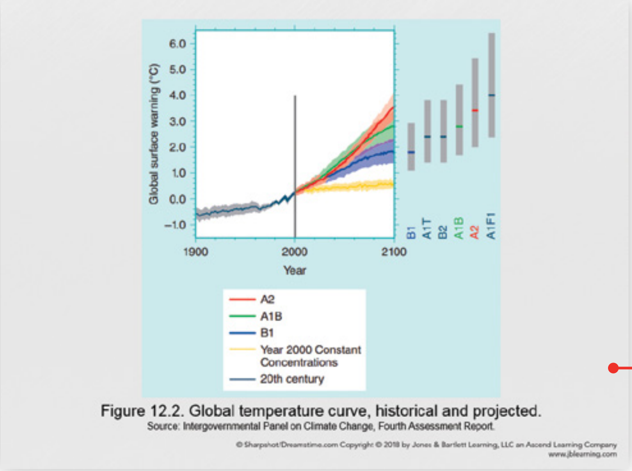
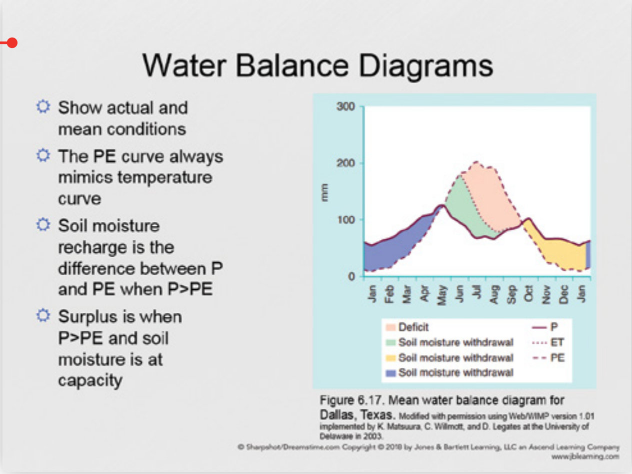


Figure 12.2. Global temperature curve, historical and projected.
Source: Intergovernmental Panel on Climate Change, Fourth Assessment Report.

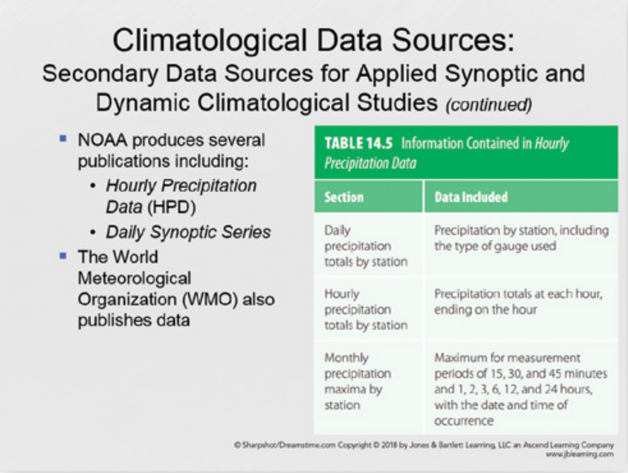
The comprehensive and time-saving **Test Bank** has been updated and expanded to include more than 1,000 exam questions.



Water Balance Diagrams

- Show actual and mean conditions
- The PE curve always mimics temperature curve
- Soil moisture recharge is the difference between P and PE when P>PE
- Surplus is when P>PE and soil moisture is at capacity

Figure 6.17. Mean water balance diagram for Dallas, Texas. Modified with permission using WebWIMP version 1.01 implemented by K. Matsuura, C. Willmott, and D. Legates at the University of Delaware in 2003.



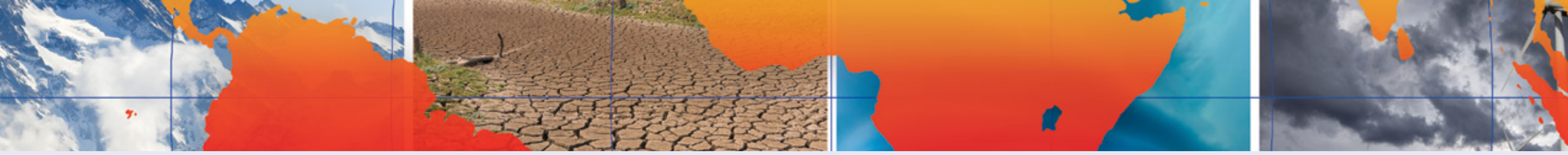
Climatological Data Sources:
Secondary Data Sources for Applied Synoptic and Dynamic Climatological Studies *(continued)*

- NOAA produces several publications including:
  - *Hourly Precipitation Data* (HPD)
  - *Daily Synoptic Series*
- The World Meteorological Organization (WMO) also publishes data

TABLE 14.5 Information Contained in *Hourly Precipitation Data*

Section	Data Included
Daily precipitation totals by station	Precipitation by station, including the type of gauge used
Hourly precipitation totals by station	Precipitation totals at each hour, ending on the hour
Monthly precipitation maxima by station	Maximum for measurement periods of 15, 30, and 45 minutes and 1, 2, 3, 6, 12, and 24 hours, with the date and time of occurrence

The **Lecture Outlines in PowerPoint format** provide lecture notes and images for each chapter of *Climatology*. Instructors with the Microsoft PowerPoint software can customize the outlines, art, and order of presentation.



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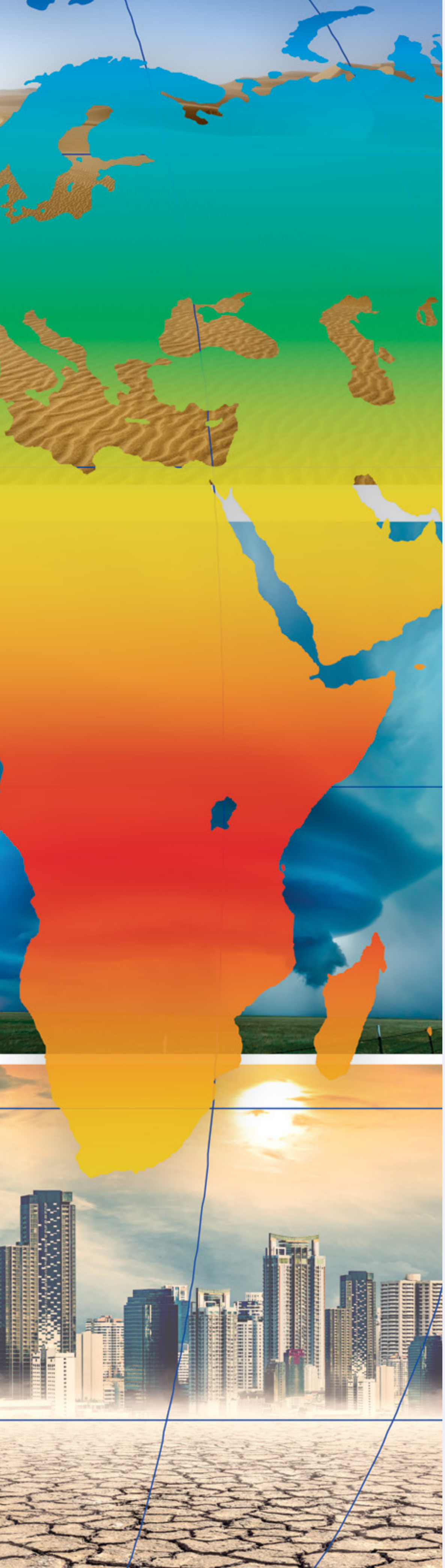
As always, we welcome and appreciate comments from anyone, but especially students, on how subsequent editions can be improved.



PART 1

The Basics

CHAPTER 1 Introduction to Climatology

CHAPTER 2 Atmospheric Structure and Composition

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CHAPTER 1

Introduction to Climatology

CHAPTER AT A GLANCE

- Meteorology and Climatology
- Scales in Climatology
- Subfields of Climatology
- Climatic Records and Statistics
- Summary
- Key Terms
- Review Questions
- Questions for Thought

Climatology may be described as the scientific study of the behavior of the **atmosphere**—the thin gaseous layer surrounding Earth's surface—integrated over time. Although this definition is certainly acceptable, it fails to capture fully the scope of climatology. Climatology is a holistic science that incorporates data, ideas, and theories from all parts of the Earth–ocean–atmosphere system, including those influenced by humans, into an integrated whole to explain atmospheric properties.

The Earth–ocean–atmosphere system may be divided into a number of zones, with each traditionally studied by a separate scientific discipline. The part of the solid Earth nearest to the surface (to a depth of perhaps 100 km) is called the **lithosphere** and is studied by geologists, geophysicists, geomorphologists, soil scientists, vulcanologists, and other practitioners of the environmental and agricultural sciences. The part of the system that is covered by liquid water is termed the **hydrosphere**; it is considered by those in the fields of oceanography, hydrology, and limnology (the study of lakes). The region comprising frozen water in all its forms (glaciers, sea ice, surface and subsurface ice, and snow) is known as the **cryosphere** and is studied by those specializing in glaciology, as well as specialized physical geographers, geologists, and oceanographers. The biosphere, which crosscuts the lithosphere, hydrosphere, cryosphere, and atmosphere, includes the zone containing all life forms on the planet, including humans. The **biosphere** is examined by specialists in the wide array of life sciences, along with physical geographers, geologists, and other environmental scientists.

The atmosphere is the component of the system studied by climatologists and meteorologists. Holistic interactions between the atmosphere and

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TABLE 1.1 Examples of Interactions Between the Atmosphere and the Other "Spheres" and Impacts on Thermal Receipt/Climate

Sphere Interacting with Atmosphere	Example of a Potential Impact
Lithosphere	Large volcanic eruptions can create a dust and soot cloud that can reduce the receipt of solar radiation, cooling the global atmosphere for months or years.
Hydrosphere	Changes in ocean circulation can cause global atmospheric circulation shifts that produce warming in some regions and cooling in others.
Cryosphere	Melting of polar ice caps can cause extra heating at the surface where ice was located because bare ground reflects less of the solar energy incident upon the surface than ice.
Biosphere	Deforestation increases the amount of solar energy received at the surface and alters atmospheric chemistry by returning carbon dioxide stored in living plant matter to the atmosphere.

each combination of the "spheres" are important contributors to the climate (**TABLE 1.1**), at scales from local to planetary. Thus, climatologists must draw on knowledge generated in several natural and sometimes social scientific disciplines to understand the processes at work in the atmosphere. Because of its holistic nature of atmospheric properties over time and space, climatology naturally falls into the broader discipline of geography.

Over the course of this book we shall see that these processes can be complex. The effects of some of these interactions cascade up from local to planetary scales, and the effects of others tend to cascade down the various scales to ultimately affect individual locations over time. The processes are so interrelated with other spheres and with other scales that it is often difficult to generalize by saying that any particular impact begins at one component of the system or side of the scale and proceeds to another.

We can state that the scope of climatology is broad. It has also expanded widely from its roots in ancient Greece. The term "climatology" is derived from the Greek word "klima," which means "slope," and reflects the early idea that distance from the equator alone (which causes differences in the angle or slope of the Sun in the sky) drove climate. The second part of the word is derived from "logos," defined as "study" or "discourse." Modern climatology seeks not only to describe the nature of the atmosphere from location to location over many different time scales but also to explain why particular attributes occur and change over time and to assess the potential impacts of those changes on natural and social systems.

Meteorology and Climatology

The two atmospheric sciences, meteorology and climatology, are inherently linked. **Meteorology** is the study of **weather**—the overall instantaneous condition of the atmosphere at a certain place and time. Weather is described through the direct measurement of particular atmospheric properties such as temperature, precipitation, humidity, wind direction, wind speed, cloud cover, and cloud type. The term "weather" refers to tangible aspects of the atmosphere. A quick look or walk outside may be all that is needed to describe the weather of your location. Of course, these observations may be compared with the state of the atmosphere at other locations, which in most cases is different.

Because meteorology deals with direct and specific measurements of atmospheric properties, discussion of weather centers on short-duration time intervals. Weather is generally discussed over time spans of a few days at most. How is the weather today? How does this compare with the weather we had yesterday? What will the weather be like tomorrow or toward the end of the week? All of these questions involve short-term analysis of atmospheric properties for a given time and place. So meteorology involves only the present, the immediate past, and the near future.

But a much more important component of meteorology is the examination of the forces that create the atmospheric properties being measured. Changes in the magnitude or direction of these forces over time and changes in the internal properties of the matter being affected by these forces create differences in weather conditions over time. Although many meteorologists are not directly involved with forecasting these changes, meteorology is the only natural science in which a primary goal is to predict future conditions. Weather forecasting has improved greatly with recent technological enhancements that allow for improved understanding of these forces, along with improved observation, data collection, and modeling of the atmosphere. Currently, weather forecasts produced by the **National Weather Service** in the United States are accurate for most locations over a period of approximately 72 hours.

By contrast, **climate** refers to the state of the atmosphere for a given place over time. It is important to note that climatologists are indeed concerned with the same atmospheric processes that meteorologists study, but the scope is different. Meteorologists may study the processes for their own sake, while climatologists study the processes to understand the long-term consequences of those processes. Climatology, therefore, allows us to study atmospheric processes and their impacts far beyond present-day weather.

There are three properties of climatic data to consider: normals, extremes, and frequencies. These are used to gauge the state of the atmosphere over a particular time period as compared with atmospheric conditions over a similar time period in the past. **Normals** refer to average weather conditions at a place. Climatic normals are typically calculated for 30-year periods and give a view of the type of expected weather conditions for a location through the course of a year. For example, climatologically normal conditions in Crestview, Florida, are hot and humid during the summer and cool but not cold in winter.

Two places could have the same average conditions but with different ranges of those conditions, in the same way that two students who both have an average of 85% in a class may not have acquired that average by earning the same score on each graded assignment. Therefore, **extremes** are used to describe the maximum and minimum measurements of atmospheric variables that can be expected to occur at a certain place and time, based on a long period of observations. For example, a temperature of 0°C (32°F) at Crestview in April would fall outside of the range of expected temperatures.

Finally, **frequencies** refer to the rate of incidence of a particular phenomenon at a particular place over a long period of time. Frequency data are often important for risk assessment, engineering, or agricultural applications. For instance, the frequency of hailstorms in a city is a factor in determining a homeowner's insurance premium. Or if an engineer designs a culvert to accommodate 8 cm (3 in.) of rain in a 5-hour period but that frequency is exceeded an average of two times per year, this rate of failure may or may not be acceptable to the citizens affected by the culvert. A farmer may want to know how many days on average exceed 1.5 cm (0.6 in.) of rain in October because October rains are problematic for any crop harvested during that month.

We can say then that both meteorologists and climatologists study the same atmospheric processes but with three primary and important differences. First, the time scales involved are different. Meteorologists are primarily concerned with features of the atmosphere at a particular time and place—the "weather"—whereas climatologists study the long-term patterns and trends of those short-term features—the "climate." Second, meteorologists are more concerned with the processes for their own sake, while climatologists consider the long-term implications of those processes. Third, climatology is inherently more intertwined with processes happening not only in the atmosphere but also in the other "spheres" because the interactions between the atmosphere and the other spheres are more likely to have important consequences over longer, rather than shorter, time scales. This is particularly true if those processes occur over large areas, because the impacts usually take longer to develop in such cases. For instance, if the Great Lakes were to totally evaporate, such a process would necessarily take place over a long time period. The difference in water level in the Great Lakes between today and tomorrow would not cause much impact on tomorrow's weather as compared with today's. A meteorologist would not need to take this atmosphere–hydrosphere interaction into account when considering tomorrow's weather. However, the difference in water content between the Great Lakes over centuries is more likely to have a noticeable and dramatic impact on climate during that time period. Interactions between the atmosphere and other spheres, such as in this example, thus must be considered when evaluating climate.

Regardless of the differences between meteorology and climatology, it is important to recognize that the distinction between the two is becoming increasingly blurred over time. A successful climatologist should have a firm grounding in the laws of atmospheric physics and chemistry that dictate the instantaneous behavior of the atmosphere. An effective meteorologist should recognize the importance of patterns over time and the impacts of those and other patterns on the Earth–ocean–atmosphere system.

The holistic perspective of climatology also carries over to include interactions between the atmosphere and social systems. The impact of people on their environment is a theme in climatology that has become more prevalent in recent years. It is being increasingly recognized that many features of the human condition are related to climate. This is especially true of climatic "extremes" and "frequencies," because it is the "abnormal" events, and conditions exceeding certain thresholds, that generally cause the greatest impact on individuals and society.

Scales in Climatology

Just as temporal scale is important, climatology also involves the study of atmospheric phenomena along many different spatial scales. There is usually a direct relationship between the size of individual atmospheric phenomena and the time scale in which that phenomenon occurs (**FIGURE 1.1**). The **microscale** represents the smallest of all atmospheric scales. Phenomena that operate along this spatial scale are smaller than 0.5 km (0.3 mi) and typically last from a few seconds to a few hours. A tiny circulation between the underside and the top of an individual leaf falls into this category, as does a tornado funnel cloud, and everything between. A larger scale is the **local scale**, which operates over areas between about 0.5 and 5 km (0.3 to 3 mi)—about the size of a small town. A typical thunderstorm falls into this spatial scale.

The next spatial scale is the **mesoscale**, which involves systems that operate over areas between about 5 and 100 km (3 to 60 mi) and typically last from a few hours to a few days. Such systems include those you may have encountered in earlier coursework, such as the mountain/valley breeze and land/sea breeze circulation systems, clusters of interacting thunderstorms known as mesoscale convective complexes, a related phenomenon associated with cold fronts termed "mesoscale convective systems," and the central region of a hurricane.

Moving toward larger phenomena, we come to the **synoptic scale**, a spatial scale of analysis that functions over areas between 100 and 10,000 km (60 to 6000 mi). Systems of this size typically operate over periods of days to weeks. Entire tropical cyclone systems and midlatitude (frontal) cyclones with their associated fronts fall into the synoptic scale. Because these phenomena are quite frequent and directly affect many people, the synoptic scale is perhaps the most studied spatial scale in the atmospheric sciences.

Finally, we can also study and view climate over an entire hemisphere or even the entire globe. This represents the largest spatial scale possible and is termed the **planetary scale**, because it encompasses atmospheric phenomena on the order of 10,000 to 40,000 km (6000 to 24,000 mi). Because in general the largest spatial systems operate over the longest time scales, it is no surprise then that planetary-scale systems operate over temporal scales that span weeks to months. Examples of planetary-scale systems include the broad wavelike flow in the upper atmosphere and the major latitudinal **pressure** and **wind** belts that encircle the planet.

Subfields of Climatology

Climatology can be divided into several subfields, some of which correspond to certain scales of analysis. For instance, the study of the microscale processes involving interactions between the lower atmosphere and the local surface falls into the realm of **boundary-layer climatology**. This subfield is primarily concerned with exchanges in energy, matter (especially water), and **momentum** near the surface. Physical processes can become complex in the near-surface "boundary layer" for two reasons. First, the decreasing effect of **friction** from the surface upward complicates the motion of the atmosphere and involves significant transfer of momentum downward to the surface. Second, the most vigorous exchanges of energy and moisture occur in this layer because solar radiant

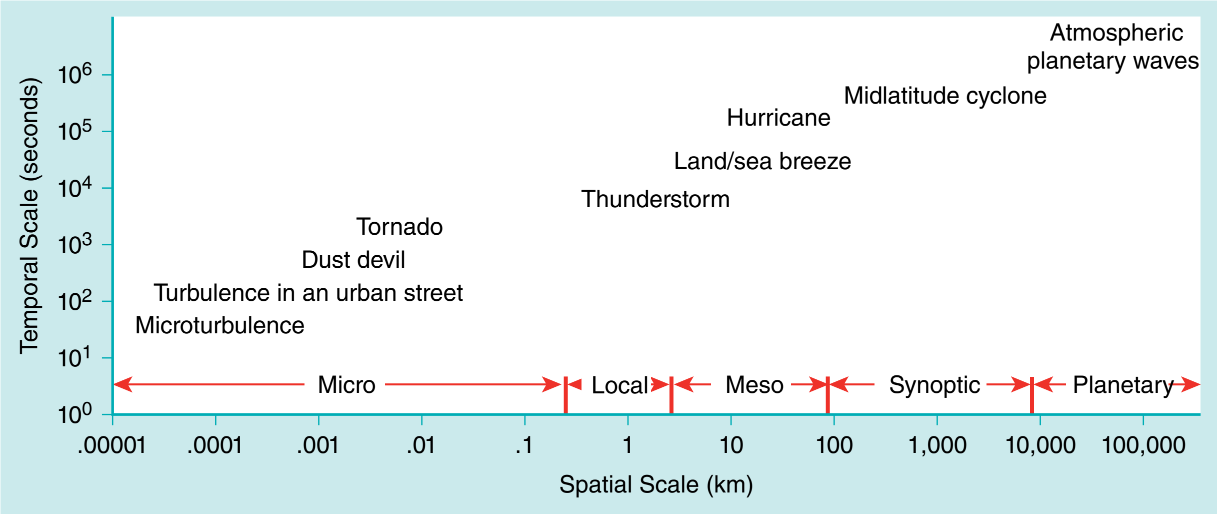

FIGURE 1.1 Spatial–temporal relationships for selected atmospheric features.

energy striking the ground warms it greatly and rapidly compared with the atmosphere above it and because the source of water for **evaporation** is at the surface. Boundary-layer climatology may be further subdivided into topics that examine surface–atmosphere interactions in mountain/alpine regions, urban landscapes, or various vegetated land covers.

Physical climatology is related to boundary-layer climatology in that it studies energy and matter. However, it differs in that it emphasizes the nature of atmospheric energy and matter themselves at climatic time scales, rather than the processes involving energy, matter, and momentum exchanges only in the near-surface atmosphere. Some examples include studies on the causes of lightning, atmospheric optical effects, microphysics of cloud formation, and air pollution. Although meteorology has traditionally emphasized this type of work to a greater extent than climatology, climatologists have contributed to our understanding of these phenomena. Furthermore, the convergence of meteorology and climatology as disciplines will likely lead to more overlap in these topics of research in the future.

Hydroclimatology involves the processes (at all spatial scales) of interaction between the atmosphere and near-surface water in solid, liquid, and gaseous forms. This subfield analyzes all components of the **global hydrologic cycle**. Hydroclimatology interfaces especially closely with the study of other “spheres,” including the lithosphere, cryosphere, and biosphere, because water is present in all of these spheres and interactions readily occur between them.

Another subfield of climatology is **dynamic climatology**, which is primarily concerned with general atmospheric dynamics—the processes that induce atmospheric motion. Most dynamic climatologists work at the planetary scale. This differs from the subfield of **synoptic climatology**, which is also concerned with the processes of circulation but is more regionally focused and usually involves more practical and specific applications than those described in the more theoretical area of dynamic climatology. According to climatologist Brent Yarnal, synoptic climatology “studies the relationships between the atmospheric circulation and the surface environment of a region.” He goes on to state that, “because synoptic climatology seeks to explain key interactions between the atmosphere and surface environment, it has great potential for basic and applied research in the environmental sciences.” Synoptic climatology may act as a keystone that links studies of atmospheric dynamics with applications in various other disciplines.

Synoptic climatology is similar in some ways to **regional climatology**, a description of the climate of a particular region of the surface. However, synoptic climatology necessarily involves the explanation of process, whereas regional climatology may not.

The study of climate can extend to times before the advent of the instrumental weather record. This subfield of climatology is termed **paleoclimatology** and involves the extraction of climatic data from indirect sources. This **proxy evidence** may include human sources such as books, journals, diaries, newspapers, and artwork to gain information about preinstrumental climates. However, the field primarily focuses on biological, geological, geochemical, and geophysical proxy sources, such as the analysis of tree rings, fossils, corals, pollen, ice cores, striations in rocks, and sediment deposited annually on the bottoms of lakes (**varves**).

Bioclimatology is a diverse subfield that includes the interaction of living things with their atmospheric environment. **Agricultural climatology** is the branch of bioclimatology that deals with the impact of atmospheric properties and processes on living things of economic value. **Human bioclimatology** is closely related to the life sciences, including biophysics and human physiology.

Applied climatology is different in its orientation from the other subfields of climatology. While the others seek to uncover causes of various aspects of climate, applied climatology is primarily concerned with the effects of climate on other natural and social phenomena. This subfield may be further subdivided. One area of focus involves attempts to improve the environment. Examples include using climatic data to create more efficient architectural and engineering design, generating improvements in medicine, and understanding the impact of urban landscapes on the natural and human environment. Other examples involve the possibility of modifying the physical atmosphere to suit particular human needs, such as with the practice of **cloud seeding**, which attempts to extract the maximum amount of precipitation from clouds in water-scarce regions.

In general, each subfield overlaps with others. We cannot fully understand processes and impacts relevant to any subfield without touching on aspects important for others and at least one other nonclimatology field. For example, an agricultural climatologist interested in the effect of windbreaks to reduce evaporation rates in an irrigated field must understand the near-surface wind profile and turbulent transfer of moisture, along with soil and vegetation properties.

Climatic Records and Statistics

Because climatology deals with aggregates of weather properties, statistics are used to reduce a vast array of recorded properties into one or a few understandable numbers. For instance, we could calculate the **daily mean temperature**—the average temperature for the entire day—for yesterday at a particular location through a number of methods. First, we could take all recorded temperatures throughout the day, add them together, and then divide by the total number of observations.

A much simpler (but less accurate) method of calculating the daily mean temperature is actually the one that is used: A simple average is calculated from the maximum and minimum temperatures recorded for the day. This method is the most common because in the days before computers were used to measure and record temperature, special thermometers that operated on the principle of a "bathtub ring" were able to leave a mark at the highest and lowest temperature experienced since the last time that the thermometer was reset. Each day, human observers could determine the maximum and minimum temperature for the previous 24 hours, but they would not know any of the other temperatures that occurred over that time span. For most of the period of weather records, we knew only the maximum and minimum daily temperatures.

Of course, the numerical average calculated by the maximum–minimum method differs somewhat from the one obtained by taking all hourly temperatures and dividing by 24. Even though we have automated systems now that can measure and record temperatures every second, we do not calculate mean daily temperatures using this more accurate method because we do not want to change the method of calculating the means in the middle of our long-term weather records. What would happen if the temperatures began to rise abruptly at the same point in the period of record that the method of calculating the mean temperature changed? We would not know whether the "change" represented an actual change in climate or was just an artifact of a change in the method of calculating the mean temperature.

But what about that average temperature? Is it actually meaningful? Let's say that yesterday we recorded a high temperature of 32°C (90°F) and a low of 21°C (70°F). Our calculated average daily temperature would be about 27°C (80°F). This number would be used to simply describe and represent the temperature of the day for our location. But the temperature was likely to have been 27°C (80°F) only during two short periods in the day, once during the mid-day hours when climbing toward the maximum and again as temperatures decreased through the late afternoon. So the term "average temperature" is actually a rather abstract notion. Most averages or climatic "normals" are abstract notions, but the advantage from a long-term (climatic) perspective is that they provide a "mechanism" for analyzing long-term changes and variability.

"Extremes" are somewhat different. As we saw earlier in this chapter, climatic extremes represent the most unusual conditions recorded for a location. For example, these may represent the highest or lowest temperatures during a particular time period. Extremes are often given on the nightly news to give a reference point to the daily recorded temperatures. We might hear that the high temperature for the day was 33°C (92°F), but that was still 5 C° (8 F°) lower than the "record high" of 38°C (100°F) recorded on the same date in 1963. As long as our recorded atmospheric properties are within the extremes, we know that the atmosphere is operating within the expected range of conditions. When extremes are exceeded or nearly exceeded, then the atmosphere may be considered to be behaving in an "anomalous" manner. The frequency with which extreme events occur is also important. Specifically, if extreme events occur with increasing frequency, the environmental, agricultural, epidemiological, and economic impacts will undoubtedly increase.

Why are climatic records important? During the 1980s and 1990s the rather elementary notion that climate changes over time was absorbed by the general public. Before that time many people thought that climate remained static even though weather properties varied considerably around the normals (averages). With heightened understanding of weather processes came the realization that climate varies considerably as well. Climatic calculations and the representation of climate for a given place over time became exceedingly important and precise. The problems associated with the calculation of various atmospheric properties still existed, however, and the methods of calculating these properties could have far-reaching implications on such endeavors as environmental planning, hazard assessment, and governmental policy.

With today's technology we would assume that calculating a simple average temperature for Earth, for instance, would be easy. However, data biases and methodological differences complicate matters. Many of these issues have been mathematically corrected in recorded data. Given the corrections, it is generally accepted that Earth's average annual temperature has risen by about 0.85 C° (1.53 F°) since the widespread instrumental record began in 1880.

Another factor that complicates the interpretation of the observed warming is the increasingly urban location of many weather stations as urban sprawl infringes on formerly rural weather stations. Early in the twentieth century many weather stations in the United States and elsewhere were located on the fringe of major cities. This was especially true toward the middle part of the century with the construction of major airports far from the urban core. Weather observations could be recorded at the airport in a relatively rural, undisturbed location. As cities grew, however, these locations became swallowed up by urban areas. This instituted considerable bias into long-term records as artificial heat from urban sources, known as the **urban heat island**,

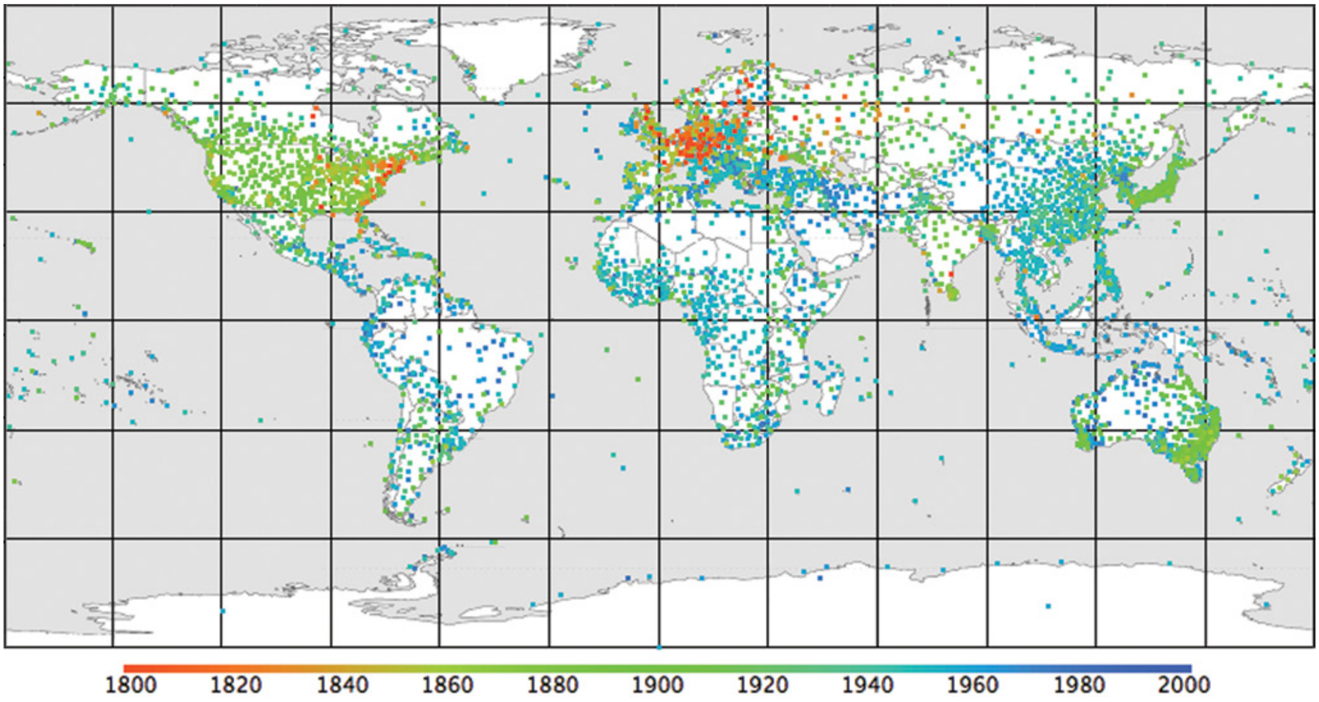

FIGURE 1.2 Location of global surface observations in the Global Historical Climatology Network at various years.

Courtesy of Kevan Hashemi. © 2015. Retrieved from: www.hashemifamily.com/Kevan/Climate/#Global%20Surface.

became part of the climatic record. Various properties, such as the abundance of concrete that absorbs solar energy effectively, the absence of vegetation and water surfaces, and the generation of waste heat by human activities contribute to the heat island. The urban heat island provides an excellent example of how humans can modify natural climates and can complicate the calculation and analysis of "natural" climatic changes.

In addition, the long-term recordings themselves may be plagued by other problems. Consider that most weather records for the world are confined to more-developed countries and tend to be collected in, or near, population centers. Developing countries, rural areas, and especially the oceans are poorly represented in the global weather database, particularly in the earlier part of the record (**FIGURE 1.2**). Oceans comprise over 70% of the planet's surface, yet relatively few long-term weather records exist for these locations. Most atmospheric recordings over oceans are collected from ships, and these recordings are biased by inconsistencies in the height of the ship-mounted weather station, the type of station used, the time of observation, and the composition of ship materials. Furthermore, ocean surface temperatures are derived in a variety of ways, from inserting a thermometer into a bucket of collected ocean water to recording the temperature of water passing through the bilge of the ship (with the heat generated by the ship included in the recording). Vast tracts of ocean were largely ignored until the recent arrival of satellite monitoring and recording technology, because the representation of surface and atmospheric properties was greatly limited to shipping lanes.

Even records taken with rather sophisticated weather stations may be biased and complicated to some degree by rather simple issues. Foremost among these are station moves. Moving a station even a few meters may ultimately bias long-term recordings as factors such as differing surface materials and solar exposure occur. Also of note is **time of observation bias**, which involved data bias based on the time of day when measurements are recorded at different stations. Finally, systematic biases and changes in the instrumentation may cause inaccuracies in measurements. The result of these, and a host of other biases, is that considerable data "correction" is required. Both the biases and the correction methods fuel debate concerning the occurrence of actual atmospheric trends.

Summary

This chapter introduces the field of climatology. It describes the scope of climatology, the inherent differences between meteorology and climatology, and the associated notions of weather and climate. Meteorology studies changes in weather, the state of atmospheric properties for a given location over a relatively short period of time, while climatology examines weather properties over time for a location. Climatology is a holistic science in that it involves understanding the