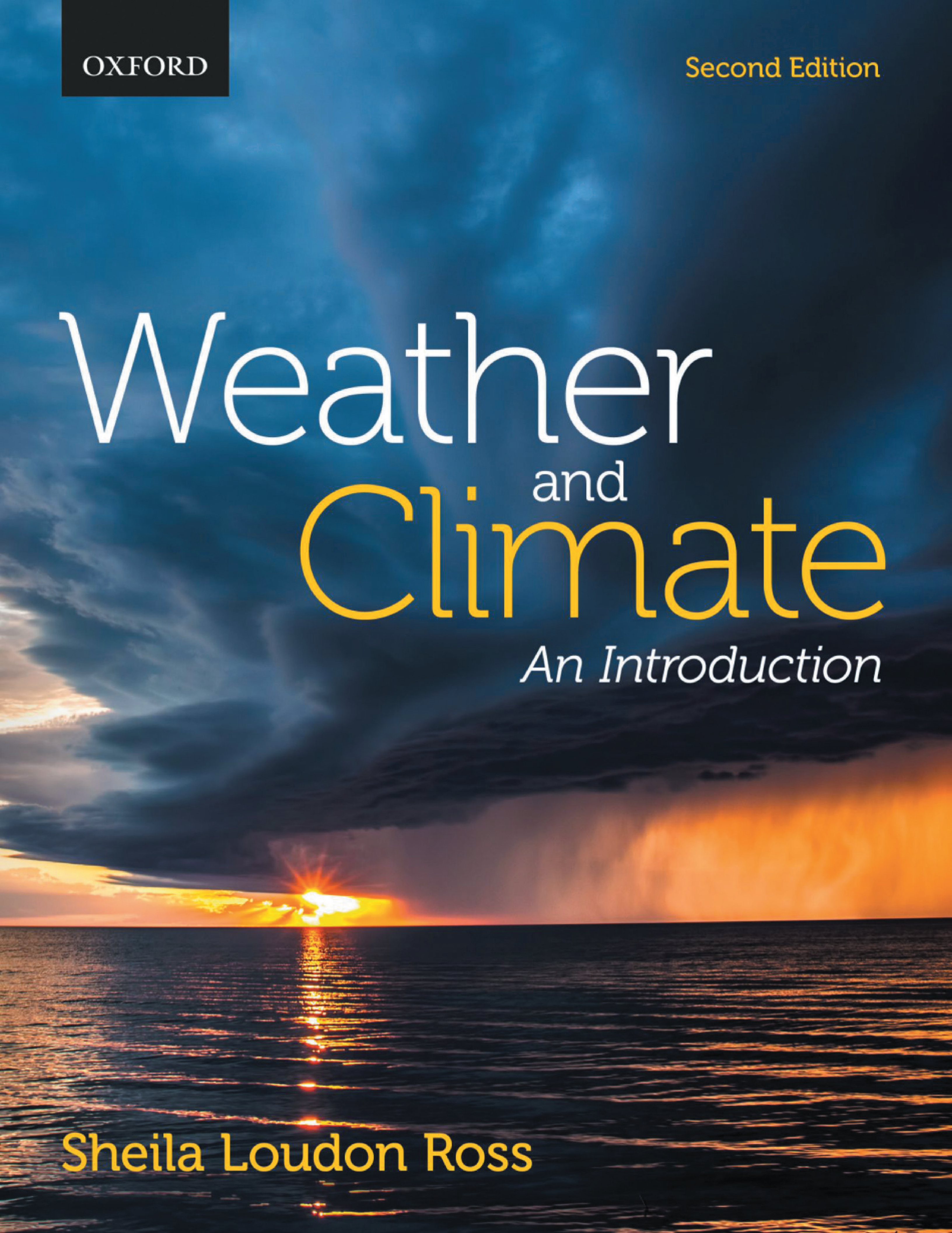

OXFORD

Second Edition

Weather and Climate

An Introduction

Sheila Loudon Ross

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Brief Contents

Contents

List of In the Field Boxes

From the Publisher

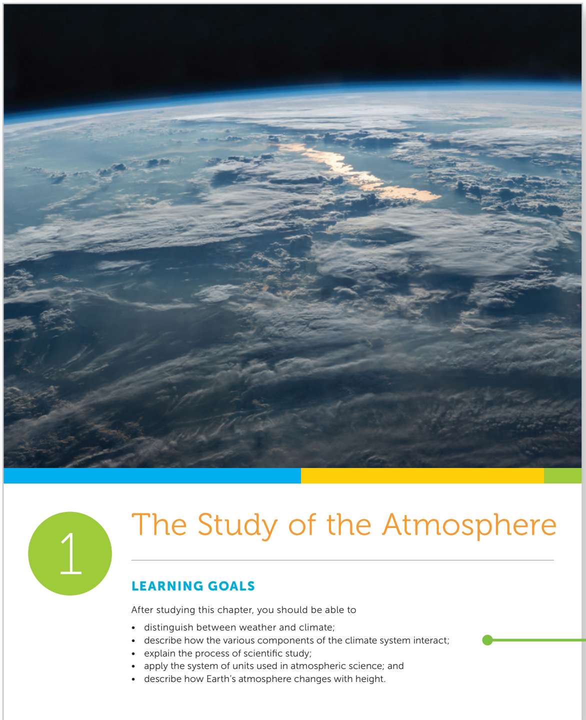
Oxford University Press is proud to present the second edition of *Weather and Climate*, an in-depth, scientifically grounded, thoroughly Canadian introduction to the study of weather and climate. With improvements that include expanded coverage of storms and severe weather, extensively updated material on climate change, and a new technical art program, this second edition builds on the strong foundation of the first edition to even better meet the needs of Canadian students. Sheila Ross's rigorous yet accessible approach to the discipline illuminates the often-hidden processes that create and influence weather and climate across the globe. Moreover, the focus on contemporary Canadian issues and research, which is balanced by examples from around the world, makes this text particularly relevant and relatable to students in Canada today.

Highlights of the Second Edition

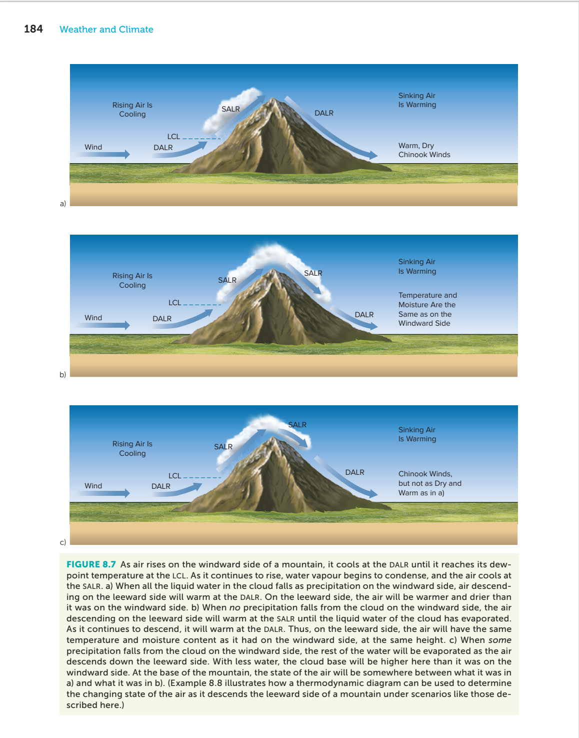
- **Increased coverage of climate change**—including an expanded and updated chapter on the changing atmosphere—helps students better understand the role of human activities in anthropogenic climate change and evaluate actions taken to address this global challenge.
- **A completely revised technical art program** illustrates concepts more clearly and accurately to enhance student understanding of the material.
- **New and expanded discussions of critical topics**—such as Earth as a system, tornadoes, arctic amplification, changes in Earth's reflectivity, ocean currents, and climate oscillations—give students greater insight into key factors related to weather and climate.
- **"Example" boxes** show students how to apply key equations to actual problems.
- **Extensive online resources** for students and instructors enhance the learning and teaching experience.

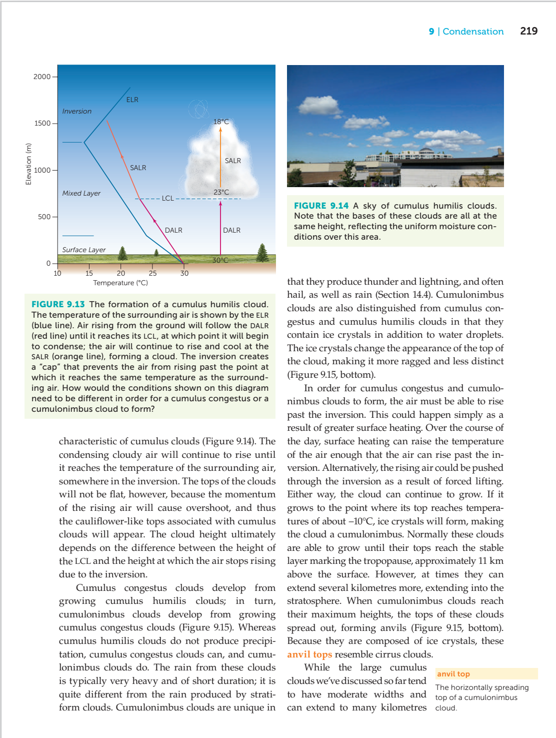
Features

Designed for students new to the discipline, this thorough introduction includes a wide array of features that will help students make the most of their learning experience.



Learning goals, revised in the second edition to be more concise, give students an at-a-glance overview of what they will encounter in each chapter, while chapter summaries remind students of the most significant concepts that have been covered.





Richly illustrated content—including new and updated figures, maps, tables, and photos—emphasizes visual learning and enhances student understanding of the material.

Marginal definitions of key terms ensure that students have a full understanding of the more discipline-specific terminology used in each chapter. Expanded definitions also appear in an end-of-text glossary for quick reference.

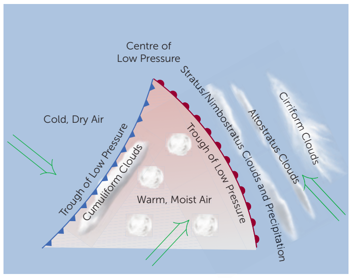


FIGURE 14.19 Idealized weather conditions associated with a mid-latitude cyclone.

either side of the jet stream can bring longer spells of clear, dry weather. When the jet stream meanders *equatorward* of a location, the polar high brings unseasonably cold, dry weather, but longer breaks can often occur when the jet stream meanders *poleward* of a location. Under such a flow regime, the subtropical high moves poleward, and unseasonably warm temperatures result. In addition, these highs are often referred to as *blocking highs* because, being *warm* highs, they extend through the troposphere (Section 14.1), blocking the paths of cyclones and, thus, forcing the cyclones to travel around them. Such a blocking pattern is known as an **omega high** (Figure 14.21). The result of such a block is that regions situated within the high, and slightly west of it, will likely experience weather that is warmer than normal, while regions to the east of the high will experience weather that is cooler than normal. In addition, because cyclones

omega high
A ridge of high pressure that forms in the shape of the Greek letter *omega* (Ω) in the upper airflow.

On the other hand, anticyclonic weather is characterized by clear skies and light winds. Recall that the clear skies associated with anticyclones are caused by sinking air and that this sinking air can also produce upper-air, or subsidence, inversions (Section 8.5.2). Clear skies mean anticyclones can bring very high temperatures in summer and very low temperatures in winter. In addition, recall that winds associated with anticyclones are light because there is a limit to the strength of the pressure gradients that can develop in anticyclones (Section 12.4; Figure 14.20). Light winds, combined with upper-air inversions, mean that, although the skies may be cloud-free, visibility in anticyclones can often be reduced by fog, haze, or pollution (Section 17.1.2).

As we have seen so far in this chapter, the cyclones of the mid-latitudes form as a result of divergence in the upper airflow, while the anti- ... mid-latitudes form below areas of ...ergence. These are the anticyclones ...ef relief from the cloudy, rainy con... ...y associated with the proximity of ... However, during periods of strong ..., the large anticyclones that lie on

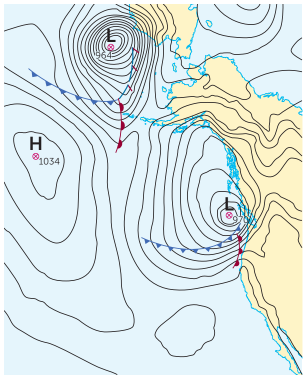


FIGURE 14.20 This weather map for 12 March 2012 at 1200 UTC shows that the pressure gradients around the two lows over the Pacific Ocean are much greater than that around the high lying just to the south of them. (The pressures labelled on the map are in hPa and the isobars are set at 4 hPa intervals.)

psychrometric equation can also be written for vapour pressure.

$$e = e_{ws} - \gamma (T - T_w) \quad (7.16)$$

In Equation 7.16, e_{ws} is the saturation vapour pressure at the wet-bulb temperature, and the psychrometric constant is equal to 65 Pa/K.

7.7 Humidity and Human Comfort

Since the amount of water vapour in the air determines how effectively our sweat will evaporate, hot and humid conditions *feel* hotter than hot and dry conditions. This is because when humidity is high our sweat will not readily evaporate, making it more difficult for our bodies to regulate our internal temperature. At first, we may just feel sticky and uncomfortable, but as temperature and humidity rise, heat stroke becomes a possibility.

To quantify our perceptions of just how hot it feels under conditions of high humidity, indices have been developed. These indices are used to warn people of the potential dangers of high temperatures combined with high humidity. In Canada, we use an index known as the **humidex**. In the United States, the *heat index*, or *apparent temperature*, is used. The humidex is calculated using temperature and dew-point temperature in a regression equation that has been developed based on peoples' perceptions of how hot it is. This index is a dimensionless number meant to represent temperature. It is analogous to **wind chill**, a measure of how cold we *feel* when it is windy as well as cold. Because they are based on our perceptions, these indices are rather abstract. We all respond quite differently to our environment; what is hot to one person might be comfortable to another.

Table 7.4 provides the relationship between ranges of humidex values and our degree of comfort. Table 7.5 is used to determine the humidex, given air temperature and relative humidity. For example, if the temperature is 35°C and the relative humidity is 50 per cent, the table shows that the humidex is 45. Table 7.4 tells us that such a humidex means people will feel great discomfort, and that they should avoid exertion. So, whereas

Example 7.15

A psychrometer reading gives a dry-bulb temperature of 16°C and a wet-bulb temperature of 14°C. Determine the vapour pressure, relative humidity, and dew-point temperature for this air.

Use Table 7.1 to obtain the saturation vapour pressure at the wet-bulb temperature, then use Equation 7.16 to calculate vapour pressure.

$$e = 1598\ \text{Pa} - 65\ \text{Pa/K}\ (16°\text{C} - 14°\text{C})$$
$$= 1468\ \text{Pa}$$
$$= 1.468\ \text{kPa}$$

Use Table 7.1 to obtain the saturation vapour pressure for 16°C, then use Equation 7.11 to calculate relative humidity.

$$RH = \left(\frac{1.468\ \text{kPa}}{1.817\ \text{kPa}}\right) \times 100\%$$
$$= 81\%$$

Note that you can also obtain relative humidity from Table 7.3 or Figure 7.16.

Use Table 7.1, and the vapour pressure of 1.5 kPa obtained above, to determine that the dew-point temperature is about 13°C.

a relative humidity of 50 per cent may not sound like anything to be concerned about, a humidex of 45 indicates that it might be.

Although indices such as the humidex are widely used, some scientists believe that an index is not really necessary. Instead, they argue, we should use dew-point temperature,

humidex
An index used in Canada to provide a measure of how warm it feels due to a combination of high temperature and high humidity.

wind chill
A measure of how cold it feels due to a combination of low temperature and high wind.

TABLE 7.4 Humidex and degree of comfort.

Humidex	Degree of Comfort
20–29	little discomfort
30–39	some discomfort
40–45	great discomfort; avoid exertion
46 and over	dangerous; possible heat stroke

Source: Environment Canada, http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=6C5D4990-1#humidex, 30 August 2016.

Equations and formulas make complex theories and processes accessible by breaking them down into their component parts, while "Example" boxes show students how to apply key equations to actual problems. Equations that students will find particularly useful for solving end-of-chapter problems are highlighted in shaded boxes throughout the text and printed inside the front and back covers of this text.

FIGURE 16.14 Savanna vegetation on the Serengeti plains, Tanzania, with widely spaced acacia trees.

when the trees lose their leaves and the grasses wither, the grazing animals that are dependent on the savanna migrate in search of food. Although it is not certain, it seems that fires occurring during the drought season are what maintain this type of vegetation. In Köppen's system, wet-dry tropical climates are classed as Aw because the precipitation of the driest month is less than 60 mm, but the total annual precipitation is not enough to support forests. The Aw climate type is the second most common climate type, covering 11.5 per cent of Earth's land surface (Peel, Finlayson, & McMahon, 2007).

There are at least two climate types that are similar to wet-dry tropical climates but that don't fit the Aw designation. The first type occurs in places where the dry season occurs during the time of *high* sun rather than *low* sun; this type is designated As in Köppen's system. These climate types are rare; an example is Honolulu, Hawaii. The second type occurs in tropical locations that are at high altitudes. Because these climates have dry seasons at the time of low sun but are too cold to be classed as tropical climates, they are designated Cwa or Cwb. An example of a place with a Cwa climate is Guadalajara, Mexico, which is located at about 21° N, at an altitude of just over 1500 m. An example of a place with a Cwb climate is Cuzco, Peru, which is located at 13½° S, at an altitude of 3400 m.

16.4.4 | Subtropical Desert and Steppe Climates (BWh, BSh)

The *subtropical desert* and *steppe climates* are hot and dry year-round. Larger annual temperature

CHECK YOUR UNDERSTANDING

How do you think the Cwa and Cwb climate types associated with high-altitude tropical locations could be included in the genetic climate classification system outlined in Table 16.1?

ranges make these climates a bit more variable than the wet equatorial climates. These dry climates lie between 10° and 30° N and S, with the steppes often forming transitional zones surrounding the drier deserts. Together, the dry desert and steppe climates of the subtropics and the mid-latitudes cover about one-third of Earth's land area (Figure 16.6). In fact, BWh—the hot, arid desert climate—is the most common climate type, as it covers 14.2 per cent of Earth's land surface (Peel, Finlayson, & McMahon, 2007). The world's largest area of desert climate extends from the Sahara in northern Africa all the way through the Middle East and includes the mid-latitude deserts of central Asia. Subtropical deserts also occur in Mexico and the southwestern United States, southern Africa, and most of Australia. Finally, the Atacama Desert, described above, is situated in the tropics along South America's west coast.

Faya-Largeau, Chad, located in the middle of the Sahara Desert, is an example of a subtropical *desert*, while Monterrey, Mexico, is an example of a subtropical *steppe* (Figure 16.15). Both climates have annual temperature ranges that are larger than those we have seen for any other tropical climate, due mostly to their higher latitudes. Faya-Largeau receives, on average, only 18 mm of rain per year. Monterrey receives considerably more—
approximately 383 mm per ye
dry climate because of its hig
the fact that most of its precipita
Using Köppen's formulas, Fa
fied as a BWh climate, while M
temperatures and more preci
as a BSh climate. Both Faya-La
are designated with the third
mean annual temperatures are

Notice that a pattern is b
Regions of wet equatorial clim

"Check Your Understanding" boxes ask students to reflect on what they have learned and apply key topics to real-world processes.

REMEMBER THIS

As an unsaturated air parcel rises, it follows the dry adiabat corresponding to its air temperature at the surface, and the isohume corresponding to its dew-point temperature at the surface. This shows that as *unsaturated* air rises, its temperature and dew-point temperature decrease, while its potential temperature and mixing ratio remain constant. The LCL of this air parcel is the point where these two lines intersect.

Above the LCL, the air parcel is saturated. As saturated air rises, it follows a saturated adiabat. This shows that as *saturated* air rises, and the water vapour in it condenses, its temperature and dew-point temperature are equal to each other and decrease together, and its saturation mixing ratio and actual mixing ratio are also equal to each other and decrease together. As the water *vapour* mixing ratio decreases, the amount of *liquid* water in the cloud increases.

8.4 Stability Types

So far, we have seen how thermodynamic diagrams can be used to study the changes in state of ascending and descending air parcels. When atmospheric soundings are plotted on these diagrams, as shown in Figure 8.9, they can be used to analyze *atmospheric stability*.

Atmospheric stability is a measure of the tendency for air—once it has been disturbed by turbulence (Section 4.4.2)—to move vertically due to temperature differences. We can characterize an air parcel as either *unstable*, *stable*, or *neutral*, based on the way in which it reacts when it is disturbed. If air that is disturbed continues in the direction of the disturbance, vertical motion is favoured, and the air is said to be *unstable*. If the disturbed air parcel returns to its original position, vertical motion is suppressed, and the air is said to be *stable*. If the disturbed air parcel remains in its new position, the air is said to be *neutral*.

The following analogy should help clarify these three stability types. Imagine a marble balanced on top of a dome (Figure 8.10a). As long as the marble is undisturbed, it will remain there, but the slightest disturbance will cause it to roll off the dome. This marble is in an *unstable* position. Now, imagine a marble sitting in the bottom of a bowl (Figure 8.10b). A slight disturbance could cause the marble to roll up the side of the bowl, but the marble will naturally roll right back to its starting position. This marble is in a *stable* position. Finally, imagine a marble on a flat surface (Figure 8.10c). If this marble is disturbed, it will roll away from its starting point and stop. This marble is in a *neutral* position; it neither keeps moving away from nor returns to its starting point.

In the atmosphere, stability is associated with temperature differences. An undisturbed air parcel will be at the same temperature as its surroundings. If the air parcel is vertically displaced by turbulence, it will likely find itself in a situation where its temperature is different from that of its surroundings (Figure 8.11). There are two possible reasons for this difference in temperature. First, the air parcel itself will experience an adiabatic temperature change resulting from its displacement. Second, the temperature of the new surroundings may be different from the temperature of the original surroundings; this difference is determined by the ELR of the air layer and the direction in which the parcel travelled. Once in its new position, if the air parcel is warmer than its surroundings, it will be less dense and, therefore, have a tendency to rise. On the other hand, if it is colder than its surroundings, it will be more dense and have a tendency to sink.

To determine atmospheric stability, we compare the temperature of a displaced air parcel—using the DALR or the SALR—to that of the surroundings—using the ELR. First, let's consider the conditions that characterize an *unstable* air layer.

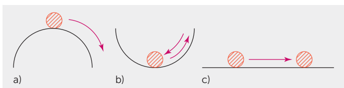


FIGURE 8.10 These diagrams provide very simple models of different stability conditions. a) A marble on a dome represents unstable conditions. b) A marble at the bottom of a bowl represents stable conditions. c) A marble on a flat surface represents neutral conditions.

"Remember This" boxes draw students' attention to key points and provide valuable tools for review.

11 | Winds 277

In the Field

I Chase the Wind

Mark Robinson, stormhunter.ca

I chase the wind. It's the basis of everything I do. Tornadoes, hurricanes, blizzards. If the wind is tossing stuff through the air, I'm there with an anemometer in one hand and a camera in the other.

Chasing the wind isn't easy or risk-free, but it's a passion that I've had for many years. During my meteorology schooling, I learned the basic equations for the fluid dynamical nature of the atmosphere, which laid out the marvelous manner in which the air moves across the oceans and the land. Going into the field to see the motion of air took the world of textbooks and made it real. Seeing the updraft of a thunderstorm punch into the upper layers of the troposphere takes things way beyond math. And if that thunderstorm produces the ultimate wind, then things become very real, very fast.

I think of thunderstorms as a sculpture of wind and water churning in the sky above me. But to get that sculpture, you need the wind to be doing the right thing. Speed and directional shear are critical for tornado development. Without these factors, the core of the storm can't get spinning and supercells can't develop.

Supercells are the ultimate prize for a storm chaser. These cells produce all types of severe weather, including giant hail, high winds, lightning, torrential rains, and tornadoes. My ultimate encounter with these storms happened in 2013. My chase partner, Jaclyn Whittal, and I were close to the town of El Reno, Oklahoma, waiting on storms to fire in the late afternoon. The atmospheric parameters were close to perfect if you wanted violent, long-track tornadoes. But as much as we wanted to see a tornado track across open fields in the middle of nowhere, we were very close to some highly populated areas. The first storms popped up right on schedule and immediately began to rotate, but very quickly they congealed into a massive mess that looked like it wasn't going to produce anything but a lot of rain and some lightning. We headed toward the southern end of the storm, hoping to at least get some shots of interesting cloud formations. What we didn't realize was that the storm had started to build one massive updraft that was corkscrewing deep inside the concealing cloud.

We halted on a road just southeast of the storm and set up our cameras. We watched as the main updraft of the storm slowly emerged from the low-level clouds, and we could see the telltale signature of a powerful storm. The wind had sculpted the white mass of the cloud that formed the storm into a massive bell shape, signifying that the storm was not only powerful, but also spinning like a top. There was almost undoubtedly a tornado buried in the grey mass of rain and cloud that seemed to scrape the ground itself.

And yet, even with all those indicators, we couldn't see the tornado. Jaclyn and I peered uselessly into the storm, trying to get a glimpse of the white funnel we knew must be there. The radar indications of a tornado got stronger and stronger. I'd never seen a radar screen that looked like this. The only way the radar could be right was if the biggest tornado the world had ever seen was bearing right down on us. And that's exactly what was happening.

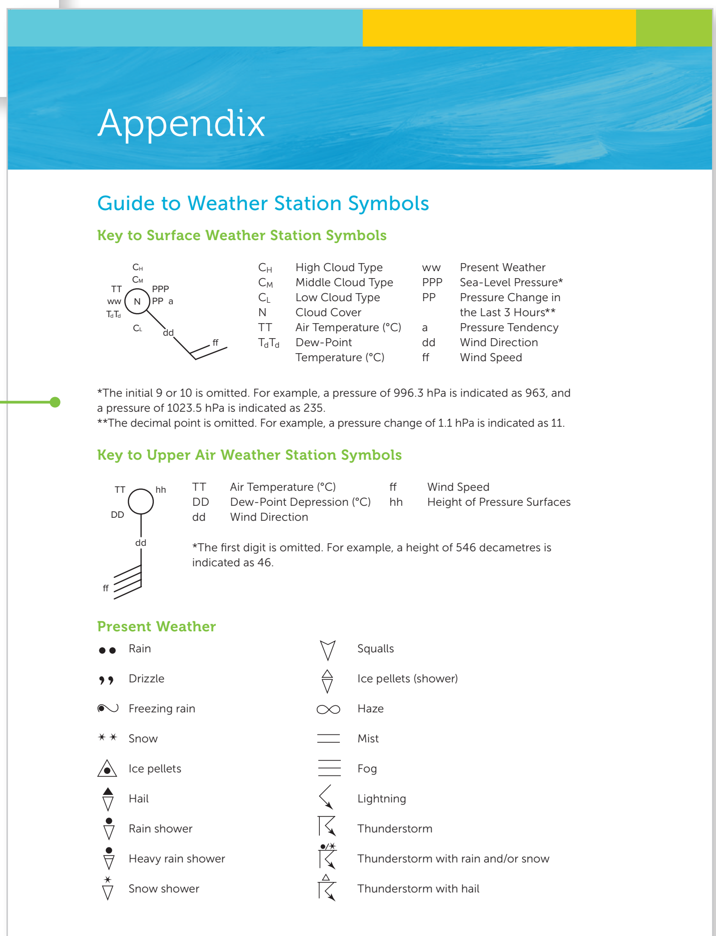
The grey wall that was roaring toward us *was* the tornado, and it was heading right for us. I yelled at Jaclyn to get in the car, and a flash of green lit up the tornado as it tore up power lines in the field. We had to make it south as fast as we could to get out of its way. We made it, but not every chaser did. Sadly, three of our colleagues—Tim Samaras, Paul Samaras, and Carl Young—were killed by the 4.5 km–wide tornado. It was a tragic day for storm chasers.

That's part of what drives me to seek out the big winds. Learning how the winds move across the planet and why storms do what they do helps me be a better meteorologist and a better forecaster. If I can take my experience with the wind and warn those in its path what's coming, then I'm doing my job. The risks of chasing the wind are real for storm chasers and for everyone who encounters storms, but it's a part of what I do, and I'll continue to be out there every day the big winds blow.

MARK ROBINSON is a meteorologist, a severe weather expert, an educator, and a storm chaser based out of Toronto, Canada. He documents and investigates severe weather throughout North America.

"In the Field" boxes—written by top researchers from across Canada—offer students insight into the types of research meteorologists and climatologists do every day. Topics covered include measuring levels of aerosols in the atmosphere, studying precipitation patterns on regional and global scales, assessing the impact of forest fires on air quality, and understanding and monitoring atmospheric characteristics of Arctic environments.

A list of weather station symbols, included in an appendix, gives students the information they need to perform in-depth analyses of weather maps.



Appendix

Guide to Weather Station Symbols

Key to Surface Weather Station Symbols

C_H	High Cloud Type	ww	Present Weather
C_M	Middle Cloud Type	PPP	Sea-Level Pressure*
C_L	Low Cloud Type	PP	Pressure Change in the Last 3 Hours**
N	Cloud Cover	a	Pressure Tendency
TT	Air Temperature (°C)	dd	Wind Direction
T_dT_d	Dew-Point Temperature (°C)	ff	Wind Speed

*The initial 9 or 10 is omitted. For example, a pressure of 996.3 hPa is indicated as 963, and a pressure of 1023.5 hPa is indicated as 235.

**The decimal point is omitted. For example, a pressure change of 1.1 hPa is indicated as 11.

Key to Upper Air Weather Station Symbols

TT	Air Temperature (°C)	ff	Wind Speed
DD	Dew-Point Depression (°C)	hh	Height of Pressure Surfaces
dd	Wind Direction		

*The first digit is omitted. For example, a height of 546 decametres is indicated as 46.

Present Weather

Rain	Squalls
Drizzle	Ice pellets (shower)
Freezing rain	Haze
Snow	Mist
Ice pellets	Fog
Hail	Lightning
Rain shower	Thunderstorm
Heavy rain shower	Thunderstorm with rain and/or snow
Snow shower	Thunderstorm with hail

End-of-chapter review questions and problems help students synthesize what they have learned, while suggestions for further research encourage students to develop their research skills by investigating key topics related to each chapter.

Review Questions

1. What is the difference between constant gases and variable gases? Give an example of each. How is residence time an important determinant of whether or not a gas will be constant or variable?
2. What sinks for oxygen are sources for carbon dioxide? What sinks for carbon dioxide are sources for oxygen?
3. How can photosynthesis lead to a) short-term carbon storage and b) long-term carbon storage?
4. How does the carbonate–silicate cycle influence climate? How does climate influence the carbonate–silicate cycle?
5. How does production and destruction of stratospheric ozone protect life on Earth from ultraviolet radiation?
6. What is the importance of each of the following variable gases in our atmosphere: water vapour, carbon dioxide, and ozone?
7. What are the differences between primary aerosols and secondary aerosols? Give examples of each.
8. What important roles do aerosols play in the atmosphere?
9. How is the composition of the troposphere similar to and different from that of the stratosphere?
10. What are the two most abundant gases in today's atmosphere? What were the two most abundant gases in Earth's primitive atmosphere? How do you account for this change?
11. What evidence do we have that oxygen did not begin to accumulate in the atmosphere until about 2 billion years ago?
12. What is the largest reservoir in the Earth system for a) carbon, b) water, and c) nitrogen?
13. What is the significance of each of the following to the evolution of Earth's atmosphere: a) distance from the sun, b) life, c) plate tectonics, d) Earth's size, and e) the solubility of carbon dioxide in water?

Suggestions for Research

1. Explore how either the carbon cycle or the nitrogen cycle is being altered by human activities. Examine the short- and long-term consequences of these changes, and find out what, if anything, is being done to slow or reverse the changes.
2. Research different theories—both past and current—that account for the evolution of Earth's atmosphere. Evaluate the evidence behind each theory, and comment on why such theories are continually being revised.

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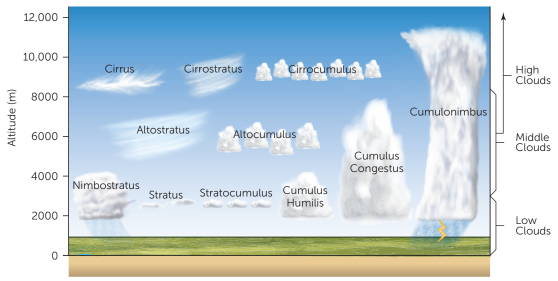
A cloud chart, located at www.oup.canada.com/Ross2e, provides a concise comparison of the most common types of clouds, to help students classify clouds when they make their own observations of the atmosphere.

Cloud Chart



Larsson/Thinkstock

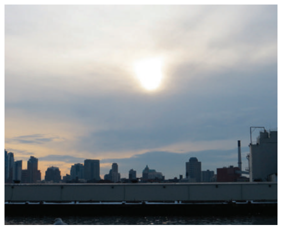
CIRRUS CLOUDS appear as fibrous streaks scattered across the sky. Because they form high in the troposphere, where it is both dry and cold, cirrus are relatively thin clouds, composed of ice crystals.

shellhawker/iStockphoto

CIRROCUMULUS CLOUDS are high-altitude clouds made of ice crystals. They are layer clouds that have been destabilized to produce tiny individual clumps of cloud that are usually arranged in a regular pattern, between which blue sky can be seen.

Alexey Romanov/Thinkstock

CIRROSTRATUS CLOUDS are high ice-crystal clouds that form a veil across the sky. This layer of cloud is often so thin that direct sunlight can cast shadows on the ground below it. The ice crystals in cirrostratus clouds can produce a halo around the sun or moon.



bellasabel/iStockphoto

ALTOSTRATUS CLOUDS are middle-height clouds that form a featureless sheet across the sky. Altostratus cloud is thicker than cirrostratus cloud, so the sun appears as though it is shining through frosted glass, and its light becomes too diffuse to cast shadows on the ground.

DWalker44/iStockphoto

ALTOCUMULUS CLOUDS are middle-height clouds that form a layer that covers most of the sky. Like cirrocumulus clouds, they are produced when a cloud layer is destabilized. Unlike cirrocumulus, the individual clumps of altocumulus cloud shadow each other and appear larger because they are closer to the ground.

Bildarchiv Okapia/Science Source

STRATOCUMULUS CLOUDS are the most common of all cloud types. They are low clouds that have characteristics of both stratiform and cumuliform clouds, being both layered and heaped in form. The individual cloud mounds are larger than they are in altocumulus clouds, and they show more tonal variation than is apparent in stratus clouds. These clouds can produce light precipitation.

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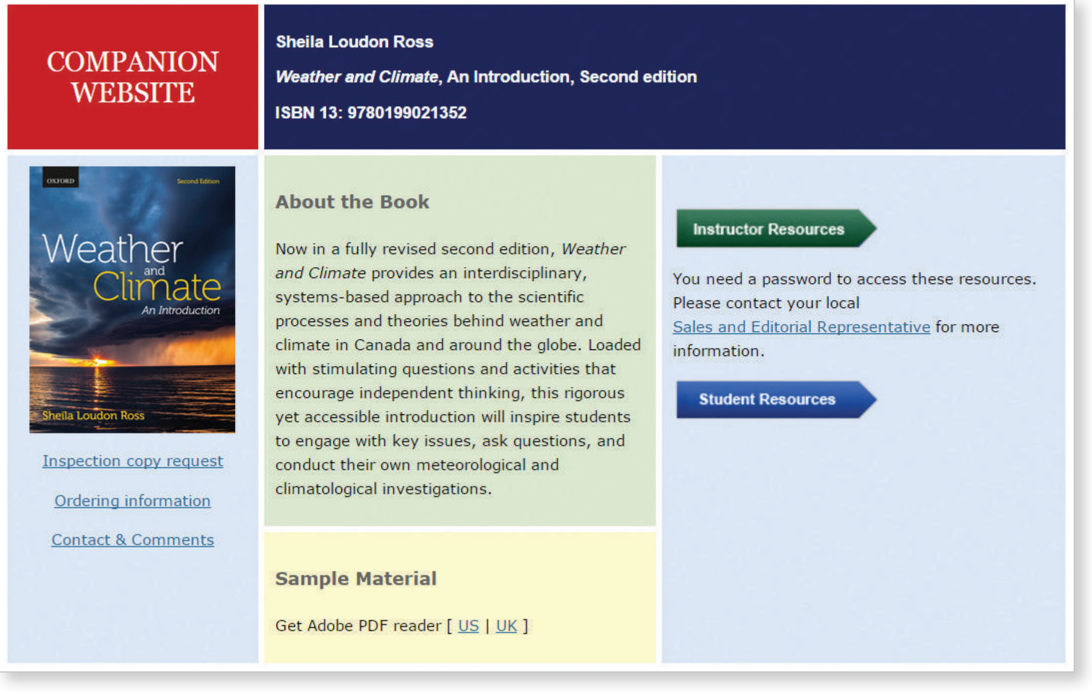

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Preface

This book is a guide to understanding the atmosphere and how it produces weather and climate. While the processes that are largely responsible for creating weather and climate are transfers and transformations of energy, mass, and motion that occur in the atmosphere, the atmosphere does not operate alone. Instead, the atmosphere is part of a system—referred to in this book as the *Earth system*—in which the atmosphere constantly interacts with the water, ice, life, and rocks of this planet. For example, clouds form as air ascends and cools *within the atmosphere*, but clouds cannot form without the water and particles that are supplied by processes operating *at Earth's surface*. Although we have quite a good understanding of many of the processes associated with cloud formation that operate within the atmosphere itself, much research still needs to be done to understand the relationships between cloud formation and such things as soil moisture, vegetation, and the type and abundance of particles released into the atmosphere. Thus, in order to fully understand clouds, we must fully understand *all* the processes associated with their formation, because changes in any of these processes will likely also change clouds. In turn, changes in clouds cause changes in Earth's climate. It follows that viewing Earth as a system allows us to better understand global change.

Although such a holistic approach to understanding Earth has ancient roots, many twentieth-century scientific thinkers and researchers tended toward specialization. This specialization likely contributed to the period's great scientific and technological advancements. However, we are becoming increasingly aware that specialization does not provide a complete understanding of how Earth operates. Such awareness led to the emergence of the discipline of Earth system science and the formulation of the Gaia hypothesis in the 1970s. These two diverse approaches to Earth science—described in sections 1.2 and 2.11 of this book—each recognize that Earth behaves as a system characterized by complex interactions and feedbacks.

In recent decades, undoubtedly as a result of this shift in perspective, the word *interdisciplinary* has increasingly appeared in university and college course descriptions and textbooks. Further, research is now often interdisciplinary in nature. This trend is illustrated in some of the "In the Field" boxes scattered throughout this book; in these boxes, a variety of Canadian atmospheric scientists describe their research, which often involves investigating linkages between the atmosphere and the processes operating *outside* the atmosphere. As the discussions in these boxes reveal, this sort of broader-based research, which falls outside traditional disciplinary boundaries, can offer many exciting challenges and rewards.

As you read through this book, take note of the many linkages within the Earth system, while keeping in mind that we are far from having a complete understanding of most of them. As we take a systems-based approach, we will undoubtedly come to understand Earth with greater clarity. Hopefully, such clarity will make it possible to more accurately predict the consequences of our actions, to reverse—or at least lessen—the impact of the environmental degradation that we have already caused, and, ultimately, to prevent further damage.

Acknowledgements

My academic career in physical geography, in particular the atmospheric sciences, began thanks to Dr Timothy Oke, professor emeritus of the University of British Columbia. After completing my graduate studies under his supervision, I was hired as a geography instructor at Capilano University, in North Vancouver. Over the years, my colleague, Karen Ewing, provided valuable mentoring and was always willing to share ideas.

I was able to do a large portion of the work on the first edition of this book thanks to a paid educational leave from Capilano University. Robert Campbell, dean of arts and sciences at the time, encouraged me to see the project through to completion, and Karen provided valuable feedback on the first drafts of some of the earlier chapters. I would also like to thank the many students I have worked with in almost 30 years of teaching at Capilano University. It is through interaction with these students that I have come to learn what works and what doesn't when explaining difficult concepts, and that enthusiasm is key. In particular, I would like to acknowledge my Geography 214 class of the 2011 spring term. During that term, as I was completing chapters for the first edition of this book, these students showed an interest in my project and made use of my draft chapter summaries as study guides.

I would like to acknowledge the work of the people at Oxford University Press that has ultimately made this book possible. Jodi Lewchuk made the necessary arrangements for work to begin on the second edition. The careful edits of Peter Chambers on both the first edition and the second edition, Jennifer Weiss on the second edition, and Janice Evans on the first edition have definitely improved the accuracy, clarity, and readability of my work. I am particularly grateful to Peter for the tremendous amount of work he put into ensuring that the diagrams for this new edition are both visually appealing and accurate. I would also like to thank the expert team of designers and formatters and the illustrator Jillian Ditner who created the diagrams you will encounter throughout the book.

Working on this book has been very fulfilling, and I am grateful that my family, including my parents, has never objected to the amount of time that I have spent on it.

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Weather and Climate

1

The Study of the Atmosphere

LEARNING GOALS

After studying this chapter, you should be able to

- distinguish between weather and climate;
- describe how the various components of the climate system interact;
- explain the process of scientific study;
- apply the system of units used in atmospheric science; and
- describe how Earth's atmosphere changes with height.

In the Earth sciences, we use the term **atmosphere** to refer to the layer of gases that surrounds a planet or other celestial body (Figure 1.1). Interestingly, we also use the word *atmosphere* more generally when referring to the *feeling* we get from our surroundings. Planetary atmospheres certainly shape the *feeling* at the surface of a planet, and Earth's atmosphere is no exception.

atmosphere
The layer of gases surrounding a planet or celestial body.

Earth would be an entirely different place without its atmosphere. To begin, the "sky" would appear black rather than blue (Figure 1.2). There would be no air to breathe, and no ozone layer to prevent the sun's dangerous ultraviolet radiation from reaching Earth's surface. Temperatures would reach extreme highs and lows, as there would be nothing to reflect away solar radiation by day, and nothing to keep in warmth by night. Because sound won't travel in a vacuum, it would be very quiet. There would be no wind, and there would certainly be no clouds, nor would there be rain or, perhaps, any liquid water at all. In short, there would be no weather. All of these characteristics of the atmosphere, and more, result from the operation of processes that are mostly invisible.

1.1 Weather and Climate

Atmospheric science is our quest to understand these processes and how they create **weather** and **climate**. Indeed, atmospheric science is often divided into two subdisciplines: **meteorology**, which is the study of weather, and **climatology**, which is the study of climate. *Weather* is the state of the atmosphere at a specific time and place. We describe the state of the atmosphere in terms of the *elements* of weather, which include atmospheric pressure, clouds, precipitation, wind, temperature, and humidity. An important characteristic of the weather elements is their ability to quickly change. In fact, the atmosphere is in a constant state of change, and this is what makes weather so changeable.

weather
The state of the atmosphere at a given place and time.

climate
The average conditions of the atmosphere.

meteorology
The study of the atmospheric processes responsible for weather.

climatology
The study of climate.

Weather is an integral part of life on this planet. It affects how we feel and what we wear.

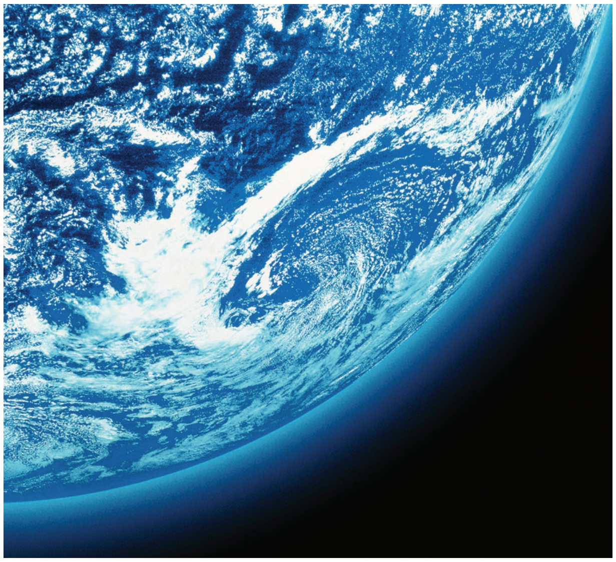
SPL/Science Source

FIGURE 1.1 Planet Earth from space. The blue haze around the edge of Earth is its atmosphere. Although Earth's atmosphere is thin in comparison to the size of the planet, this layer of gases has a dramatic impact on the conditions at Earth's surface.

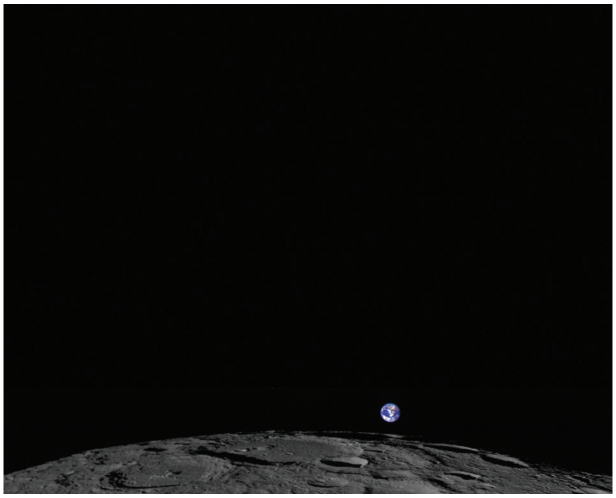
NASA/GSFC/Arizona State University

FIGURE 1.2 The moon's "sky." With no atmosphere, the moon's "sky" appears black.

◀ When viewed from space, Earth's atmosphere appears to be a simple, thin blue layer that is quite separate from the surface of the planet. In actuality, the atmosphere is part of a complex system in which it continually interacts with the surface, effectively shaping climate and, ultimately, the planet's ability to sustain life.
Photo: NASA

It might cause us to cancel plans, and it might give us something to talk about with strangers. It creates an ever-changing skyscape to fill us with wonder and delight when we take the time to pay attention. However, the effects of weather can also be far from trivial. Weather can ruin crops, flatten buildings, sink ships, cause floods or droughts, and much more (Figure 1.3). Most importantly, weather provides an essential service: as clouds form and rain falls, weather filters and replenishes our water supplies. A practical motivation to study the atmosphere is to understand what causes weather to change and, thus, to be able to make **weather forecasts** (Chapter 15).

While weather is characterized by change, climate is less about change and more about what stays the same—although even climate varies over the long term. As such, climate is often defined simply as "average weather," but a complete description of the climate of a place usually also includes information about extremes. The difference between weather and climate is nicely illustrated by comparing a weather map to a climate graph (Figure 1.4). A weather map depicts atmospheric conditions at a *moment* in time. On the other hand, a climate graph is based on temperature and precipitation measurements made over a period of 30 years, which are then averaged to provide so-called *climate normals*. Thirty years is the period recommended by the World Meteorological Organization (WMO) for obtaining an accurate depiction of the climate of a place. Canada's most recently available set of climate normals is for the period from 1981 to 2010. These statistics can be found at Environment Canada's Weather Office website (climate.weather.gc.ca). If you visit this website, you will notice that information on weather extremes—such as extreme maximum and minimum temperatures, and extreme daily precipitation—is also provided.

51Systems/iStockphoto

FIGURE 1.3 A section of Calgary during the Alberta flooding in June 2013. Over 100,000 people were displaced by the flooding, which was caused by extremely heavy rainfall. Up to 200 mm of rain fell in some of the southwestern parts of the province.

REMEMBER THIS

Weather is short term, while climate is long term.

The climate graph in Figure 1.4a depicts climate at the *regional* scale for Regina, Saskatchewan, and its immediate surroundings. Climate graphs are included throughout this book to illustrate factors that control climate at a regional scale. The most important of these climate controls is latitude: low latitude climates are warmer than high latitude climates. In addition, most coastal climates experience milder temperatures and more rainfall than do most continental climates. It can even make a difference to climate if a place is located on a west coast or an east coast. For example, in Canada, prevailing winds from the west mean that west coast climates are more strongly influenced by the ocean than are east coast climates. Mountain ranges also affect climate. Some of the wettest places on Earth are on the windward sides of mountains, while some of the driest places are on their leeward sides (Figure 1.5). There is even the familiar correlation

weather forecast
An estimate of the future state of the atmosphere.

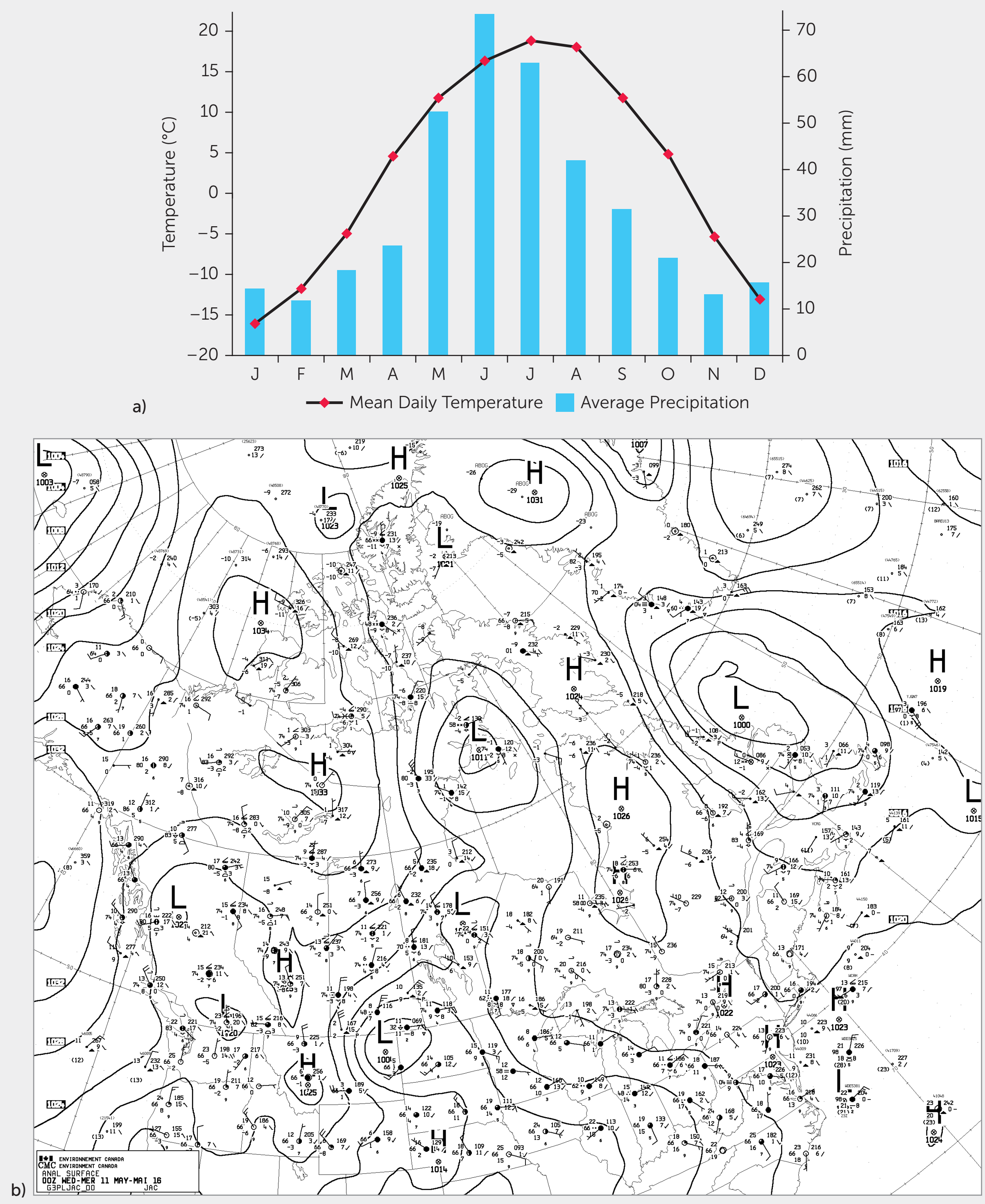

FIGURE 1.4 a) A climate graph for the mid-latitude continental location of Regina, Saskatchewan. b) A weather map of Canada for 11 May 2016 at 0000 UTC.

Sources: a) Data from Environment Canada, National Climate Data and Information Archive, "Canadian Climate Normals 1971–2000" for Regina Int'l A, www.climate.weatheroffice.gc.ca/climate_normals, accessed 9 May 2012; b) Environment Canada, Weather Office, www.weatheroffice.gc.ca/analysis/index_e.html, 11 May 2016.

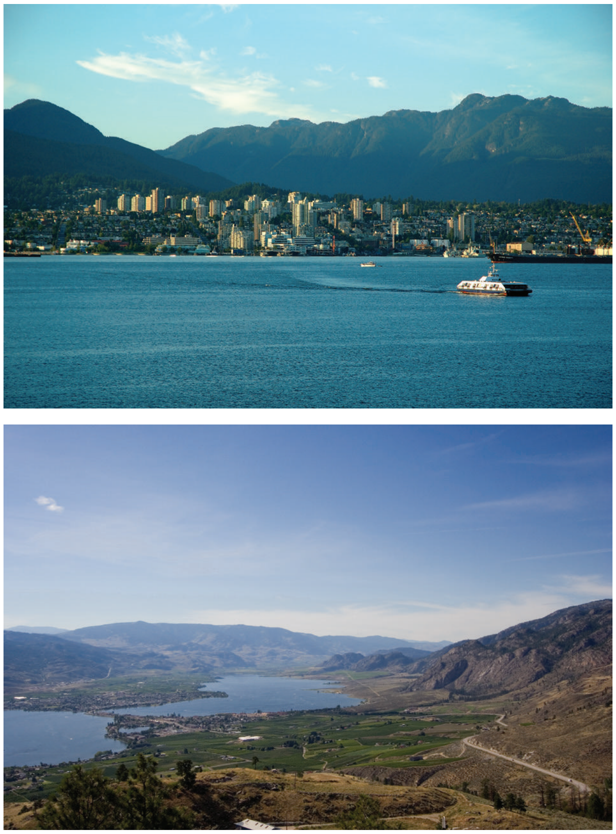

FIGURE 1.5 Mountains affect climate. *Top:* Situated on the windward side of the Coast Mountains, Vancouver receives high levels of precipitation, with some locations on the city's north shore receiving more than 2500 mm of precipitation per year. *Bottom:* Osoyoos, in the southern Okanagan, is located in the rain shadow of these mountains and receives only about 300 mm of precipitation per year.

between increasing altitude and decreasing temperature. We will consider these controls on regional climates in more depth in Chapter 16.

Climate is studied at scales both smaller and larger than the regional scale. The smallest scale climates occur over areas of a few square metres to several square kilometres. In Chapter 6, we will see how the characteristics of a surface—such as a lawn or a parking lot—influence energy flows, thereby creating **microclimates**. Such microclimates include anything from a cool, shady spot under a tree to the "heat island" created by an urbanized surface. Indeed, the effects of an urban surface may cause the climates of some cities to differ from that of the surrounding region.

Today we are increasingly interested in climate at the *planetary* scale; the average temperature of our planet is currently just below 15°C. This temperature results from a combination of the amount of energy Earth receives from the sun, the amount of this energy Earth reflects back to space, and the **greenhouse effect** created by Earth's atmosphere (Section 6.4). A planet's greenhouse effect results from the presence of **greenhouse gases** in its atmosphere, and makes the planet warmer than it would be otherwise. Today we are particularly motivated to understand the complexities of climate at the planetary scale because human activities are increasing the amount of greenhouse gases in the atmosphere, and causing changes to the atmosphere and surface that are affecting Earth's reflectivity. The *net* result of these changes is an observed increase in global temperature of close to 1°C over the last 100 years (Figure 1.6). Known as **global warming**, this increase in temperature has, in turn, affected other aspects of Earth's climate. Such **anthropogenic** climate change is addressed throughout this book and in Section 17.3 in particular.

microclimate
The climate of a small area at Earth's surface.

greenhouse effect
The part of a planet's temperature attributable to the presence of greenhouse gases in its atmosphere.

greenhouse gas
A gas that allows the shorter wavelength radiation from the sun to pass through the atmosphere, while it absorbs the longer wavelength radiation leaving Earth's surface.

global warming
The increase in Earth's temperature caused by increasing concentrations of greenhouse gases associated with human activities.

anthropogenic
Related to human activities.

system
A set of parts that interact.

REMEMBER THIS

There are three controls on Earth's temperature at the planetary scale:

- the amount of energy Earth receives from the sun,
- Earth's reflectivity, and
- Earth's greenhouse effect.

1.2 The Earth System

To best understand weather and climate, we must recognize that the atmosphere does not act independently. Instead, it is part of a **system** that

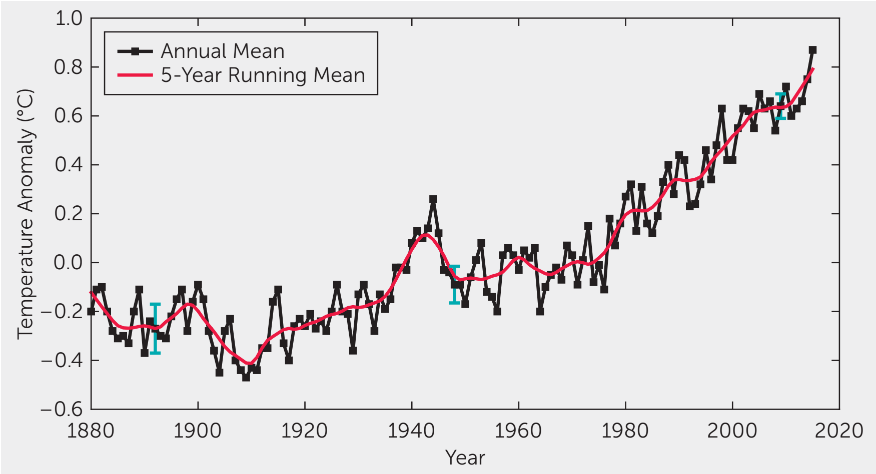

FIGURE 1.6 The increase in Earth's temperature from 1880 to 2015.

Source: Adapted from NASA Goddard Institute for Space Studies, http://data.giss.nasa.gov/gistemp/graphs/, accessed 16 August 2016.

Over the last few decades, we have come to recognize the importance of identifying and studying the interactions between the parts of the Earth system. Such studies go beyond traditional discipline boundaries and represent a new approach to understanding Earth. This approach is known as *Earth system science*—science that takes a *holistic* view of Earth. Earth system science has been facilitated by our increasing understanding of how our planet works, and the approach has been motivated by the awareness of the significant impact of human actions on natural processes. In fact, it has been suggested that we have now entered a new geological epoch in which humans have become a major force rivalling the forces of nature. The name proposed for this new epoch of the geological time scale is the *Anthropocene*, or the recent age of man. Significantly, the concept of the Anthropocene not only recognizes that humans now play a major role in Earth processes, it also implies that, perhaps, armed with our increasing understanding of Earth, we may now have the power to reverse our damaging effects. Thus, a systems approach to studying Earth allows us to consider not only natural processes but also those processes associated with human actions, in order to better understand, predict, and even mitigate the consequences of our actions.

lithosphere
The rocks of Earth.

biosphere
Life on Earth.

hydrosphere
The water of Earth.

cryosphere
The ice of Earth.

we call the *Earth system*. The five major parts of the Earth system are the **lithosphere**, the **biosphere**, the **hydrosphere**, the **cryosphere**, and, of course, the atmosphere itself. The lithosphere is made up of the rocks of the planet, the biosphere comprises all life on the planet, the hydrosphere includes all the water of the planet, and the cryosphere includes the ice of the planet (Figure 1.7).

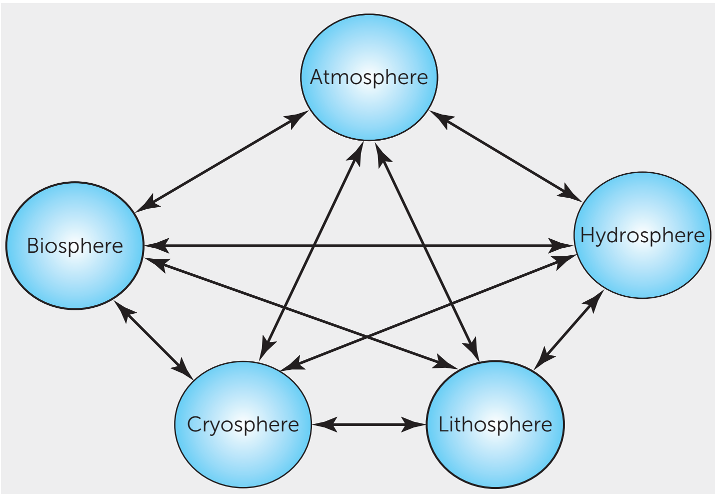

FIGURE 1.7 A schematic depiction of the interactions between the five spheres of the Earth system.

As you might expect, Earth system science must draw from—and integrate—knowledge from many areas of science, including atmospheric science. The focus of this book is, of course, the atmosphere and, as such, the content of this book contributes to our overall understanding of Earth as a system. However, although this book focuses on the atmosphere, a systems thinking approach implies that the workings of the atmosphere cannot be well understood without consideration of processes operating outside the atmosphere. As a result, you will notice that such interactions are considered throughout this book; together these interactions make up the *climate system*—the system responsible for Earth's climate (Figure 1.8).

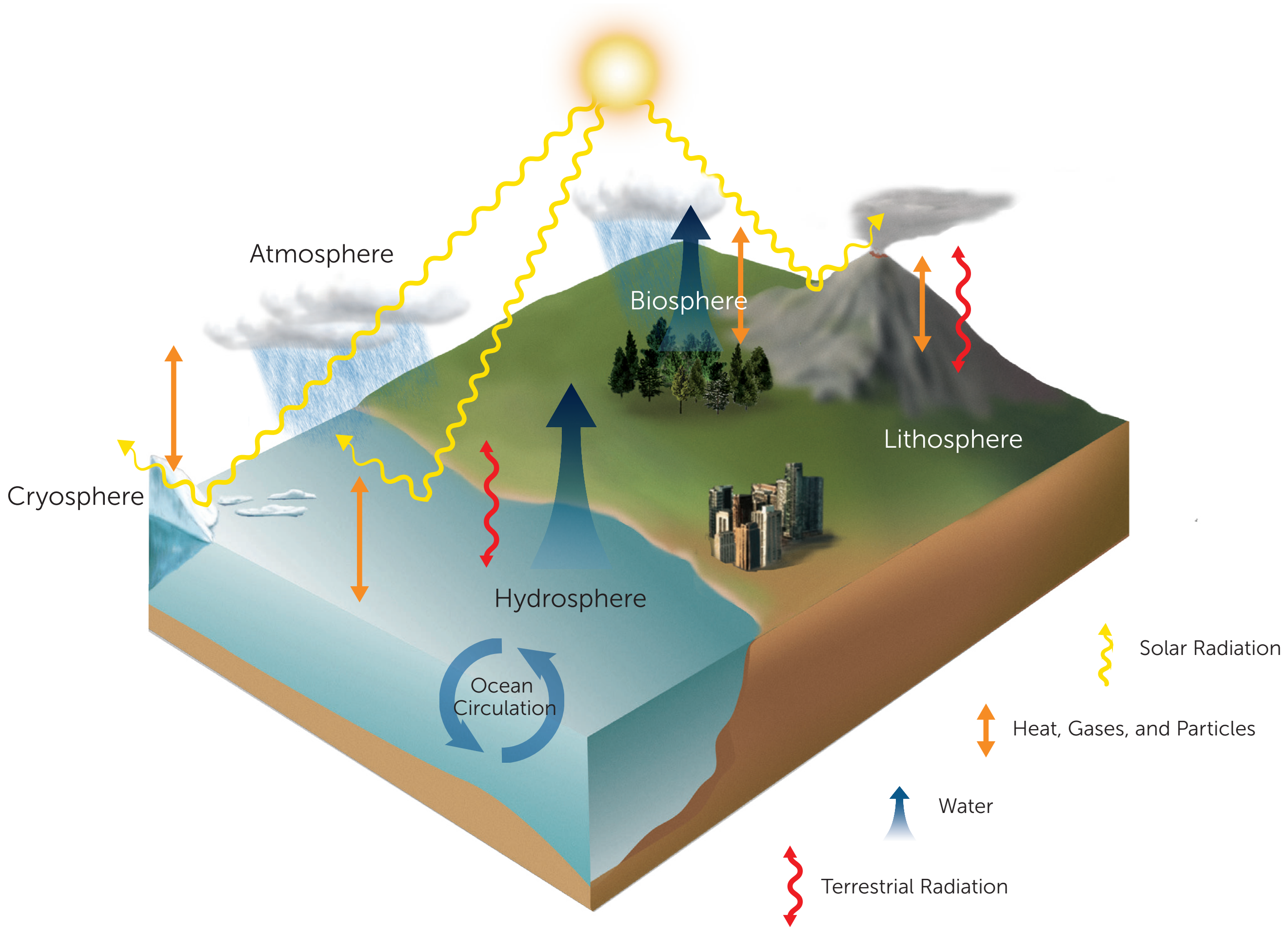

FIGURE 1.8 The climate system. Flows of energy and material connect the atmosphere to the rest of the Earth system.

Understanding the climate system is a central goal of Earth system science largely because of our need to understand, and deal with, anthropogenic climate change. The *atmosphere* is, of course, where most of the processes associated with climate happen. Such processes include, but are not limited to, the absorption and reflection of radiation by gases and particles; the vertical and horizontal motions of the air itself; and the phase changes of water that lead to the formation of clouds and precipitation.

As water changes phase, both water and heat are transferred between the atmosphere and the *hydrosphere*. Water is important to the climate system in other ways. In liquid form, water has a tremendous capacity to store heat. This means that cold air can warm significantly if it moves over warmer water as large amounts of heat can be transferred from the water to the air. In addition, bodies of water are very good *absorbers* of the sun's radiation, whereas in the form of ice or snow—the *cryosphere*—water is a very good *reflector* of the sun's radiation. Further, gases can dissolve in water. For example, carbon dioxide—an important greenhouse gas—is constantly exchanged between the atmosphere and the ocean. An increase in atmospheric carbon dioxide causes more carbon dioxide to dissolve in the oceans, while a drop in atmospheric carbon dioxide causes it to diffuse out of the oceans and into the air.

Like water, life—whether in the form of plants, animals, or bacteria—also exchanges gases with the atmosphere. Consider your own **respiration**, which removes oxygen from the atmosphere and returns carbon dioxide; consider also the process of **photosynthesis**, which does the opposite. In fact, throughout Earth's long

respiration
The life process in which oxygen is removed from the atmosphere and carbon dioxide is returned.

photosynthesis
The life process in which energy from the sun is used to convert carbon dioxide and water to oxygen and carbohydrates.

history, life has significantly impacted the composition of the atmosphere, and thus influenced climate, as we will see in Chapter 2. Apart from the exchange of gases, the *biosphere* influences the climate system in other ways. Forests are good absorbers of the sun's radiation, while grasses are more reflective, and bare ground is more reflective still. However, scientists believe that forests—especially the tropical rainforests—have a net cooling effect on Earth despite their low reflectivity. This cooling effect results in part because forests remove carbon dioxide from the atmosphere, but other factors are also responsible. To begin, trees absorb water from the soil and then release water vapour into the air through the stomata in their leaves. Because the transformation of water from liquid to vapour requires energy, the air is cooled. In addition, through this process of cycling water from the soil to the air, tropical rainforests are believed to help sustain the rainy climate to which they are adapted. The clouds that are produced when water is returned to the atmosphere will reflect sunlight, further contributing to cooling.

feedback effect

A mechanism that operates within a system to either amplify or lessen an initial change.

Even the rocks of the *lithosphere* play important roles in the climate system. Whenever a volcano erupts, it sends particles and gases into the atmosphere. Because particles associated with volcanic eruptions tend to be reflective of the sun's radiation, the short-term effect of a large volcanic eruption is often cooling. However, over the long term, an extended period of volcanic activity can cause warming because carbon dioxide emitted by volcanoes accumulates in the atmosphere. Further, while volcanoes *add* carbon dioxide to the atmosphere, the chemical breakdown of rocks at Earth's surface—a process known as weathering—*removes* carbon dioxide from the atmosphere. The ways in which these geological processes influence the atmosphere's composition will be explored further in Chapter 2.

Finally, *human actions* now impact the climate system at the global scale (Chapter 17). Most significantly, when we mine and burn fossil fuels—coal, oil, and natural gas—we are returning carbon dioxide to the atmosphere much more quickly than it would return naturally. This causes carbon dioxide to accumulate in the atmosphere. We are also making other changes to the atmosphere, and to Earth's surface, that alter the reflectivity of our planet to the sun's radiation. Just as the climate system is impacted by all parts of the Earth system, these other parts are, in turn, influenced by the climate system. All of these interactions, and more, will be considered in depth throughout this book.

REMEMBER THIS

We have good reasons to understand the atmosphere:

- forecasting the weather,
- predicting how human actions might influence climate at a variety of scales, and
- understanding Earth from a systems perspective.

Simply due to the sheer number of interactions involved, the study of Earth as a system can be a daunting task. This task is further complicated by the operation of **feedback effects**—disturbances in systems that lead to a sequence of events that eventually either amplify or lessen the initial disturbance. A *positive* feedback effect is a mechanism that operates within a system to *amplify* the effects of an initial change. A *negative* feedback effect is a mechanism that operates within a system to *lessen* the effects of an initial change. While positive feedback effects can be destabilizing, negative feedback effects can be stabilizing. There are many simple everyday examples of negative feedback. For example, when you are cold, you put on a sweater and feel warm again. If you fail an exam, you might study harder and do better the next time. As mentioned above, human actions are causing Earth's temperature to increase; this change in temperature is an example of a disturbance in the climate system that is likely triggering several positive feedback effects. A simple one is the *ice-albedo feedback effect*, which occurs because warming causes ice to melt. As ice melts, the reflectivity of the planet decreases, absorption of the sun's radiation increases, and warming is amplified (Figure 1.9). Unfortunately, few negative feedback effects are

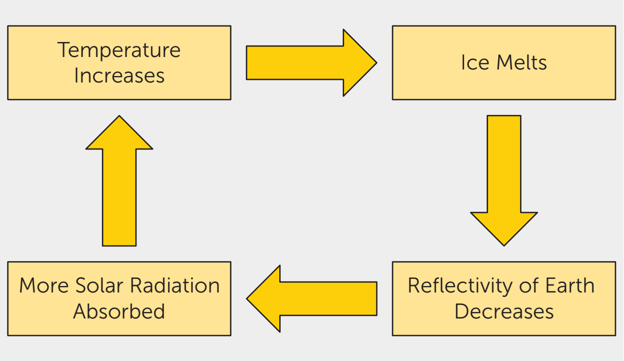

FIGURE 1.9 The loop associated with the ice-albedo feedback effect.

likely to be triggered by increasing temperatures. We will explore feedback effects associated with climate change in Chapter 17.

REMEMBER THIS

- Positive feedback effects are destabilizing because they strengthen the effects of disturbances.
- Negative feedback effects are stabilizing because they lessen the effects of disturbances.

1.3 The Role of Science

The purpose of science is to understand the complexities in the world around us by trying to find order, or patterns. In fact, scientists often marvel at the fact that there *is* order in nature. In practising science, we begin by making observations that provoke us to ask questions and investigate further. These investigations can ultimately lead us to the development of **scientific laws** and **theories** that can be used to describe and explain how the world works. Laws and theories are similar in several ways: they are widely accepted by the scientific community, they can be used to make predictions, and they can be rejected if shown to be untrue. Yet there are important differences between laws and theories as well.

Laws provide a *description* of how nature works, and they can be expressed in words, mathematical equations, or both. An example of a scientific law used in atmospheric science is the radiation law known as the *Stefan–Boltzmann law* (Section 5.2.1). In *words*, this law tells us that the amount of radiation emitted by an object increases with the fourth power of the temperature of that object. The *mathematical* expression of this law is given in Equation 5.4. In either form, this law *describes* the relationship between temperature and the amount of radiation emitted. It was determined by experiment, and it can be used in its mathematical form to make predictions.

Theories provide an *explanation* of how nature works. Theories are generally far more complex than laws, as they tend to encompass a large body of knowledge. Unlike laws, they cannot be expressed as a single equation, although they can include equations. An example of a theory described in this book is the *polar front theory*, which provides a detailed description of the structure and development of the storms known as mid-latitude cyclones—major producers of clouds, precipitation, and winds in the mid-latitudes (Section 14.2.1). This theory came about as a result of the work carried out by several Norwegian scientists interested in being able to forecast the weather. Over the years, the polar front theory has been modified as further investigation has increased our understanding of the processes that create these storms of the mid-latitudes.

Scientific investigation follows the **scientific method** and begins with observation. Observation can be as simple as perceiving some aspect of the world around us and wondering how it operates, but there are many possible sources of observations, such as the results of an experiment or unexplained patterns in a set of measurements. If an observation arouses our curiosity, we will ask a question. After further observation, we might form a **hypothesis**—an initial attempt to answer the question posed. Here is an example of how this method might operate: first, we *observe* that the sky is blue; next, we *ask why* the sky is blue; then, we *speculate on a reason* for the sky being blue. Once we make a hypothesis, we must test it. If testing shows the

scientific law
A precise statement that describes the behaviour of nature and is believed to always hold true.

scientific theory
A body of knowledge that provides a detailed explanation for a set of observations.

scientific method
A series of steps followed in scientific investigation.

hypothesis
A tentative explanation for an observation.

hypothesis to be true, we will accept it, although we have not yet *proven* it. If testing shows the hypothesis to be untrue, we will reject it.

We can test a hypothesis by performing an experiment, making further observations, or utilizing a **model**. Models are representations of reality that scientists use to describe, explain, and predict. They are particularly useful in atmospheric science, where traditional experiments are often difficult—if not impossible—to perform. The essential purpose of a scientific model is to simplify reality so that we can understand it. There are three types of models: conceptual, physical, and mathematical.

model

A representation of reality used to help in understanding complex or abstract natural phenomena.

CHECK YOUR UNDERSTANDING

What observations could you make about clouds? What questions could you derive from your observations? How might you follow the scientific method to investigate those questions?

Conceptual models—also known as *mental models*—represent our attempts to present our ideas about how something works. They are often used in teaching to show relationships or to explain abstract concepts, and they are generally presented as diagrams. A very simple example is the loop diagram used to illustrate the feedback mechanism described in Section 1.2 (Figure 1.9). Another example is the diagram, created by the Norwegian meteorologists as part of their polar front theory, that shows the stages in the life cycle of a mid-latitude cyclone (Figure 14.6).

An example of a *physical model* in atmospheric science is a rotating annulus, which has been used to perform "dishpan" experiments (Figure 12.23). In these experiments, the annulus is filled with water to represent the fluid character of the atmosphere. It is then heated at the outer edge to represent the equator and cooled in the middle to represent the poles, and it is rotated to represent Earth's rotation. Dishpan experiments allow us to investigate the *causes* of the large-scale wind patterns over Earth by varying certain conditions. For example, by varying the speed of rotation of the annulus we can investigate the effect of Earth's rotation on global wind patterns (Section 12.3). Another example of a physical model is a cloud chamber, which—as its name suggests—allows us to simulate, and thus explain, processes at work in clouds. Cloud chambers have helped us to understand the processes that turn cloud droplets into raindrops (Section 10.3).

general circulation model (GCM)

A computer program that represents the physics of the atmosphere through a set of equations.

REMEMBER THIS

There are five steps in the scientific method:

1. making an observation;
2. asking a question;
3. formulating a hypothesis;
4. making further observations, conducting an experiment, and/or utilizing a model; and
5. reaching a conclusion, by which science moves forward.

Mathematical models allow us to investigate the effects of a change in conditions by varying the numerical inputs to the model. Such models can be as simple as one equation with one variable, or as complex as a computer program that makes use of vast sets of equations and takes hours to run. Many of the equations introduced in this book could be thought of as models. For example, in Chapter 6 we will derive a simple equation for calculating the temperature of a planet based on the output of the sun, the planet's distance from the sun, and the planet's reflectivity (Equation 6.3). Each of these variables can be changed to explore its effects on the planet's temperature. Working on a larger scale, computer models known as **general circulation models**, or GCMs, are attempts to simulate the workings of Earth's entire climate system. These models are currently being used to make predictions about how climate might change as a result of human activities (Section 17.3).

Our investigations will certainly not always result in the formulation of laws and theories—in

CHECK YOUR UNDERSTANDING

What are the characteristics of a good model?

fact, most of the time they don't—but they do often lead to important advances in science or technology. They can also result in significant warnings to humankind, as the following story illustrates. F. Sherwood Rowland and Mario J. Molina's now-famous work on the depletion of the ozone layer was triggered by an *observation* made by another scientist, James Lovelock. In the early 1970s, Lovelock was making measurements of atmospheric composition with a new device he had invented, which could detect minute concentrations of gases. His measurements showed that a group of synthetic gases known as chlorofluorocarbons (CFCs) was accumulating in the atmosphere. Although he reported his findings, he was not concerned about them because, at the time, CFCs were regarded as harmless. Rowland and Molina, however, were curious about what might ultimately end up happening to these gases. By conducting *experiments*, they determined that once CFCs reached the layer of the atmosphere known as the stratosphere, they would likely be broken down by ultraviolet radiation and release chlorine.

Curious about what would happen to this chlorine, Rowland and Molina made use of a *mathematical model* that had been developed by previous researchers. The results showed that one chlorine atom is capable of destroying hundreds of thousands of ozone molecules and that a product of these reactions is chlorine monoxide. This work led Rowland and Molina to put forward the *hypothesis* that CFCs could destroy Earth's *ozone layer*—the layer of the atmosphere that protects life on Earth from the harmful effects of ultraviolet radiation. Although this hypothesis caused alarm and led some countries to ban the use of CFCs in aerosol sprays in the late 1970s, there was no proof that the ozone layer was indeed being destroyed until two separate research groups discovered the ozone hole over Antarctica in 1985 (Section 17.2) . Further *observations* showed that the ozone hole was not only an area of low ozone concentrations, it was also an area containing high amounts of chlorine monoxide. From this, researchers drew the conclusion that ozone was indeed being destroyed by the chlorine from CFCs. Shortly thereafter, action was taken to ban CFCs on a global level and, for their discovery, Rowland and Molina won the 1995 Nobel Prize in Chemistry.

REMEMBER THIS

We can see the scientific method at work in the early research on the depletion of the ozone layer.

1. Observation: CFCs are accumulating in the atmosphere.
2. Question: What will happen to the CFCs?
3. Hypothesis: The chlorine from the CFCs is destroying the ozone layer.
4. Further observations: There is a hole in the ozone layer, and that hole contains high amounts of chlorine monoxide.
5. Conclusion: Chlorine from CFCs is destroying the ozone layer.

1.4 The Role of Math: A Language and a Tool

As explained in the previous section, most scientific laws can be written as mathematical equations, and many scientific models are mathematical. In science, math provides a way of communicating the *form* of a relationship. For this reason, math has often been described as the *language* of science. The famous physicist Richard Feynman was referring to math when he eloquently wrote, "If you want to learn about nature . . . it is necessary to learn the language that she speaks in. She offers her information only in one form" (1967, p. 52). In order to understand science, then, it is essential to understand math.

In addition to being the *language* of science, math is also an important *tool* of science. First, math provides us with a set of numbers that we can use to quantify our observations. For example, most of the elements of weather can be expressed quantitatively. We can say that the temperature is *11°C* or that *3 mm* of rain fell in the last *6 hours*. Numbers allow us to keep records and look for patterns. Second, as mentioned above, math provides us with a means to make predictions. For example, as we will see in Chapter 8, parcels of air cool at a regular rate as they rise in the atmosphere; thus, we can use math to predict the temperature an air parcel will have once it has risen a certain distance (Example 1.1).

Example 1.1

We know that an unsaturated air parcel cools at a rate of 10°C for every kilometre it rises in the atmosphere. If the air temperature at Earth's surface is 26°C, what will be the temperature of this air if it rises 2.3 km?

$$26°\text{C} - 2.3\ \text{km}\ (10°\text{C/km}) = 3°\text{C}$$

Using math, we predict that if the air rises 2.3 km, it will cool to 3°C.

Mathematical equations are introduced throughout this book; those that are particularly important are highlighted in shaded boxes. In most cases, a new equation is followed by an example to illustrate its use. For each of these examples, consider that the equation is being used as a language to help you understand a new concept, as a tool to make a prediction, or both.

1.5 Dimensions and Units

In order to make measurements and perform calculations, we need a consistent, generally accepted set of units with which to work. In this book, we will use the system of units known as the MKS system, which corresponds to the internationally adopted International System of Units (SI). This system is based on seven basic dimensions; we will use four of them: length, mass, time, and temperature (Table 1.1). Notice that the name "MKS" comes from the first letters of the base units corresponding to the first three dimensions: metres, kilograms, and seconds. The base units for temperature are degrees kelvin. A kelvin degree is the same size as a Celsius degree, but while 0 K corresponds to absolute zero, 0°C corresponds to the freezing point of water. Both units will be used in this book. All other dimensions are derived from the basic ones. An example of a derived dimension is **density**, ρ, which is defined as the amount of mass, *m*, in a unit volume, *V* ($\rho = m/V$). Thus, using the basic units, we derive the units of density to be kilograms per cubic metre (kg/m^3). Four derived dimensions that are commonly used in atmospheric science are **force**, **energy** or **work**, **power**, and **pressure** (Table 1.2).

density
The amount of mass in a unit volume.

force
An action capable of accelerating an object.

energy
The capacity to do work.

work
The transfer of energy by mechanical means.

power
The rate at which energy is transferred, or work is done.

pressure
The force per unit area.

TABLE 1.1 Four of the basic dimensions of the MKS system, along with their units.

Dimension	Unit
Length	metre (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)

The units used for *force* can be explained using Sir Isaac Newton's first two laws of motion. His first law states that if an object is stationary, it will remain stationary unless an unbalanced force is applied to make it move, and if an object is moving at a constant speed and in a constant direction, it will continue to do so unless an unbalanced force is applied to change its speed, direction, or both. In the context of physics, a change in speed or direction is an *acceleration*. Therefore, we can use Newton's first law to define *force* as an action capable of accelerating an object. Newton's second law then tells us that the force, *F*, required to accelerate a given mass is simply the product of the mass, *m*, and the acceleration, *a*.

$$\text{Force} = F = m\,a = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} = 1\ \text{newton} \qquad \textbf{(1.1)}$$

TABLE 1.2 Four derived dimensions of the MKS system.

Derived Dimension	Unit	Basic Unit
Force	newton (N)	$kg \cdot m \cdot s^{-2}$
Energy (Work)	joule (J)	$kg \cdot m^2 \cdot s^{-2}$
Power	watt (W)	$kg \cdot m^2 \cdot s^{-3}$
Pressure	pascal (Pa)	$kg \cdot m^{-1} \cdot s^{-2}$

Equation 1.1 shows that the basic units of force are $kg \cdot m \cdot s^{-2}$, or the units for mass (kg) multiplied by the units for acceleration ($m \cdot s^{-2}$ or m/s^2). The name given to these units is, appropriately, newtons (N).

The definition of *energy* as the capacity to do *work* shows that energy and work are related. Through this definition, energy and work both have the same units. To determine these units, we use the definition of work, which is that work, *W*, is done when a net force, *F*, moves an object through a distance, *d*.

$$\text{Work} = W = F\,d = kg \cdot m \cdot s^{-2} \cdot m = kg \cdot m^2 \cdot s^{-2} = 1 \text{ joule} \quad \textbf{(1.2)}$$

Equation 1.2 gives the basic units of energy and work as $kg \cdot m^2 \cdot s^{-2}$. The name given to these units is joules (J). Just as the units for force recognize Newton's work on motion, the units for energy recognize the work of James Prescott Joule on energy.

Power is the rate at which energy flows, or work is done. Using this definition, power is energy, *E*, or work, *W*, divided by time, *t*.

$$\text{Power} = \frac{E}{t} \text{ or } \frac{W}{t} = kg \cdot m^2 \cdot s^{-2} \cdot s^{-1} = kg \cdot m^2 \cdot s^{-3} = 1 \text{ watt} \quad \textbf{(1.3)}$$

Equation 1.3 shows that the basic units of power are $kg \cdot m^2 \cdot s^{-3}$. The name given to these units is watts (W) after James Watt, an engineer known for his work in improving the efficiency of steam engines. Watt also developed the units of *horsepower*: one horsepower is equivalent to 746 watts. Related to power is **energy flux density**, the rate of energy flow per unit area of surface. The units used for energy flux density are watts per square metre (W/m^2). In climatology, energy flux density is used to quantify energy flows through a surface.

Finally, *pressure*, *P*, is defined as the force, *F*, per unit area, *A*.

$$\text{Pressure} = P = \frac{F}{A} = kg \cdot m \cdot s^{-2} \cdot m^{-2} = kg \cdot m^{-1} \cdot s^{-2} = 1 \text{ pascal} \quad \textbf{(1.4)}$$

Equation 1.4 shows that the basic units of pressure are $kg \cdot m^{-1} \cdot s^{-2}$, or pascals (Pa), after Blaise Pascal, who clarified the meaning of pressure. **Atmospheric pressure** is the force exerted by the atmosphere on Earth's surface. This force results from the *weight* of the atmosphere. Using Newton's second law, weight, *W*, can be defined as the force on an object due to gravity.

energy flux density
The rate of the flow of energy per unit area of surface.

atmospheric pressure
The force exerted by the atmosphere on Earth's surface.

$$W = m\,g \quad \textbf{(1.5)}$$

In Equation 1.5, *g* is 9.8 m/s^2, which is the acceleration due to gravity.

Atmospheric pressure is regularly measured as part of routine weather observations. In Canada, it is usually reported in *kilo*pascals (kPa). In Canadian meteorological offices, however, hectopascals (hPa) are also used. There are 100 pascals in a hectopascal. The average atmospheric pressure at sea level is 101.325 kPa, or 1013.25 hPa (Example 1.2).

Example 1.2

Given that the average pressure at sea level is 101.325 kPa, and that Earth's radius is 6.37×10^6 m, approximate the mass of the atmosphere.

First, convert the pressure to pascals: 101.325 kPa = 101,325 Pa. Then use Equation 1.5 in Equation 1.4, and solve for *m*.

$$P = \frac{m\,g}{A}, \quad m = \frac{P\,A}{g} = \frac{[(101{,}325\,Pa)\,4\pi\,(6.37 \times 10^6\,m)^2]}{9.8\,m/s^2} = 5.27 \times 10^{18}\,kg$$

It likely comes as a surprise that the atmosphere is so heavy.

CHECK YOUR UNDERSTANDING

How would changes in Earth's size, or changes in the mass of the atmosphere, affect sea level pressure?

1.6 The Structure of the Atmosphere

The **standard atmosphere** is a set of values representing the average vertical distribution of pressure, temperature, and

standard atmosphere
A set of values that represents the average vertical distribution of pressure, temperature, and density in the atmosphere.

TABLE 1.3 The standard atmosphere.

Height (km)	Temperature (°C)	Pressure (kPa)	Density (kg/m^3)
0	15.0	101.325	1.23
1	8.5	89.874	1.11
2	2.0	79.501	1.01
3	−4.5	70.121	0.91
4	−11.0	61.660	0.82
5	−17.5	54.048	0.74
6	−23.9	47.217	0.66
7	−30.5	41.105	0.59
8	−36.9	35.651	0.53
9	−43.4	30.800	0.47
10	−49.9	26.499	0.41
11	−56.5	22.699	0.37
12	−56.5	19.400	0.31
14	−56.5	14.170	0.23
16	−56.5	10.352	0.17
18	−56.5	7.565	0.12
20	−56.5	5.529	0.09
25	−51.6	2.549	0.04
30	−46.6	1.197	0.02
35	−36.1	0.559	0.01
40	−22.1	0.288	0.004
45	−8.1	0.152	0.002
50	−2.5	0.078	0.001
60	−26.2	0.021	0.0003
70	−53.6	0.005	0.00008
80	−74.6	0.001	0.00002
90	−86.3	0.0002	0.000003
100	−78.0	0.00003	0.0000006

density in the atmosphere (Table 1.3). These values are calculated, but they correspond well with averages of observations made by balloons and aircraft. Figure 1.10, created using the data in Table 1.3, provides a visual representation of the atmosphere's *average* structure. Notice that pressure and density decrease almost exponentially with height, while the change in temperature with height defines four distinct layers—two in which temperature *decreases* with height, and two in which temperature *increases* with height.

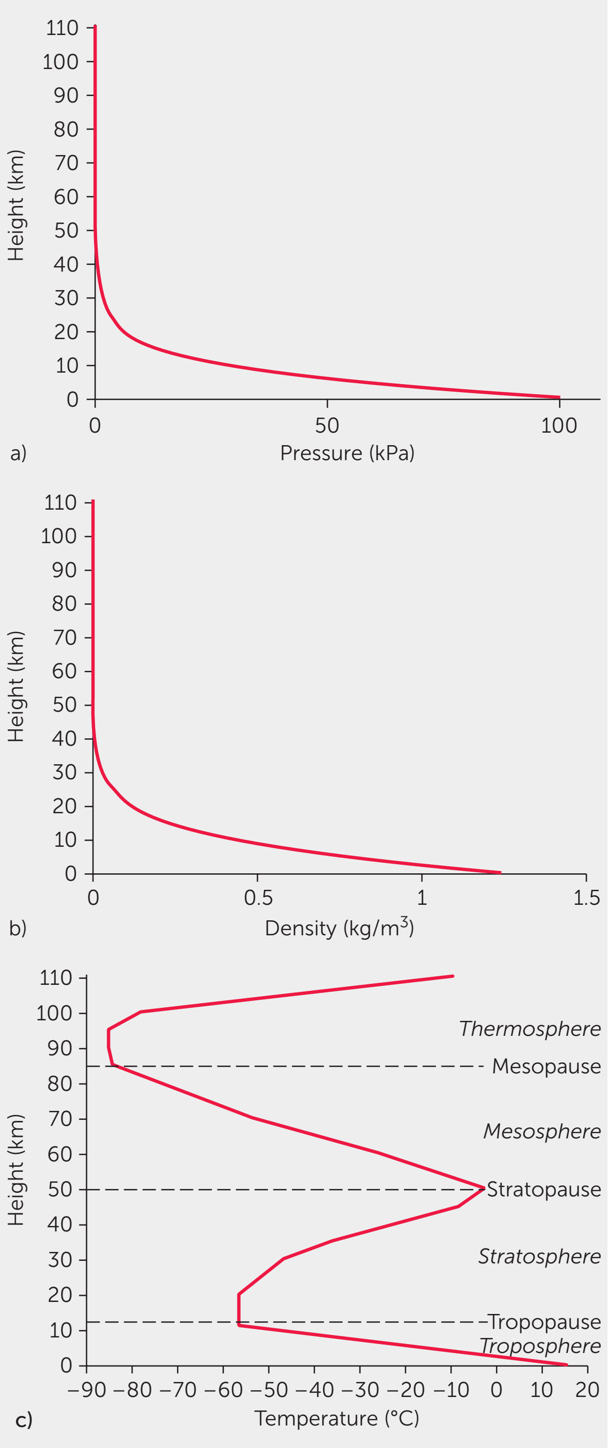

FIGURE 1.10 a) The change in pressure with height in the atmosphere. b) The change in density with height in the atmosphere. c) The change in temperature with height in the atmosphere.

1.6.1 | Pressure and Density

Pressure decreases with height in the atmosphere because, as shown in Example 1.2, pressure results from the weight of the overlying atmosphere. Pressure is greatest at Earth's surface because the weight of the entire atmosphere lies above. Higher up, there is less overlying atmosphere, so the pressure is less. In a similar way, water pressure is greatest on the ocean floor because of the entire weight of the water lying above. In fact, divers and submarines must adjust for the increase in pressure as they go deeper, or they will be crushed.

Density decreases with height in the atmosphere because air is compressible—that is, it can be squeezed into a smaller volume (Section 3.3). Because air near the surface is compressed by the weight of the air above, density is greatest at the surface. It is because the atmosphere rapidly thins with height that high-altitude hikers must carry oxygen (Figure 1.11). An important result of the atmosphere's compressibility is that half the mass of the atmosphere is squeezed into its lowest 5.5 km, while the other half is spread over many tens of kilometres (Figure 1.10a). Table 1.3 shows that the pressure at 5.5 km is about 50 kPa, which is about half of the pressure exerted by the *entire* mass of the atmosphere at sea level.

The fact that *density* decreases with height explains why the decrease in *pressure* with height is almost exponential, rather than linear. In the higher-density air near the surface, pressure will drop very quickly; higher up, where air molecules are farther apart, pressure will drop more slowly.

CHECK YOUR UNDERSTANDING

Notice that the standard atmosphere shows that surface air is warmer than air above. What keeps this warm surface air from continually rising?

FIGURE 1.11 Climbers on the Khumbu Icefall, Mount Everest, heading for their base camp, which lies at an altitude of just over 5000 m. High-altitude hikers such as these carry oxygen to compensate for the thinning atmosphere on the ascent.

1.6.2 | Temperature

The change in temperature with height shows alternating layers of decreasing and increasing temperature (Figure 1.10c). The lowest layer, the **troposphere**, extends from Earth's surface to the **tropopause**, located at an average height of 11 km. As shown by the standard atmosphere, temperature decreases through the troposphere at an average rate of 6.5°C/km (Table 1.3); the tropopause is the height at which temperature stops decreasing. The troposphere is warmest on the bottom because it is heated by Earth's surface, in much the same way as a stove element warms the air above. Because tropical latitudes are warmer than polar latitudes, the effects of Earth's surface will extend higher into the atmosphere in tropical latitudes. Thus the tropopause can be as high as 16 km in the tropics, while it reaches only about 8 km above the poles. Additionally, because it is warmed from the bottom, the troposphere is a turbulent layer throughout which heat, water vapour, and particles originating at Earth's surface are thoroughly mixed. Both turbulence and water vapour are needed for weather and, as a result, the troposphere is the layer in which all our weather occurs and almost all clouds form.

troposphere
The layer of the atmosphere extending from Earth's surface to an average height of 11 km.

tropopause
The top of the troposphere.

The next layer of the atmosphere, the **stratosphere**, stretches from the tropopause to the **stratopause**, located at an altitude of about 50 km. This layer contains very little moisture because almost all of the water vapour from Earth's surface is removed by the weather processes operating in the troposphere. From the tropopause to an altitude of about 20 km, temperature remains constant with height. Above this *isothermal* layer, temperature begins to increase with height, a condition called an **inversion**. Because of this inversion, the stratosphere is not turbulent—with the warmest air at the top, there is little vertical movement and, therefore, little mixing. If particles from Earth's surface make it to the stratosphere, they can remain there for several years. Thus, volcanic eruptions can have a longer lasting impact on climate if the gases and dust they produce reach the stratosphere (Figure 1.12). In addition, the stratosphere contains most of the atmosphere's ozone. Because this gas absorbs ultraviolet radiation from the sun, the *ozone layer* not only protects life on Earth from the harmful effects of this radiation, it also warms the stratosphere. Since the stratosphere is heated by the sun, it is warmest on top.

stratosphere
The layer of the atmosphere extending from, on average, 11 to 50 km above Earth's surface.

stratopause
The top of the stratosphere.

inversion
An increase in temperature with altitude.

mesosphere
The layer of the atmosphere that extends from about 50 km above Earth's surface to about 85 km above the surface.

mesopause
The top of the mesosphere.

thermosphere
The top layer of the atmosphere. Its base is located at an altitude of about 85 km; it has no well-defined top.


ARLAN NAEG/AFP/Getty Images

FIGURE 1.12 When Mount Pinatubo in the Philippines erupted in June 1991, it sent an explosion of ash high into the atmosphere.

REMEMBER THIS

The troposphere

- is defined by a decrease in temperature with height,
- contains almost all the water vapour in the atmosphere,
- is turbulent, and
- produces weather.

The stratosphere

- is defined by an increase in temperature with height,
- contains almost all the ozone in the atmosphere, and
- is non-turbulent.

Above the stratosphere is the **mesosphere**, a layer in which temperature decreases with height from the relatively warm stratopause up to the **mesopause** at about 85 km. This height also marks the bottom of the **thermosphere**, a layer in which temperature begins to increase again due to strong absorption of the shortest wavelengths of the sun's radiation. At the bottom of the thermosphere, most of this very short wavelength radiation has been absorbed, leaving little to warm the mesosphere.

Due to the nature of gases, there is no clearly defined boundary between the top of the atmosphere and space. Instead, the transition is very gradual. Because of air's compressibility, 80 per cent of the atmosphere's mass lies in the troposphere, and 99.9 per cent of its mass lies below the stratopause. Of the remaining 0.1 per cent, 99 per cent is in the mesosphere, meaning that there is very little air left at the altitude of the thermosphere. However, even at a height of roughly 400 km above Earth's surface, the International Space Station's orbit is influenced by the effects of friction with Earth's atmosphere.

Temperatures in the upper thermosphere can reach upward of about 1000°C. Yet despite the very high temperatures, the thermosphere would not *feel* warm, because the air is so thin. High temperatures mean molecules are moving fast, but for heat to be transferred, molecules must collide. At Earth's surface, a person is hit by billions of molecules every second, and heat is rapidly transferred. In the thermosphere, such collisions are relatively rare, so there is little heat transfer. Thus, although the molecules at the upper limits of the atmosphere are moving at the speed of 1000°C molecules, there are not enough of them to transfer this heat.

Until very recently, people were confined to Earth's surface and knew next to nothing about conditions throughout most of the atmosphere. Undoubtedly, some observers would have intuitively realized that pressure should decrease with height above Earth's surface, but the changes in temperature with height would have been far less easy to anticipate. By climbing mountains, people realized that temperature decreased with altitude, and many assumed it would continue to do so. Others argued, however, that since the upper atmosphere is closer to the sun, temperatures must start to increase again at some point. With our advanced technology, we have not only reached the top of the atmosphere but beyond to space, and we now know that both suppositions were correct.

As our frontiers have expanded, so has our knowledge, but the more observations we make, the more there is to explain.

1.7 Chapter Summary

1. Processes at work in the atmosphere create weather and climate. Weather describes the state of the atmosphere at a given time and place. The elements of weather include temperature, pressure, humidity, wind, clouds, and precipitation. Climate describes the average conditions of the atmosphere on a variety of scales, from the micro scale to the planetary scale.
2. The atmosphere is part of the Earth system, which also includes the rocks, the water, the ice, and the life of the planet. Earth system science is a holistic approach to understanding Earth that considers interactions between the atmosphere and Earth's other spheres, as well as the impact of human actions on Earth processes. The Earth system is extremely complex and is made even more complicated by the operation of feedback effects, which are mechanisms that develop within systems and reinforce or lessen the effects of an initial change.
3. Science is about trying to understand and explain the observations we make about the world. Scientific investigation follows the scientific method. It has led to our discovery of laws that *describe* the way nature works, most of which can be expressed as mathematical equations. Scientific investigation has also led to our development of theories—large bodies of knowledge used to *explain* the way nature works.
4. Math acts as both a language and a tool in science. Measurements and calculations make use of the internationally adopted MKS system of units. Four derived dimensions are important in atmospheric science: force, energy or work, power, and pressure.
5. Pressure and density decrease with height in the atmosphere. Pressure decreases with height because the mass of the atmosphere lying above decreases with height. Density decreases with height because air is compressible. The decrease in density with height causes pressure to decrease exponentially with height.
6. The change in temperature with height defines four atmospheric layers: the troposphere, the stratosphere, the mesosphere, and the thermosphere. The troposphere is the layer closest to the surface where all weather occurs. It contains more moisture and is more turbulent than the stratosphere, the layer directly above. In comparison, the stratosphre contains more ozone.

Review Questions

1. What are some reasons for studying the atmosphere?
2. How are weather and climate different from one another?
3. What characteristics of a place might influence its climate?
4. In what ways are scientific laws similar to scientific theories? In what ways do they differ?
5. What are the three types of models that researchers use? How do they use these models to advance science?
6. How can we account for the almost exponential decrease in both pressure and density with height in the atmosphere?
7. How are the troposphere and the stratosphere different from one another? What accounts for these differences?

Suggestions for Research

1. Investigate the sorts of studies that atmospheric researchers do in the field. To find this information, you could consult journal articles and abstracts, visit websites maintained by Environment Canada or other organizations involved in conducting atmospheric research, or even talk to some of the professors at your university who have participated in atmosphere-related research projects.
2. Find specific examples of conceptual models, physical models, and mathematical models that have been used in atmospheric research. For each model, describe how it represents reality, and explain how researchers have used it to make predictions and/or test hypotheses.

References

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2 The Composition of the Atmosphere

LEARNING GOALS

After studying this chapter, you should be able to

- describe the composition of Earth's atmosphere, and the processes by which the most common gases enter and leave the atmosphere;
- evaluate the roles of carbon dioxide, water vapour, ozone, and aerosols in the climate system; and
- outline the evolution of Earth's atmosphere.

In Chapter 1, you learned about the *structure* of the atmosphere; in the present chapter, you will learn about the *composition* of the atmosphere. With the exception of Mercury, all of the planets in our solar system have atmospheres, but Earth's atmosphere is a unique mix that makes life possible: it directly supports most life processes, it protects life from harmful radiation from the sun, and its composition helps produce the ideal climate for life. In fact, as you will see in Chapter 5, reflection and absorption of radiation by the atmosphere helps keep Earth from becoming too warm or too cold.

You will also find in this chapter the story of how our atmosphere has evolved. As you will see, life has played an important role in creating the atmosphere that supports it. Ironically, human activities are now influencing the composition of the atmosphere in ways that could be detrimental to life. We will focus on these changes in Chapter 17.

2.1 The Chemical Composition of Air

Our atmosphere is a mixture of gases, commonly referred to as *air*. The major gases in Earth's atmosphere are listed in Table 2.1. Together, nitrogen (N_2) and oxygen (O_2) make up 99 per cent of the atmosphere, while argon (Ar) makes up most of the remaining 1 per cent. Next in abundance are water vapour (H_2O) and carbon dioxide (CO_2). The concentrations of all other atmospheric gases are very small; for this reason they are more commonly expressed in parts per million (ppm) rather than percentages (1 per cent equals 10,000 ppm). Only one group of gases listed in Table 2.1, the chlorofluorocarbons (CFCs), does not occur naturally. These gases have been gradually increasing in the atmosphere since they were first synthesized in the 1930s. There are also hundreds of other gases, not listed, that occur in even smaller quantities; these can be detected only by very sensitive instruments.

constant gases
Gases that have consistent concentrations across the atmosphere, up to a height of about 80 km.

variable gases
Gases that have different concentrations in different areas of the atmosphere and at different times.

TABLE 2.1 The composition of Earth's atmosphere

Constant Gases	Per Cent of Air by Volume[a]
Nitrogen (N_2)	78.08
Oxygen (O_2)	20.95
Argon (Ar)	0.93
Neon (Ne)	0.00182
Helium (He)	0.00052
Hydrogen (H_2)	0.00006
Variable Gases	
Water Vapour (H_2O)	0.25
Carbon Dioxide (CO_2)	0.04
Methane (CH_4)	0.0002
Nitrous Oxide (N_2O)	0.00003
Carbon Monoxide (CO)	0.000009
Ozone (O_3)	0.000004
Chlorofluorocarbons (CFCs)	0.00000005[b]

[a] The percentages given in this table are expressed by volume of *dry* air for all of the gases except for water vapour. The value given for water vapour is its *average* percentage by volume of *moist* air. The amount of water vapour in the atmosphere is so variable that changes in this quantity will significantly affect the percentage by volume of all the other atmospheric gases.
[b] This percentage is for CFC-12 specifically.

Table 2.1 is divided between **constant gases** and **variable gases**. Constant gases are well mixed throughout the atmosphere up to a height of about 80 km. On time scales of hundreds of years, they exist in approximately the same concentrations. No matter when or where a sample of air is taken, the concentration of a constant gas shouldn't change. For example, in a sample of air containing 100 molecules, 78 should be nitrogen. Nitrogen, oxygen, and the inert gases are all constant gases. Variable gases are those that have concentrations that *vary* in time and space. The concentration of a

◀ The gases and particles that make up Earth's atmosphere scatter light from the sun, producing the brilliant colours we often see at sunrise and sunset.
Photo: Dean_Fikar/Thinkstock

variable gas will likely be different depending on when, or where, a sample of air is taken.

Carbon dioxide is one of the variable gases. As shown in Figure 2.1, carbon dioxide exhibits both a seasonal variation and a general upward trend. Because plants use carbon dioxide for photosynthesis, the concentration of this gas is lower in summer and higher in winter. Surprisingly, although the graph in Figure 2.1 is representative of carbon dioxide concentrations for the entire planet, the seasonal variation is still evident. The northern hemisphere pattern dominates because the southern hemisphere is mostly ocean.

In addition to showing seasonal variation, Figure 2.1 shows the increase in carbon dioxide concentrations that has occurred since measurements began at Hawaii's Mauna Loa Observatory in 1958. At that time, the amount of carbon dioxide in the atmosphere was 316 ppm; today it is just over 400 ppm. By examining ice cores, researchers have *estimated* that the pre-industrial value of atmospheric carbon dioxide was about 280 ppm. These ice cores show that carbon dioxide concentrations have likely not significantly exceeded 280 ppm for at least the last 800,000 years (Section 16.7). Thus, the amount of carbon dioxide in the atmosphere has increased just over 40 per cent since the beginning of the industrial revolution. This increase is mostly due to fossil fuel combustion, deforestation, and the degradation of soils. Over the last decade, the average *rate* of increase of carbon dioxide concentration has been a little higher than 2 ppm per year (NOAA, 2016). Because carbon dioxide is a greenhouse gas, this increase in its concentration is the main driver of the observed increase in global temperature noted in Section 1.1 and shown in Figure 1.6.

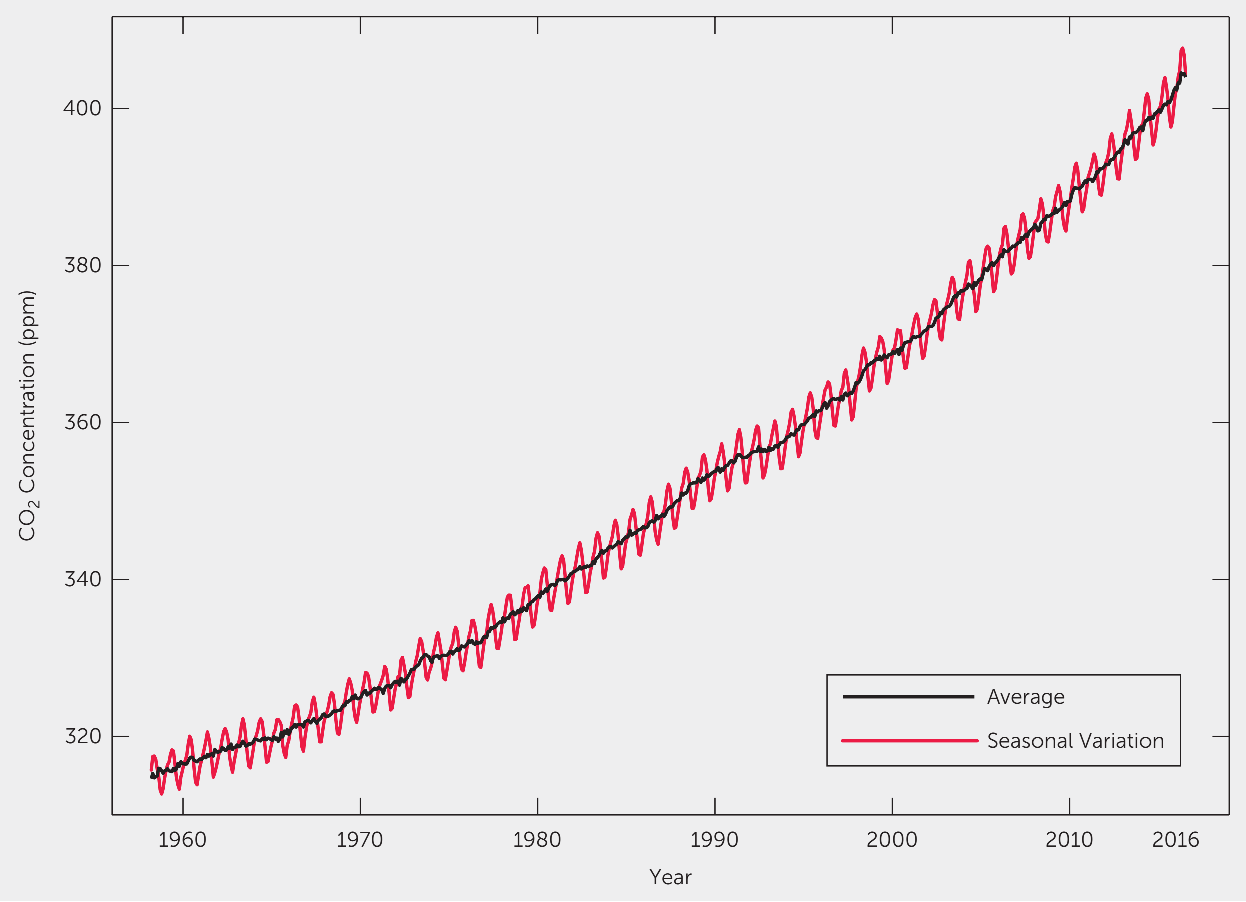

FIGURE 2.1 Mean carbon dioxide measurements at Mauna Loa Observatory in Hawaii.

Source: Data from NOAA, Earth System Research Laboratory, Global Monitoring Division, http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html, August 2016.

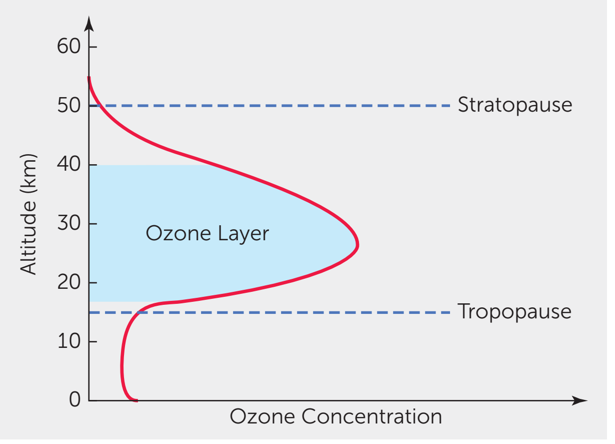

FIGURE 2.2 The variation of ozone with height in the atmosphere.

Source: Adapted from Turco, 2002, p. 411.

biogeochemical cycle
The various pathways that chemical elements repeatedly follow as they flow through the atmosphere, rocks, water, ice, and life of Earth.

reservoir
A storage place.

stock
The amount of a substance in a reservoir of a system.

flow
The rate of movement of substances into and out of a reservoir in a system.

source
A process by which a substance enters a reservoir.

sink
A process by which a substance leaves a reservoir.

steady state
A condition that exists when the inflows to a reservoir are equal to the outflows from the reservoir.

Ozone (O_3) is also a variable gas. In particular, this gas varies with height in the atmosphere (Figure 2.2). It is most abundant in the stratosphere, where it forms the *ozone layer*. The concentration of ozone in the stratosphere is about 10 ppm. The ozone concentration given in Table 2.1 is the concentration ozone would have if it were mixed evenly throughout the atmosphere.

Water vapour is the *most* variable gas in the atmosphere. If water vapour were mixed evenly throughout the atmosphere, its concentration would be about 0.25 per cent. In reality it varies, in both space and time, from almost nothing to about 4 per cent. There is usually more water vapour in the air in the summer, when it is hot, than there is in the winter, when it is cold. Even over the course of a day, the amount of water vapour in the air can change significantly—a rain storm might add water vapour to the air, while a continental air mass might bring in much drier air. Atmospheric water vapour varies from place to place as well. There is more in equatorial regions, for example, than there is over deserts or at the poles. In addition, most water vapour lies in the lowest two km of the atmosphere; there is virtually no water vapour above the tropopause.

2.2 Gases in the Climate System: Stocks and Flows

Most elements that make up gases—such as the carbon of carbon dioxide—don't just occur in the atmosphere. Instead, they flow through the Earth system in cycles known as **biogeochemical cycles**. As the prefixes *bio* and *geo* imply, these cycles involve both the living and non-living parts of our planet, respectively; the materials that flow through the Earth system are *chemicals*, and the flows are driven by *chemical reactions*. Two biogeochemical cycles that are of particular significance to the atmosphere are the nitrogen cycle and the carbon cycle. Both of these cycles will be considered in this chapter. In the context of biogeochemical cycles, the atmosphere and the other spheres of the Earth system are **reservoirs**, or storage places, for substances being cycled (Figure 2.3). The **stock** is the amount of a substance that has accumulated in a reservoir. Stocks change through time as a result of **flows** into and out of the reservoir.

Processes by which substances enter a reservoir—say, the atmosphere—are called **sources**, and processes by which substances leave a reservoir are called **sinks** (Figure 2.3). For example, respiration is a *source* for atmospheric carbon dioxide because this process *adds* carbon dioxide to the atmosphere. On the other hand, photosynthesis is a *sink* for carbon dioxide because this process *removes* carbon dioxide from the atmosphere. A sink might also be a chemical transformation that occurs in the atmosphere. For example, an important sink for methane gas (CH_4) is its reaction with hydroxyl radicals (OH), as shown by Equation 2.1.

$$CH_4 + OH \rightarrow CH_3 + H_2O \qquad \textbf{(2.1)}$$

A condition known as **steady state** exists when the flows into a reservoir are equal to the flows out

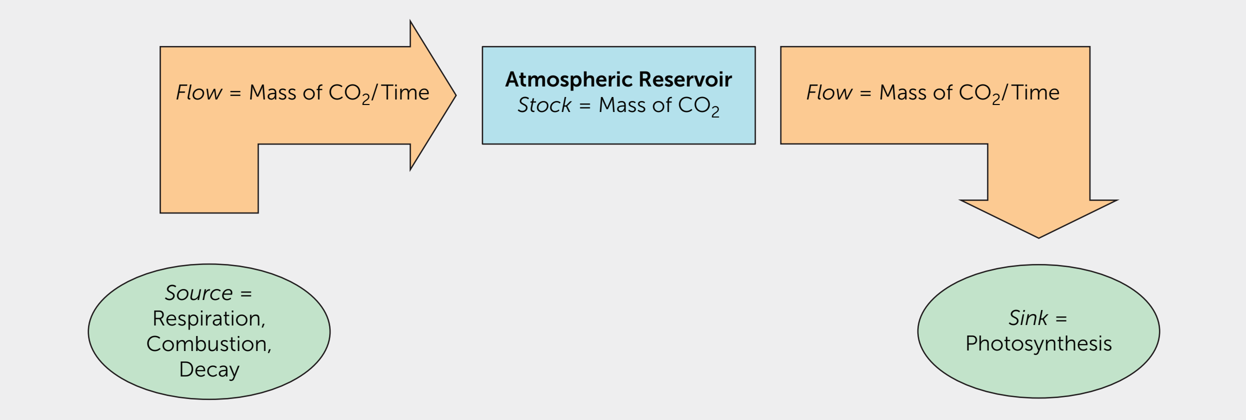

FIGURE 2.3 This diagram illustrates the atmosphere as a reservoir, with some of the sources and sinks for carbon dioxide.

of that reservoir and, as a consequence, the stock remains constant. Over the short term, and under conditions free from such artificial interventions as industrial activity, most atmospheric gases are close to being in steady state. When an atmospheric gas is in steady state, a molecule of that gas can be expected to remain in the atmosphere for a certain amount of time, known as its **residence time**. The residence time of a gas in steady state can be calculated as shown in Equation 2.2 and Example 2.1.

$$\text{Residence Time} = \frac{\text{Reservoir Size}}{\text{Inflow/Outflow Rate}} \quad \textbf{(2.2)}$$

In this equation, the reservoir size is the *stock* of the gas in the atmosphere. As the equation demonstrates, residence time will be longest when the stock of a gas is large and/or when the gas flows in and out of the reservoir slowly. The latter is generally the case for gases with low reactivity.

Example 2.1

The methane sink shown in Equation 2.1 occurs at a rate of about 400 megatonnes (Mt) per year. Considering that the stock of methane in the atmosphere is about 4000 Mt, what is the residence time of methane?

Use Equation 2.2.

$$\text{Residence Time} = \frac{4000\ \text{Mt}}{400\ \text{Mt/yr}} = 10\ \text{yrs}$$

This is a relatively short residence time.

(This example is based on Turco, 2002, p. 376.)

Table 2.2 gives residence times for some atmospheric gases. Nitrogen has the longest residence time—on average, a molecule of nitrogen that enters the atmosphere will remain there for 1,600,000 years; this is because nitrogen is abundant and not very reactive. Oxygen has a shorter residence time because there is less of it and it is considerably more reactive. As you can see, longer residence times are characteristic of the constant gases, while shorter residence times are associated with the variable gases. This is because the longer a gas stays in the atmosphere, the more time it has to become thoroughly mixed. The large variability of water vapour is linked to

residence time
The average amount of time that a substance might be expected to remain in a reservoir of the Earth system.

TABLE 2.2 Residence times for select atmospheric gases

Atmospheric Gas	Residence Time
Nitrogen (N_2)	1,600,000 years
Oxygen (O_2)	3000–4000 years
Water Vapour (H_2O)	10 days
Carbon Dioxide (CO_2)	100–300 years[a]
Methane (CH_4)	12 years
Nitrous Oxide (N_2O)	121 years
Ozone (O_3)	hours to days
Chlorofluorocarbons (CFCs)	100 years[b]

[a] Because of the complexity of the carbon cycle, this value is difficult to estimate.

[b] This residence time refers to CFC-12 specifically.

its very short residence time. As we will see in Chapter 17, residence time is an important consideration when comparing the impacts of various anthropogenic changes to atmospheric composition. Think of it this way—if a gas has damaging effects, its potential to do damage is much greater if it has a long residence time than if it has a short residence time.

Carbon dioxide is one of those troublesome gases—it causes warming and it has a relatively long residence time. The increase in carbon dioxide shown in Figure 2.1 indicates that this gas is no longer in steady state. Due to human actions, the flows of carbon dioxide into the atmosphere are now greater than the flows of carbon dioxide out of the atmosphere. As a result, the stock of carbon dioxide in the atmosphere is increasing (Figure 2.1). Scientists have warned that continuing increases in carbon dioxide could lead to dangerous changes in the climate system and that to prevent such changes we need to stabilize atmospheric carbon dioxide concentrations at below 450 ppm—recall that today the concentration of carbon dioxide in the atmosphere is about 400 ppm. A systems perspective on this problem indicates that in order to stabilize the amount of atmospheric carbon dioxide at today's levels, our emissions of carbon dioxide must drop considerably. This is because as long as inflows of carbon dioxide to the atmosphere remain greater than outflows from the atmosphere—even if the difference is only slight—the amount of carbon dioxide in the atmosphere will continue to increase.

nitrogen fixation

The process by which nitrogen gas is removed from the atmosphere and converted to a soluble form of nitrogen that can be taken up by plants.

denitrification

The process by which bacteria convert nitrogen in the soil to nitrogen gas or nitrous oxide gas.

photodissociation

A process in which a molecule is split apart by the absorption of radiation.

nitrogen cycle

The biogeochemical cycle in which nitrogen is transferred between the various reservoirs of the Earth system.

2.3 Nitrogen (N_2)

Most of Earth's nitrogen is stored in the atmosphere as molecular nitrogen (N_2), and though nitrogen is required to synthesize proteins, the triple bonds of molecular nitrogen make this form of nitrogen inaccessible to life. Thus, an essential process known as **nitrogen fixation** operates to convert atmospheric nitrogen into forms of nitrogen that organisms can use. Most nitrogen fixation is performed by certain soil bacteria that produce *fixed* forms of nitrogen, such as nitrate ions (NO_3^-) and ammonium ions (NH_4^+). A much smaller amount of nitrogen is fixed in the atmosphere itself by lightning. The high temperatures associated with a lightning strike cause nitrogen and oxygen gases to combine to form nitrogen oxide gas (NO) or nitrogen dioxide gas (NO_2). When these nitrogen oxide gases dissolve in atmospheric water, they produce nitrate ions. The nitrate ions formed this way are rained out of the atmosphere and into the soil. Because it is soluble in water, fixed nitrogen can be taken up by plants. When plants—or the animals that consume them—die, their decomposition returns the fixed nitrogen to the soil where it is once again available to plants. Nitrogen fixation transfers nitrogen from the atmosphere to the biosphere, making this process an important link in the nitrogen cycle, and the only sink for atmospheric nitrogen (Figure 2.4). Because atmospheric nitrogen exists more or less in steady state, the sink for this gas must be balanced by a source.

The *source* for atmospheric nitrogen is **denitrification**—a process in which certain other soil bacteria convert the fixed forms of nitrogen back into nitrogen gas or nitrous oxide gas (N_2O). The only sink for nitrous oxide is **photodissociation** in the stratosphere, which produces either nitrogen gas or nitrogen oxide gases. Because it needs to reach the stratosphere before it will be broken apart, nitrous oxide has a relatively long residence time in the atmosphere of about 121 years (Table 2.2).

REMEMBER THIS

Several different forms of nitrogen gases can occur in the atmosphere:

- molecular nitrogen (N_2),
- nitrous oxide (N_2O),
- nitrogen oxide (NO), and
- nitrogen dioxide (NO_2).

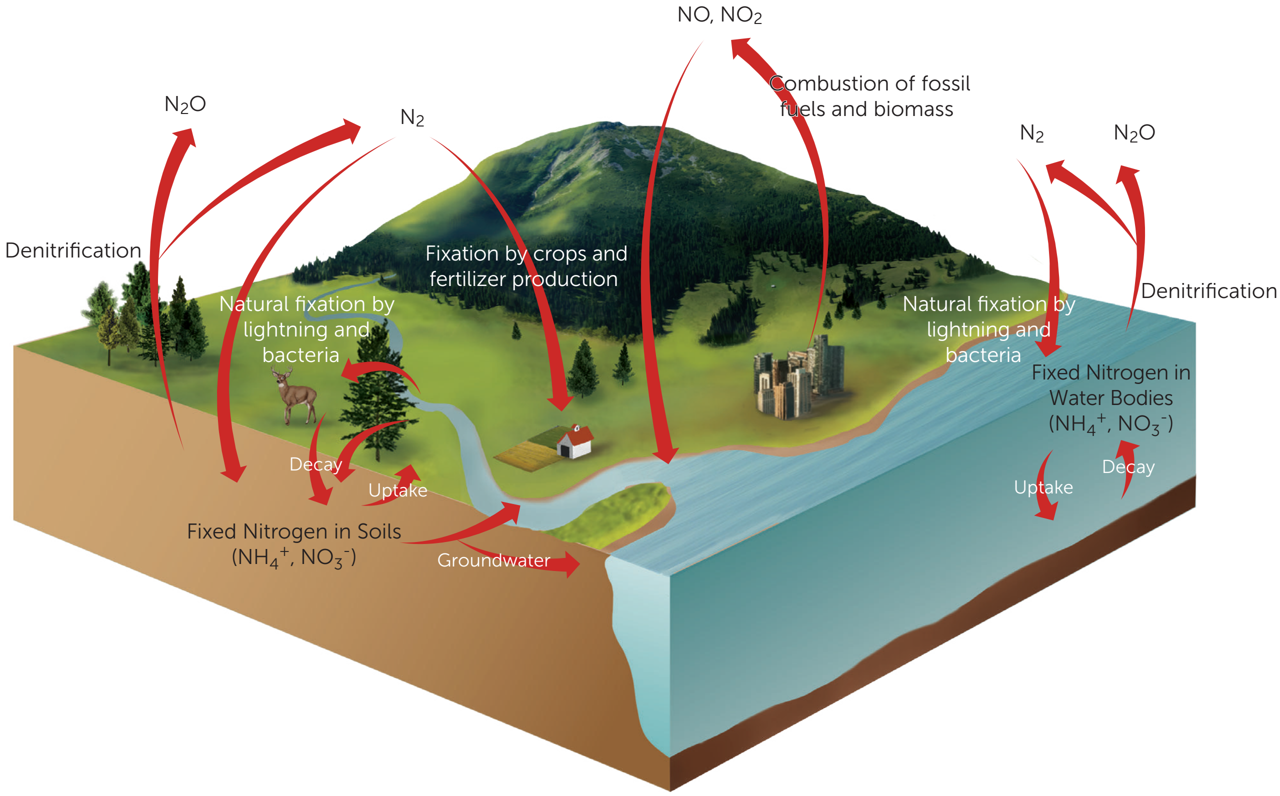

FIGURE 2.4 The nitrogen cycle. The arrows in this diagram depict the flows of nitrogen through the Earth system. These flows have been accelerated by human activities that fix nitrogen. Today, nitrogen fixation by fertilizer production, crops, and combustion exceeds natural nitrogen fixation by lightning and bacteria.

The human impact on the **nitrogen cycle** is tremendous. Put simply, human activities have increased the amount of fixed nitrogen in the environment to such an extent that flows of nitrogen through the Earth system are now more than double their pre-industrial values. Because a lack of fixed nitrogen in the soil limits plant growth, farmers have traditionally planted nitrogen-fixing crops. To further increase the amount of nitrogen in the soil in an effort to feed an ever-growing population, a method was devised in the early half of the twentieth century to artificially fix atmospheric nitrogen and thereby produce synthetic nitrogen fertilizers. This process is known as the Haber process, named after its inventor. The use of fertilizers increases the amount of fixed nitrogen in soils, which can enhance plant growth and agricultural productivity, but large amounts of fixed nitrogen can have negative impacts. Excess soil nitrogen can diffuse into the atmosphere as nitrogen oxide gases; it can also end up in waterways as nitrates. Large amounts of this nutrient in water bodies can cause algae blooms. As the algae die and decay, they use up oxygen dissolved in the water, resulting in fish kills. High nitrate levels in drinking water can cause health problems. In addition, with more fixed nitrogen in soils, denitrification increases, and more nitrous oxide is returned to the atmosphere. Increasing nitrous oxide in our atmosphere is of concern for two reasons. First, nitrous oxide is a greenhouse gas. Along with the increase in carbon dioxide, the increase in nitrous oxide is contributing to global warming (Section 17.3). Second, recall that nitrous oxide is transformed to nitrogen oxide gases in the stratosphere. There, these gases destroy ozone (Section 17.2).

In addition to intentional fixing of nitrogen to produce fertilizers, we also inadvertently fix nitrogen through combustion of biomass and fossil fuels. Nitrogen oxide gases are a by-product of combustion. As we will see in Chapter 17, nitrogen oxide gases are toxic and can lead to the formation of acid rain.

2.4 Oxygen (O_2)

The major *source* of oxygen for the atmosphere is photosynthesis. Photosynthesis is the process through which plants use energy from the sun to convert carbon dioxide and water into organic matter, or carbohydrate (CH_2O), and oxygen (Figure 2.5). This process is shown in Equation 2.3.

$$CO_2 + H_2O \leftrightarrow CH_2O + O_2 \quad \textbf{(2.3)}$$

Through photosynthesis, the *inorganic* carbon in carbon dioxide is converted into the *organic* carbon of carbohydrate, and carbon is transferred from the atmosphere to the biosphere. The double arrow in the equation shows that this reaction can go either way.

In fact, three of the atmospheric *sinks* for oxygen are represented by the reverse of Equation 2.3. One of these sinks is respiration. During respiration, the carbohydrates in animals combine with oxygen to produce carbon dioxide and water. A second important sink for oxygen is decomposition. As organic material, or carbohydrate, is decomposed, the bacteria responsible consume oxygen and produce carbon dioxide. When oxygen is not available, as in a wetland, **anaerobic decomposition** occurs, and the bacteria produce methane *and* carbon dioxide. Equation 2.4 is a simplified chemical equation for this process.

anaerobic decomposition

A process of decay that occurs when oxygen is unavailable.

$$2CH_2O \rightarrow CO_2 + CH_4 \quad \textbf{(2.4)}$$

A third sink for oxygen is combustion. As organic matter burns, oxygen is consumed and carbon dioxide is produced.

Oxidation of minerals is also a *sink* for oxygen, although it is a fairly minor sink compared to the other three. A familiar example of oxidation is rusting, which is the oxidation of iron. Minerals in Earth's crust that contain iron can be oxidized, producing either ferric iron (Fe^{3+}) or ferrous iron (Fe^{2+}). As can be seen from the above processes, oxygen is quite reactive; were it not for photosynthesis, the atmosphere might be quickly depleted of this gas.

oxidation

The addition of oxygen to a compound, which is accompanied by a loss of electrons.

carbon cycle

The biogeochemical cycle in which carbon is transferred between the various reservoirs of the Earth system.

ViktorCap/iStockphoto

FIGURE 2.5 A deciduous forest canopy. Through the process of photosynthesis, plants remove carbon dioxide from the atmosphere and release oxygen.

2.5 Carbon Dioxide (CO_2)

Most of Earth's carbon is stored in rocks, whereas the atmosphere is Earth's smallest reservoir of carbon. Like nitrogen and oxygen, carbon dioxide is essential to life. Unlike nitrogen and oxygen, carbon dioxide influences climate because it is a greenhouse gas. The presence of greenhouse gases in the atmosphere makes Earth warmer than it would be without them, thus the term *greenhouse effect* (Section 5.6). Without greenhouse gases in its atmosphere, Earth would have an average surface temperature of about –18°C instead of about 15°C; this means that Earth has a greenhouse effect of 33°C. Without the greenhouse effect, Earth would be less suited to supporting life. However, increasing levels of atmospheric carbon dioxide brought about by human activities (Figure 2.1) are strengthening the greenhouse effect—this will likely be detrimental to life (Section 17.3.2).

The **carbon cycle** is an extremely complex biogeochemical cycle. It is associated with *organic* processes such as photosynthesis and respiration, and *inorganic* processes such as rock weathering and volcanic eruptions (Figure 2.6). A further

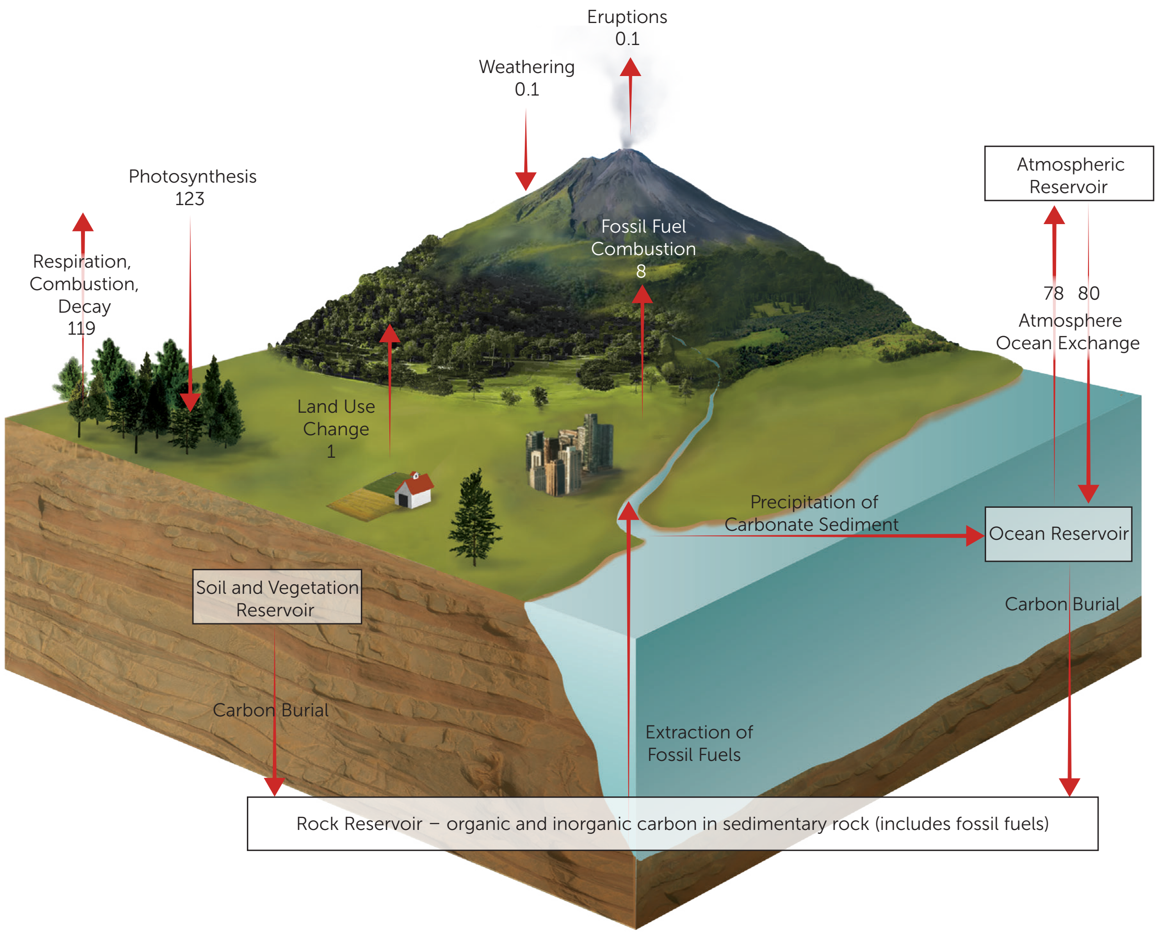

FIGURE 2.6 The carbon cycle. The arrows in this diagram depict the flows of carbon through the Earth system. These flows are measured in PgC/yr. (A PgC is a petagram of carbon, where 1 petagram equals 1 billion metric tonnes.) You can see that due to fossil fuel combustion and land use change, more carbon dioxide flows into the atmosphere than leaves the atmosphere. The result is that atmospheric carbon dioxide is increasing. As carbon dioxide has accumulated in the atmosphere, both the ocean and the biosphere have responded by absorbing increasing amounts of carbon dioxide. As a result, the atmosphere–ocean exchange of carbon and the short-term organic carbon cycle are no longer in balance.

complication is that some of these are short-term processes, while others are very long term. This complexity makes it difficult to pinpoint the residence time of carbon dioxide, although it is usually given as about 100 to 300 years (Table 2.2). In addition, carbon dioxide dissolves in the oceans in such a way that there is normally a balance between the amount of carbon dioxide in the atmosphere and that dissolved in the oceans. Warmer water holds less carbon dioxide than colder water but, for a given water temperature, if the amount of carbon dioxide in the atmosphere increases, the amount in the ocean will too. As on land, some of the carbon dioxide dissolved in the ocean is used for photosynthesis, and carbon dioxide is released back into the water through the processes of decay and respiration. Dissolved carbon dioxide that is not used for photosynthesis forms a weak acid known as carbonic acid in the oceans (see Equation 2.5 later in this section).

In the organic carbon cycle, the sources for carbon dioxide are sinks for oxygen, and the sources for oxygen are sinks for carbon dioxide (Equation 2.3). When carbon dioxide is removed from the atmosphere through photosynthesis, it can be quickly returned by decomposition, respiration, or combustion. In these cases, carbon is stored for the short term as organic matter in the biosphere. However, under certain circumstances carbon is removed from this short-term cycle and, instead of returning to the atmosphere as carbon dioxide, it will be stored for the long term—several hundred thousand years or more—in the rocks of the lithosphere.

REMEMBER THIS

- Photosynthesis is a *source* for oxygen and a *sink* for carbon dioxide.
- Respiration is a *source* for carbon dioxide and a *sink* for oxygen.
- Decomposition is a *source* for carbon dioxide and a *sink* for oxygen.
- Combustion is a *source* for carbon dioxide and a *sink* for oxygen.

Such long-term storage of carbon occurs under conditions in which organic matter cannot decompose due to lack of oxygen. On land, this happens when organic matter accumulates in wetlands or is buried. In the oceans, organic matter that does not decompose as it sinks will accumulate on the seafloor. Either way, the organic matter might be buried in sediment that eventually forms sedimentary rock. When there is a lot of organic matter present, and the conditions are right, what we know as fossil fuels—coal, oil, and natural gas—will form in the rock. Coal is formed from plant matter that has accumulated in wetlands, while oil and natural gas tend to form from organic matter buried on the seafloor. Thus, fossil fuels are the remains of once-living organisms. This burial of organic carbon represents a long-term storage of carbon and the second-largest reservoir of carbon in the Earth system.

carbonate–silicate cycle
The inorganic part of the carbon cycle, in which carbon dioxide is removed from the atmosphere as silicate rocks weather, and returned to the atmosphere hundreds of thousands to millions of years later by volcanic eruptions.

Changes in the rate of organic carbon burial can affect climate. For example, during the Carboniferous Period, about 300 million years ago, large coal beds were formed. (Most oil and natural gas deposits were formed more recently.) The swampy conditions of the time meant that the rate of burial of organic carbon was particularly high. As a result, atmospheric carbon dioxide levels dropped and climate cooled, leading to an ice age. Another consequence of the burial of carbon was an increase in the amount of oxygen in the atmosphere.

CHECK YOUR UNDERSTANDING

Why would high rates of organic carbon burial lead to high oxygen levels?

Organic carbon stored in rocks is eventually returned to the atmosphere through chemical weathering of these rocks. This is a natural process that slowly returns carbon dioxide to the atmosphere over millions of years. When we mine and burn fossil fuels, the process is chemically the same, but it is greatly accelerated. In fact, burning fossil fuels at present rates returns as much carbon dioxide to the atmosphere in one year as would be returned by hundreds of thousands of years of weathering (Wallace & Hobbs, 2006, p. 45).

Another long-term storage of carbon is associated with the inorganic part of the carbon cycle. In this cycle, known as the **carbonate–silicate cycle**, the *source* for carbon dioxide is volcanic eruptions, and the *sink* for carbon dioxide is the chemical weathering of rocks containing silica (Figure 2.7). The carbonate–silicate cycle helps illustrate the importance of the motions of Earth's tectonic plates to the climate system. The movements of the tectonic plates are responsible not only for driving volcanic activity, but also for building the mountain ranges that provide fresh rock for weathering. Here it is important to note a clear difference between the way the weathering of organic carbon influences the carbon cycle and the way the weathering of silicate rocks influences the carbon cycle. The chemical weathering of rocks containing organic carbon, which is part of the organic carbon cycle described above, is a *source* for carbon dioxide. In direct contrast, the chemical weathering of silicate rocks is a *sink* for carbon dioxide.

REMEMBER THIS

- The weathering of rocks containing organic carbon is a *source* for carbon dioxide.
- The weathering of silicate rocks is a *sink* for carbon dioxide.

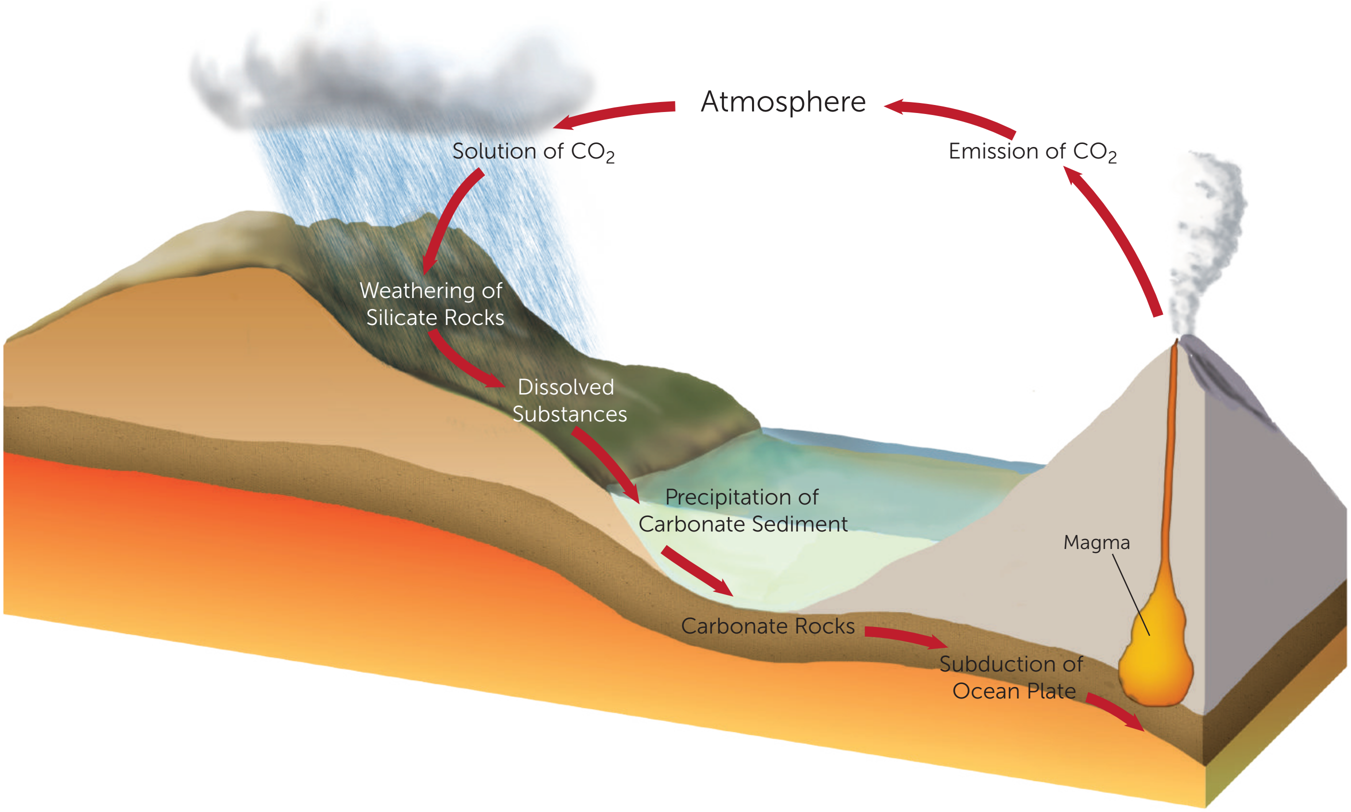

FIGURE 2.7 The carbonate–silicate cycle. Carbon dioxide is removed from the atmosphere as it dissolves in precipitation, and it is returned to the atmosphere as it erupts from volcanoes. Note that this cycle is part of the carbon cycle depicted in Figure 2.6.

The first step in the weathering of many rocks occurs when carbon dioxide dissolves in rain water to form carbonic acid (H_2CO_3), as shown in Equation 2.5.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \quad \textbf{(2.5)}$$

The next step is the dissociation of carbonic acid into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-), as shown in Equation 2.6.

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad \textbf{(2.6)}$$

The resulting acidic rain water then reacts with rocks at Earth's surface, forming solid products as well as ions in solution.

The ions important to the carbonate–silicate cycle are calcium ions (Ca^{2+}) from calcium silicate ($CaSiO_3$) in rocks. These ions, along with the bicarbonate ions, eventually end up in the oceans. There, marine organisms use them to produce the calcium carbonate ($CaCO_3$) that makes up their shells and skeletons (Equation 2.7).

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2CO_3 \quad \textbf{(2.7)}$$

This reaction can also take place abiotically—without life—but most of the time organisms are involved. When marine organisms die, their shells and skeletons sink. As they do so, many of them dissolve, but those that don't dissolve accumulate on the seafloor where they eventually form carbonate rock, the most common form of which is limestone. This rock is the largest reservoir for carbon in the Earth system.

REMEMBER THIS

- Carbon is stored for the long term due to two processes—the burial of organic carbon and the weathering of silicate rock.
- Carbon is added to the atmosphere over the long term by volcanic eruptions.

As part of oceanic crust, carbonate rock is eventually subducted at convergent plate boundaries. Subduction exposes the rock to increasingly higher temperatures. This leads to metamorphism or, with further heating, to melting and the formation of magma. These processes release carbon dioxide that is eventually returned to the atmosphere through volcanic eruptions. If carbon dioxide were not returned, Earth would slowly cool because atmospheric carbon dioxide would be gradually depleted by the weathering of rocks.

CHECK YOUR UNDERSTANDING

If Earth were to become completely glaciated, so that all the rocks were buried in ice, how might the carbonate–silicate cycle work to warm the climate back up again?

Some scientists now believe that the carbonate–silicate cycle is part of a negative feedback mechanism that operates in the climate system to help maintain Earth's temperature. This feedback operates because carbon dioxide levels influence climate, and climate, in turn, influences weathering. When atmospheric carbon dioxide levels increase, temperatures increase. Warmer conditions are usually also wetter conditions. Warm temperatures and more moisture lead to increased rates of chemical weathering of rock. Suppose that a period of active volcanism increases the amount of carbon dioxide in the atmosphere. This will increase temperatures and, therefore, weathering rates. As weathering rates increase, the amount of carbon dioxide in the atmosphere will, in turn, gradually decline. This will cause temperatures to drop back down again (Figure 2.8). This mechanism is a *negative* feedback because the initial temperature *increase* leads to a chain of events that ends in a temperature *decrease* (Section 1.2). A *decrease* in carbon dioxide levels would, of course, trigger the same feedback effect, but in reverse.

latent heat
The energy associated with phase changes.

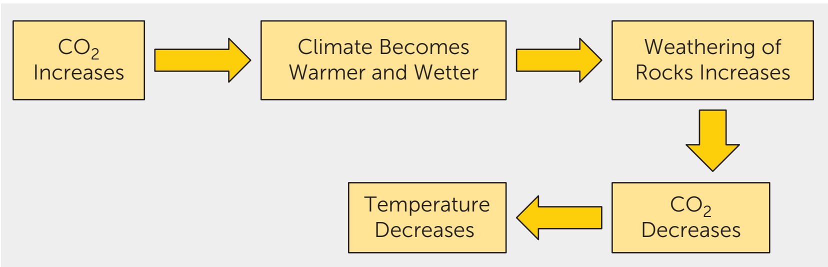

FIGURE 2.8 The carbonate–silicate cycle is believed to act as a negative feedback mechanism, which operates to stabilize Earth's climate over the long term.

CHECK YOUR UNDERSTANDING

Do you think the chemical weathering of rocks could be relied on to reduce the amount of carbon dioxide presently accumulating in the atmosphere, thus preventing global warming? Why or why not?

2.6 Water Vapour (H_2O)

While most of Earth's nitrogen is stored in the atmosphere, and most of Earth's carbon is stored in the rocks, most of Earth's water is stored in the oceans. Water is remarkable in that it is the only substance that can exist in all three phases—solid, liquid, and gas—at normal Earth temperatures. Further, as water changes phase, it absorbs and releases tremendous quantities of heat—known as **latent heat** (Section 4.1.2). Thus, phase changes are important in transferring heat in the atmosphere, and these changes provide a source of energy for storms. In addition, the phase changes of water are responsible for most of what we know as weather, and weather is a part of the most familiar biogeochemical cycle of all: the **hydrologic cycle** (Figure 2.9).

Because it involves phase changes rather than chemical changes, the hydrologic cycle is much simpler than the cycles of nitrogen, oxygen, and carbon. The *source* of water vapour for the atmosphere is **evaporation**, and the *sink* is **condensation**—the process that forms clouds and ultimately precipitation. Water vapour tends to condense fairly quickly, making the residence time for water vapour in the atmosphere only about 10 days (Table 2.2).

Once water falls back to Earth as precipitation, it can run over the ground as *runoff*, or it can infiltrate into the ground. If not taken up by plants, water continues to seep downward, becoming *groundwater*. Both groundwater and surface runoff flow into rivers, ultimately ending up in the ocean. The only way back to the atmosphere is through evaporation. Water may be evaporated directly from the ocean, other water bodies, or the soil, or it may be pulled up from the soil by plant roots and returned to the atmosphere as vapour through the plant's leaves. This process by which plants return water vapour to the atmosphere is known as **transpiration**. Because both evaporation and transpiration result in water returning to the atmosphere as vapour, the two processes together are often simply referred to as *evapotranspiration*.

hydrologic cycle
The biogeochemical cycle in which water is transferred between the various reservoirs of the Earth system.

evaporation
The process by which a substance, usually water, changes phase from a liquid to a gas.

condensation
The process by which a substance, usually water, changes phase from a gas to a liquid.

transpiration
The process by which water vapour is returned to the atmosphere through the stomata in the leaves of plants.

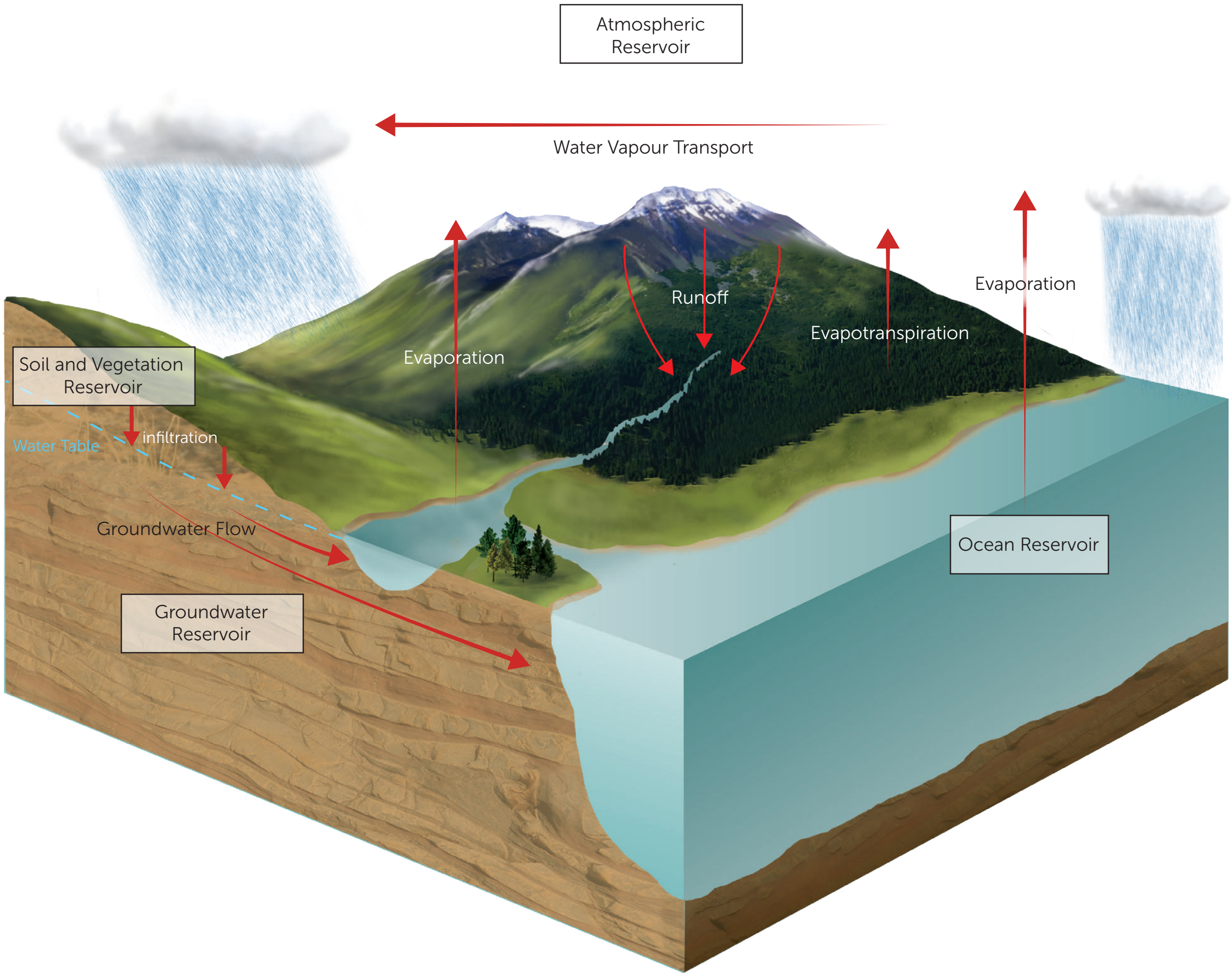

FIGURE 2.9 The hydrologic cycle. The arrows in this diagram depict the flows of water through the Earth system. How do you think human activities might be impacting this cycle?

CHECK YOUR UNDERSTANDING

How do you think the water cycle and the carbon cycle might be linked?

ultraviolet radiation

Radiation with wavelengths ranging from 0.1 to 0.4 μm.

Through phase changes, water is responsible for much of what we know as weather. In addition, water, in its various forms, strongly influences climate. To begin, water vapour is a powerful greenhouse gas that contributes about double the warming of carbon dioxide. In addition, just like greenhouse gases, the water *droplets* that make up clouds absorb Earth's radiation. For this reason, cloudy nights are often warmer than clear nights. But clouds can also cool. Think of how cool it can suddenly become when a cloud passes over the sun on a warm summer afternoon. This cooling occurs because the water droplets in clouds *reflect* the sun's radiation. In Section 6.5, we will see that the effect of clouds on Earth's climate is not straightforward: some cloud types have a net warming effect, while others have a net cooling effect.

REMEMBER THIS

Clouds are good absorbers of radiation from Earth and good reflectors of radiation from the sun.

The reflectivity of the water on Earth's surface also has an impact on climate. As ice, water is very reflective of the sun's radiation (Section 5.4). Earth's polar ice caps, for example, reflect a significant amount of solar radiation back into space. In lakes or oceans, on the other hand, water has a very low reflectivity, making water bodies very good absorbers of solar radiation. If the amount and type of clouds, or the amount of ice, or the surface area of the oceans changes, so does Earth's reflectivity and, therefore, its climate.

CHECK YOUR UNDERSTANDING

How is water's role in weather different from water's role in climate?

2.7 Ozone (O_3)

Ozone has several roles in Earth's atmosphere. First, it absorbs **ultraviolet radiation** from the sun, thus protecting life on Earth from this harmful radiation. The ozone layer of the stratosphere is responsible for this important task. Second, it absorbs Earth's radiation; thus, it is a greenhouse gas. Finally, because of its highly reactive nature, ozone is a pollutant. Even at very low concentrations, on the order of only parts per billion, it is damaging to certain materials, like rubber and plastic, and it is harmful to people, animals, and plants.

The ozone layer forms in two steps. First, oxygen molecules absorb ultraviolet radiation in the 0.1 to 0.2 μm wavelength range (1 μm [micron] = 10^{-6} metres), splitting the oxygen molecules into oxygen atoms by the photodissociation reaction shown in Equation 2.8.

$$O_2 + \text{ultraviolet radiation} \rightarrow O + O \qquad \textbf{(2.8)}$$

Second, the newly formed oxygen atoms collide with oxygen molecules, forming ozone (Equation 2.9).

$$O + O_2 + M \rightarrow O_3 + M \qquad \textbf{(2.9)}$$

M represents a molecule that is needed to carry away excess energy; this molecule can be any gas molecule in the atmosphere.

Once formed, ozone absorbs ultraviolet radiation in the wavelength range from 0.2 to 0.3 μm and, in the process, is split into an oxygen atom and an oxygen molecule (Equation 2.10).

$$O_3 + \text{ultraviolet radiation} \rightarrow O + O_2 \qquad \textbf{(2.10)}$$

While equations 2.8 and 2.9 together represent the *source* for ozone, Equation 2.10 represents the *sink*. Notice that the oxygen atom formed in Equation 2.10 is once again available to form ozone; thus, there is a continuing cycle of ozone production and destruction that maintains a steady level of ozone in the stratosphere. Because these reactions occur very quickly, ozone has a short residence time of hours to days (Table 2.2).

As a result of the above sequence of events, ozone, together with oxygen, completely absorbs ultraviolet wavelengths shorter than about 0.3 μm.