Chapter 1

Monitoring the Weather

LEARNING OBJECTIVES

- Distinguish between weather and climate, meteorology and climatology.
- List some of the readily available sources of regional and national weather information.
- Explain why the drawing of a weather map requires weather observations that are simultaneous.
- Identify the principal weather systems that are plotted on a surface weather map.
- Distinguish between the types of weather usually associated with high pressure systems and low pressure systems.
- Characterize the relationship between air masses and fronts.
- Distinguish between geostationary and polar-orbiting weather satellites.
- Identify the advantages of infrared satellite images versus visible satellite images in monitoring the Earth-atmosphere system.
- Present the fundamental principles of weather radar.
- Give some examples of how the habit of observing the sky and changing cloud cover might provide indications of future changes in the weather.

Central Question

What are some basic characteristics of the atmosphere and weather?

Case-in-Point

Blizzards then and now

Across the Dakota Territory and Nebraska, 12 January 1888 began mild, almost spring-like, a welcome respite from several weeks of persistent bitter cold. Farmers took advantage of the pleasant weather, attending to chores in pastures a distance from the safety of their homes. Neither farmers nor other residents of the isolated settlements that dotted the Northern Prairie could know a ferocious blizzard was sweeping southeastward over eastern Montana and bearing down on the Dakota Territory and Nebraska. The blizzard struck suddenly with winds strengthening to gale-force, plunging temperatures, and swirling snow that cut visibility to near zero. In some places the wind-chill plummeted to near −40°C (−40°F). Anyone caught out in the open became disoriented, unable to find their way to shelter.

In Nebraska, the storm hit just as school let out for the day. Because the day started mild, students dressed inadequately for the deteriorating conditions, trudging home from country schools through blinding snow and cold winds. More than a hundred of them never made it to their destinations, victims of exposure (hypothermia). All told, as many as 500 people perished from the storm, the deadliest blizzard on record in the American prairie. Because so many school children perished, the storm is referred to as the *Children's Blizzard*.

About two months later, on 12–14 March 1888, a powerful coastal storm (nor'easter) accompanied by heavy snow and strong winds blasted the Eastern Seaboard from Washington, DC, northward into southern New England. A nor'easter is a storm that tracks offshore, parallel to the Atlantic coast, and is named for the strong northeast winds that affect coastal areas. This *Blizzard of '88* brought to a standstill virtually all activity. Particularly hard hit was New York City, which reported a three-day snowfall total of 53 cm (21 in.) (Figure 1.1). Winds up to 65 km per hr (40 mph) whipped snow into drifts 4.5–6.0 m (15–20 ft.) deep. Much greater snowfalls (generally 100–125 cm or 40–50 in.) and deeper snowdrifts (to 12 m or 40 ft.) were reported over southeastern New York, western Connecticut, and western Massachusetts. On land, more than 300 people lost their lives to exposure, accidents, or overexertion, while at sea almost 200 ships sunk or were damaged with nearly 100 lives lost. Hundreds of trains stalled in deep snow drifts, marooning passengers for days, and telephone and telegraph lines were severed all over the Northeast.

Figure 1.1
Scene of the aftermath of the blizzard of 12–14 March 1888 at Park Place in Brooklyn, NY. [Courtesy of NOAA Photo Library, Historic NWS Collection]

The *Children's Blizzard* and the *Blizzard of '88* surprised the people impacted. At the time, the U.S. Army Signal Corps had operated the nation's weather service for more than 17 years, and observers at 154 weather stations nationwide telegraphed weather observations three times a day to headquarters in Washington, DC. *Indications* (later called weather forecasts) were issued based on surface weather observations alone. In St. Paul, MN, an experimental office was charged with forecasting cold waves and blizzards for the Northern Plains. The technology of the day and limited understanding of the atmosphere put meteorologists at a distinct disadvantage in forecasting storms, especially nor'easters that track offshore. There was no means of monitoring the upper atmosphere, no satellites, no radar, no wireless communications with ships at sea, and no computer models for forecasting the weather.

Efforts to communicate weather warnings to the public were often unsuccessful. The public received most (if not all) of their weather information from newspapers that could be a day or two old. The officer in charge of the St. Paul office knew a blizzard headed toward the Dakota Territory and Nebraska and sent warnings via telegraph. However, the telegraph lines ran along the railroad tracks, too far away from most of the region's residents for them to receive any advance warning.

The historic blizzards of 1888 were rivaled in ferocity by four nor'easters that hit major metropolitan areas of the mid-Atlantic during the winter of 2009-10, and more recently the January 2016 blizzard. Each 2009-10 storm brought widespread 25–50 cm (10–20 in.) swaths of wind-driven snowfall, with greater amounts locally. Three of the 2010 storms impacted the 15 million residents of the Washington, DC-Philadelphia, PA urban corridor. Two arrived back-to-back (4–7 and 9–11 February), causing widespread power outages and shutting down commercial aviation, ground transportation, shipping, and the local economy. School systems closed for at least a week and offices of the Federal Government closed four successive days. These storms were primarily responsible for establishing seasonal snowfall records in Richmond, VA (71.1 cm or 28.0 in.), Washington, DC (142.2 cm or 56.0 in.), Baltimore, MD (195.6 cm or 77.0 in.), and Philadelphia, PA (199.9 cm or 78.7 in.).

The 22–24 January 2016 snowstorm rated a rare Category 5 "Extreme" for the northeastern U.S. on the National Oceanic and Atmospheric Administration (NOAA) Regional Snowfall Index. Unlike the 1888 storms, forewarning arrived up to a week in advance with extensive preparation. Meteorologists issued blizzard warnings and stressed the potential historical nature of the snowstorm. Eleven states and Washington, DC had pre-storm state of emergency declarations and thousands of members of the U.S. National Guard readied. Among numerous storm-related impacts, thousands of flights were cancelled, New York City and Newark, NJ were placed under travel bans, and a significant portion of the Washington, DC-area Metro bus and train service was suspended. Significant amounts of snow fell over a large swatch of the Mid-Atlantic and Northeast (Figure 1.2). NOAA reported that 102.8 million people were impacted by the snowstorm, with 24 million of those experiencing snowfall in excess of about 51 cm (20 in.) and 1.5 million with snow exceeding 76 cm (30 in.). The maximum snowfall was 107 cm (42 in.) at Glendary, WV. Despite the forewarning, 55 fatalities are attributed to the storm.

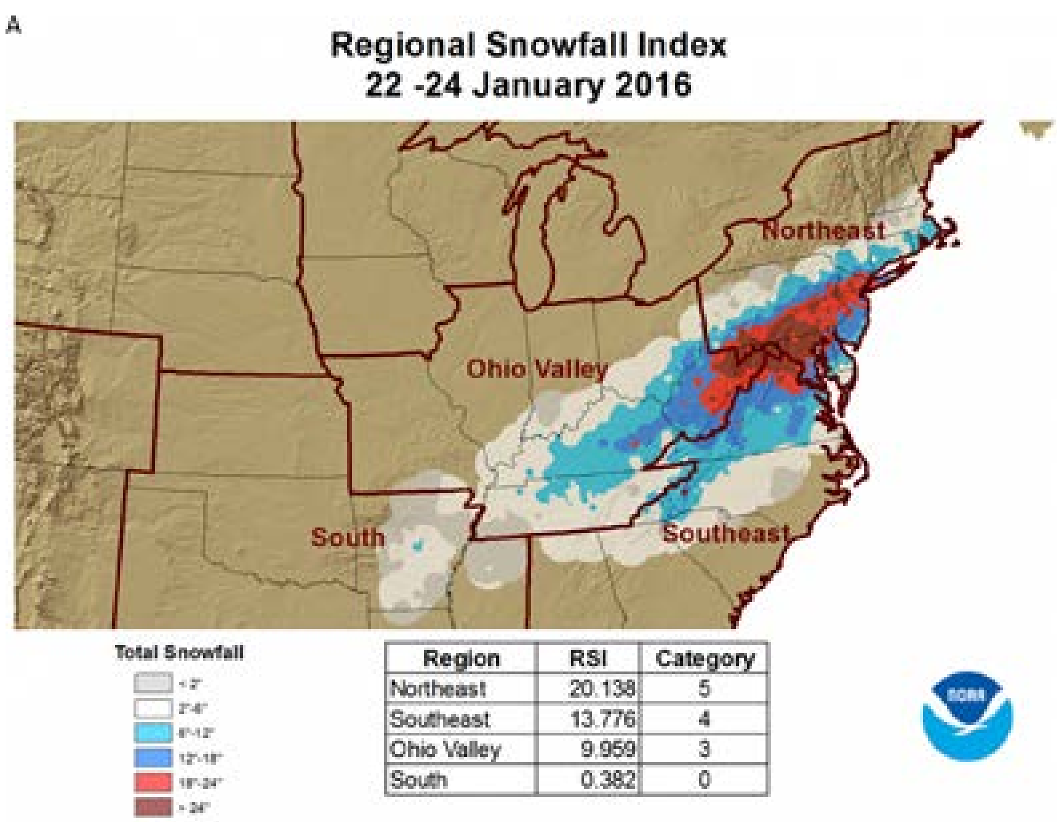


Figure 1.2
(A) Total snowfall (in inches) from the 22–24 January 2016 snowstorm. The Northeast region received a Category 5 “Extreme” rating on the Regional Snowfall Index. [Courtesy of NOAA]. (B) Post-storm snowfall in a Fairfax, VA neighborhood. [Photo by Jarek Tuszyński/Creative Commons]

Weather forecasters were better prepared in 2009-10 and 2016 because the science of meteorology, including the understanding of nor’easters, matured considerably since 1888. Today, Earth-orbiting weather satellites continuously monitor a storm’s developing cloud shield and track its movements, radar locates snow bands sweeping onshore, and observational data from the surface and upper atmosphere feed into sophisticated numerical weather forecast models running on supercomputers. Well in advance of a storm’s arrival, the NOAA National Weather Service (NWS) issues winter storm watches and warnings and rapidly communicates them to the public and public service agencies. Some school districts and businesses announce closings more than 12 hours before the first snowflake is expected, giving people time to stock up on food and other supplies in case they become marooned at home, as many were in the mid-Atlantic area during the winter of 2009-10 and the January 2016 storm.

While the historic winter storms of 1888, 2009-10, and 2016 clearly demonstrate how weather analysis and forecasting benefited from advances in scientific knowledge and technology, there is still more to be learned of Earth’s atmosphere. It is evident, for example, that atmospheric conditions favoring development of nor’easters are linked to complex changes in the planetary-scale circulation. There is more on this topic in Chapter 10.

For more on the Children’s Blizzard, refer to: Laskin, D, 2004: *The Children’s Blizzard*. Harper Collins Publishers, 307 pp.

All about nor'easters

Topic in Depth 1.1

1.1 Introduction

Weather Studies: Introduction to Atmospheric Science provides a systematic study of the dynamic atmospheric environment. The textbook first explores weather observational techniques and basic scientific principles that govern the atmosphere. It then investigates a wide variety of atmospheric phenomena ranging from high and low pressure systems to tornadoes and hurricanes. The final chapters of delve into more specialized topics such as weather forecasting, atmospheric optics, and global climate change. The behavior of the atmosphere is not arbitrary; rather its workings are explainable in scientific terms, drawn from many scientific disciplines, such as physics and chemistry. Although the atmosphere is governed by natural laws, questions are likely to persist regarding past, present, and future weather and climate.

The textbook contains numerous "Topics in Depth" to enrich certain topics with videos, animations, and links to weather imagery. Key to studying weather is combining textbook knowledge with current observations. Some Topics in Depth will link directly to current weather maps.

Chapter 1 introduces and describes tools and basic understandings that guide the investigation of the atmosphere.

1.2 Weather and Climate

Everyone experiences the weather and its far-reaching influence. Weather dictates how people dress, drive, and choose recreational activities. Before setting out in the morning, most check the latest weather forecast on their smartphone, computer, television, or radio, or even glance out the window to look at the sky. These daily experiences help develop a basic understanding of how the atmosphere functions.

Weather is defined as the state of the atmosphere at a particular place and time in terms of the current value of quantitative variables such as temperature, humidity, cloudiness, precipitation, and wind speed and direction. Thousands of weather stations around the world monitor weather variables at Earth's surface at least hourly every day. A place and time is specified when describing weather because the atmosphere is dynamic and changes from one place to another and with time. When the weather is cold and snowy in New York City, it might be warm and humid in Miami and hot and dry in Phoenix, and tomorrow's weather may differ markedly from today's weather. *If you don't like the weather, wait a minute* is an old saying that is not far from the truth in many places. **Meteorology** is the study of the atmosphere, processes that cause weather, and the life cycle of weather systems.

While weather often varies from one day to the next, the weather of a particular location tends to follow reasonably consistent seasonal variations, with temperatures higher in summer and lower in winter. Additionally, the tropics are associated with warmer weather and less seasonal temperature contrasts than at higher latitudes. Because arithmetic averages of weather elements (e.g., temperature, precipitation) taken over a span of years are often the easiest way of describing typical weather conditions, **climate** has been traditionally defined as weather conditions at a locality averaged over a specified time interval. By international convention, average values of weather elements are computed for a 30-year period beginning with the first year of a decade. At the close of a decade, the averaging period is moved forward ten years. In 2020, climatic summaries were based on weather records from 1981–2010; in 2021 this shifted to a 1991–2020 averaging period. Thirty-year average monthly and annual temperatures and precipitation totals are used to describe the climate of a locality as are average seasonal snowfall, length of growing season, percent of possible sunshine, and number of days with dense fog. Climate is the ultimate environmental control in that it governs, for example, the cultivatable crops, the fresh water supply, and the heating and cooling requirements for homes.

In addition to average values of weather elements, the description of a locale's climate encompasses extremes in weather (e.g., highest and lowest temperature, greatest 24-hr snowfall and rainfall). Tabulation of extreme values usually covers the entire period of record (or the period since observations were made at the same location). Records of weather extremes provide information on the variability of climate at a particular place and give a more complete and useful description of climate. Farmers, for example, are interested in knowing not only the average summer rainfall, but also the frequency of extremely wet or dry summers. **Climatology** is the study of climate, its controls, and spatial and temporal variability.

The definition of climate has expanded to describe the state of the climate system as a whole. The state of *Earth's climate system*, composed of the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere, results from internal and external influences, mutual interactions, and feedbacks. Chapter 15 provides a detailed look at Earth's climate system.

1.3 Accessing Weather Information

A key part of this course is accessing current weather data. Whether through a smartphone, computer, television, or radio, weather information is available practically everywhere. Weathercasts are routine segments of the local morning, noon, and evening news reports. All-news channels feature weather segments throughout the day.

Weather information can obtained by reading reports in local or national newspapers (in print or online) or listening to the radio. Most newspapers include a weather column or page featuring maps and statistical summaries. Radio stations provide the latest local weather conditions and forecasts, but may not include a summary of weather conditions across the nation unless a newsworthy event has occurred, such as a tornado outbreak or hurricane.

Another rich source of weather information is the Internet, which provides access to national and regional weather maps, satellite and radar images depicting large-scale cloud, precipitation, and atmospheric circulation patterns, weather forecasts, plus updates on environmental issues, such as trends in global climate, stratospheric ozone, and air quality. All National Weather Service Forecast Offices maintain websites to display a variety of current meteorological, climatological, and hydrological information. The course's online RealTime Weather Portal also contains a host of real-time weather data (Figure 1.3). There are hundreds of additional websites that offer other types of weather services, such as live webcams, to view local weather conditions and email or text alerts for severe weather events.

Figure 1.3
A tablet PC displaying a surface weather map linked from the RealTime Weather Portal. [Photo by E.W. Mills]

Since the dawn of the computer era, a more efficient and much more popular way to retrieve weather information is through weather software applications for desktops, laptops, and mobile devices. There are thousands of different weather apps that disseminate a variety of weather data. From a local beach forecast to tracking real-time radar, apps have revolutionized the way people get weather information.

A valuable source of local weather and climate information is the **NOAA Weather Radio All Hazards (NWR)**. As a public service, the *National Weather Service (NWS)*, a line office of the *National Oceanic and Atmospheric Administration (NOAA)*, operates low-power, VHF high band FM radio transmitters that broadcast continuous weather information (e.g., regional conditions, local forecasts, marine warnings, local climatological statistics) directly from NWS Forecast Offices 24 hours a day, 7 days a week. A series of messages is repeated every 4–6 minutes and some messages are updated hourly. When weather-related hazards threaten, NWS forecasters interrupt routine broadcasts and issue watches, warnings, or advisories.

Working with federal, state, and local emergency managers and the Federal Communications Commission's Emergency Alert System, the NWR provides the public with warnings and post-event information for all types of hazards: weather, natural (e.g., earthquakes, tsunamis, volcanic eruptions), technological (e.g., oil spills, chemical leaks), and other non-weather emergencies (e.g., terrorist attacks, Amber alerts, 911 Telephone outages). The NWS works with federal, state and local emergency managers and the Federal Emergency Management Agency (FEMA) in broadcasting weather and non-weather (e.g., civil emergencies, evacuation, Amber

Alerts) emergency messages over NWR. In addition, many broadcasters monitor NWR for weather and non-weather emergency messages conveyed to the Emergency Alert System.

NWR station listings

Topic in Depth 1.3

A special *weather radio* is required to receive NWR transmissions because the seven broadcast frequencies (from 162.40 to 162.55 MHz) are outside the range of standard AM/FM radios. Some weather radios are designed to sound an alarm or switch on automatically when a weather watch or warning or other emergency information is issued (Figure 1.4). The latest generation weather radio is equipped with the *Specific Area Message Encoding (S.A.M.E.)* feature that sounds an alarm only if a weather watch or warning is issued for a specific county or limited local area programmed (selected) by the user. Depending on terrain, the maximum range of NOAA weather radio broadcasts is approximately 65 km (40 mi.). More than 1000 transmitters are operating in all 50 states, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, and the U.S. Pacific Territories, with the goal of bringing 95% of people in the U.S. and its territories within range of NOAA weather radio broadcasts. In many communities, NOAA weather radio broadcasts are also available through audio programming channels on television. Environment Canada's Meteorological Service has transmitters at 185 sites in its *Weatheradio* network, broadcasting in the nation's two official languages. A few of the transmitters operate on FM frequency, and most use the same broadcast frequencies as NWR. Over 90% of Canadians can access *Weatheradio* broadcasts.

Figure 1.4
At the push of a button, this weather radio broadcasts weather reports, forecasts, watches and warnings issued by the National Weather Service. [Courtesy of Bruce Thomas, Midland Radio]

1.4 Time Keeping

Weather observations are made simultaneously at weather stations around the world. Simultaneous observations are necessary if the state of the atmosphere over a large area is to be portrayed accurately on a weather map at a specific time. This portrayal is also the basis for weather forecasting. Weather maps used in this course are given in *Z time* (also known as Greenwich Mean Time). The meaning of Z time and the conventional basis for time keeping are subjects of this section.

For millennia, humans kept track of their activities by the daily motions of the Sun. Local noon was a convenient reference, marking the time of day when the Sun reached its highest point in the observer's sky. However, locations only a few tens of kilometers to the east or west would have different *Sun times.* Beginning in the mid-1800s, with advances in transportation and communication made possible by railroads and telegraphs, travel east or west could be confusing and even potentially hazardous because of local time differences and the railroads argued for the standardized time keeping scheme we use today. Civil time zones were instituted in the United States and Canada on 18 November 1883 to standardize time keeping in North America. The concept of international time zones was officially adopted on 22 October 1884 at the International Meridian Conference, held in Washington, DC.

Time zones (Figure 1.5) were established based on longitude, which is measured as degrees east and west of the *prime meridian*, which is zero degrees longitude. Because early astronomical determinations of time had been made at The Old Royal Observatory in Greenwich, England, the 1884 Conference designated the meridian of longitude passing through the observatory as the prime meridian. For more than 50 years, Greenwich Mean Time (GMT) was used for meteorological observations. GMT is based upon the daily rotation of Earth with respect to a "mean Sun." Often the single letter Z (phonetically pronounced "zulu") designated the time within the Greenwich Time zone (centered on the prime meridian). Today, the preferred time system is the more precise Coordinated Universal Time or Universel Temps Coordinné (UTC), based on an atomic clock and reckoned according to the stars. For practical purposes, Z, GMT, and UTC are equivalent.

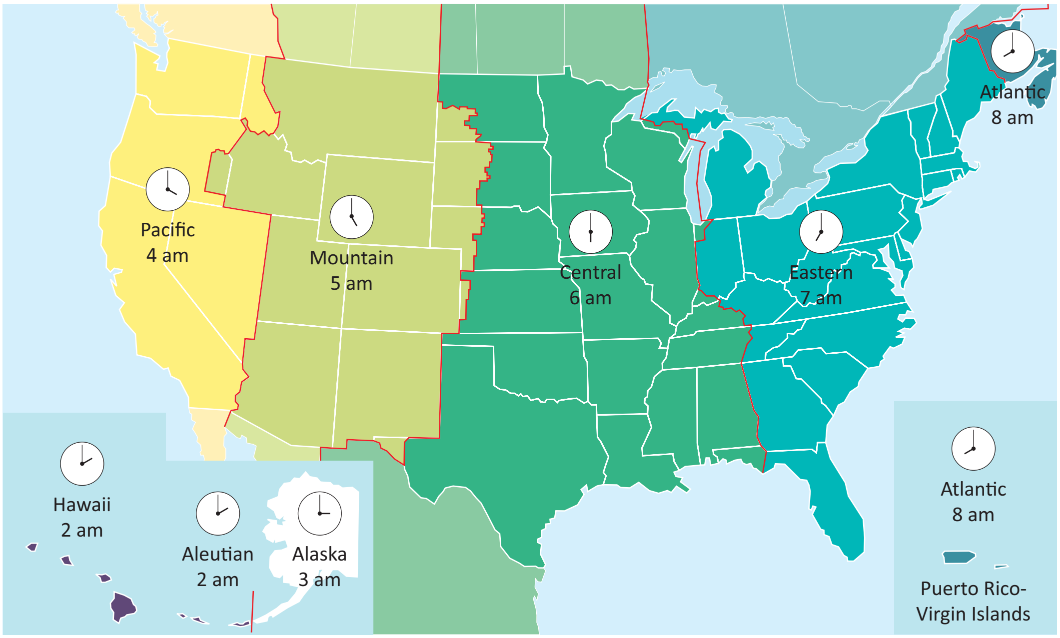


Figure 1.5
Times zones in the United States, Puerto Rico and the Virgin Islands, southern Canada, and northern Mexico showing Standard Times equivalent to 1200 Z.

Earth makes one complete rotation (360°) on its axis with respect to the Sun once every 24 hrs. Hence, Earth rotates through 15° of longitude every hour (360° divided by 24 hrs equals 15° per hr). Ideally, Earth should be divided into 24 civil time zones each having a width of 15° of longitude. The central meridian of each time zone is defined as a longitude that is evenly divisible by 15. For example, the central meridian of the Central Time Zone in North America is 90°W longitude. Since 90° divided by 15 equals 6, Central Standard Time (CST) is 6 hrs different from the time at Greenwich. Earth rotates eastward so that Greenwich time is ahead of CST by 6 hrs. When it is noon at Greenwich, it is 7 a.m. Eastern Standard Time (EST), 6 a.m. CST, 5 a.m. Mountain Standard Time (MST), and 4 a.m. Pacific Standard Time (PST).

Boundaries between most time zones are adjusted to accommodate political boundaries of nations. In a few cases, nations adhere to a local civil time that may differ by a half hour from the central meridian of that time zone. To head off potential confusion, time is expressed according to a 24-hr clock so that, for example, 7:45 a.m. is 0745 and 2:20 p.m. is 1420. While most of the United States observes Daylight Saving Time, UTC is fixed and does not shift to a summer schedule. Hence, it is necessary to adjust the time by one hour where and when Daylight Saving Time is observed. During summer, residents of the U.S. Central Time Zone lag Greenwich time by 5 hrs instead of 6 hrs. Hence, 0700 Central Daylight Time (CDT) = 0600 Central Standard Time (CST) = 1200Z. Currently, Daylight Saving Time begins on the second Sunday of March (when time “springs forward” one hour) and ends the first Sunday of November (when time “falls back” one hour).

Official U.S. time

Topic in Depth **1.4**

By international agreement, surface weather observations are taken at least 4 times every 24 hrs at 0000Z, 0600Z, 1200Z, and 1800Z, with upper-air measurements via balloon-borne instruments (radiosondes) made at 0000Z and 1200Z. In the United States, surface observations are taken hourly (at the top of the hour), composite radar charts are also issued hourly at 35 minutes past the hour, and fronts are analyzed on weather maps every 3 hrs beginning at 0000Z.

1.5 Weather Systems and Weather Maps

To make weather watching more meaningful and useful for this course, the remainder of this chapter is devoted to a description of what to watch for, beginning with features plotted on the national weather map.

Temperature, dewpoint, wind, and air pressure are among the many atmospheric variables routinely monitored by instruments at surface weather stations. These data are transmitted to a central facility where they are assembled and plotted on surface weather maps. Special symbols are used on national weather maps to identify and locate the principal weather-makers, pressure systems and fronts (Figure 1.6). For an historical sketch on the origins of weather maps, see *For Further Exploration* Essay 1.1 at the end of this chapter.

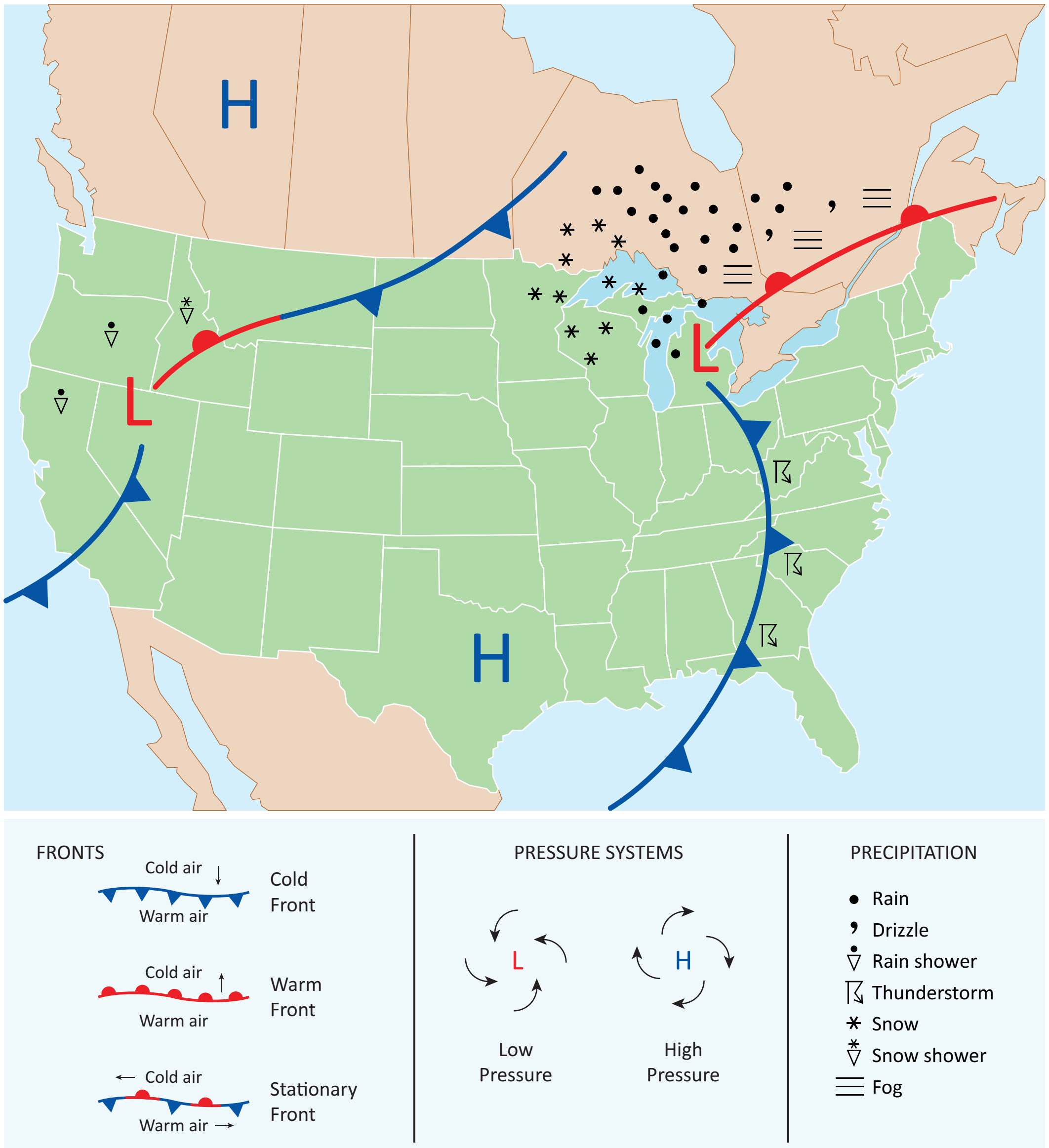


Figure 1.6
On a weather map, symbols represent the state of the atmosphere over a broad geographical area at a specific time.

Pressure systems are of two main types, *highs* (or anticyclones) and *lows* (or cyclones). The high and low designations refer to air pressure. We can think of **air pressure** as the weight per unit area of a column of air that extends upward from Earth's surface (or any altitude within the atmosphere) to the top of the atmosphere. At any specified time, air pressure at Earth's surface varies from one place to another. On a weather map, *H* or *High* symbolizes the center of regions where the air pressure is high compared to surrounding areas. Conversely, *L* or *Low* signifies the center of regions where the air pressure is low compared to surrounding areas.

Current pressure system and fronts

Topic in Depth 1.5

As you examine weather maps, note the following about pressure systems:

- Highs (anticyclones) feature descending air and are usually accompanied by fair weather, hence they are described as *fair-weather systems*. Highs that originate in northwestern Canada bring cold, dry weather in winter and cool, dry weather in summer to much of the coterminous United States. Highs that develop further south over land may bring hot, dry weather in summer and mild, dry weather in winter. Furthermore, summer winds around a warm high centered over the southeastern states transport warm, humid air from the Gulf of Mexico over a broad swath of the eastern U.S. into southeastern Canada.
- Viewed from above in the Northern Hemisphere, surface winds in a high-pressure system blow in a clockwise and outward spiral as shown in Figure 1.7A. Calm conditions or light winds are typical over a broad area at the center of a high.
- Lows (cyclones) feature ascending air and typically produce cloudy, rainy, or snowy weather, hence they are described as *stormy-weather systems*. An exception may be lows that develop over broad regions of arid or semiarid terrain, such as the Desert Southwest, especially in summer. In such areas, intense solar heating of the ground raises the air temperature and lowers the surface air pressure, producing a low that remains stationary over the hot ground and is not accompanied by stormy weather.
- Viewed from above in the Northern Hemisphere, surface winds in a low-pressure system blow in a counterclockwise and inward spiral as shown in Figure 1.7B.
- Both highs and lows move with the prevailing wind several kilometers above the surface, arcing generally eastward across middle latitude regions, such North America, and the weather changes at places in their paths. Highs follow lows and lows follow highs causing the weather to shift from stormy to fair and back again (which can be monitored as changes in air pressure). Chapter 10 has more to say about the tracks of high and lows in the middle latitudes and Chapter 12 describes tropical low pressure systems.
- Lows that track across the northern United States or southern Canada are more distant from sources of moisture and usually produce less rain or snowfall than lows that track further south (such as lows that travel out of eastern Colorado and move along the Gulf Coast or up the Eastern Seaboard).
- Weather on the left side (west and north) of an extratropical cyclone's track (path) tends to be relatively cold, whereas weather on the right (east and south) of the cyclone's track tends to be relatively warm. For this reason, winter snows are more likely to the west and north of the path of a low-pressure system.

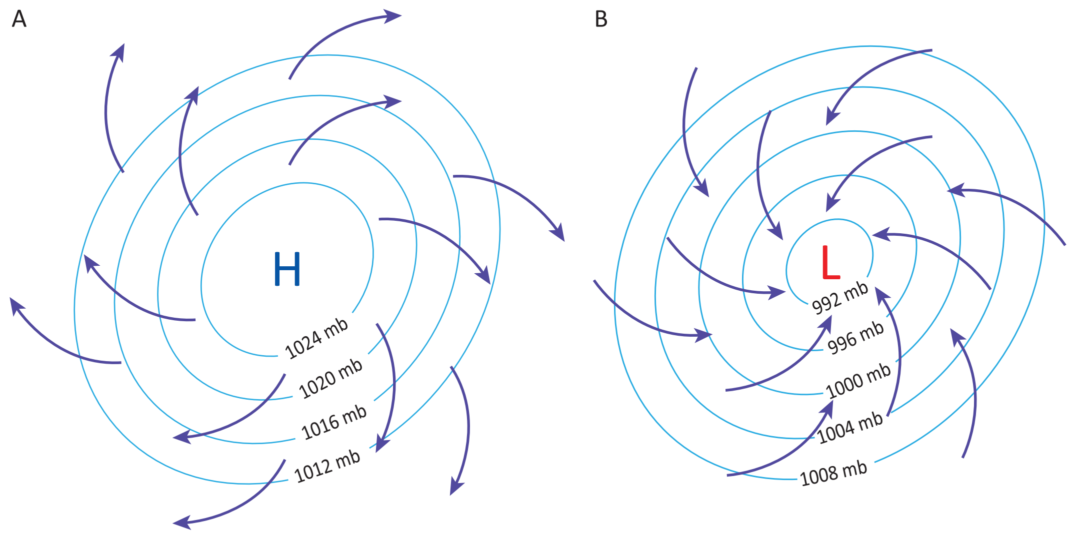


Figure 1.7
Viewed from above in the Northern Hemisphere, winds near the Earth's surface blow (A) clockwise and outward from a high-pressure system, and (B) counterclockwise and inward into a low-pressure system. Blue lines are isobars, passing through places with the same air pressure in millibars (mb). Isobars are drawn at intervals of 4 millibars.

Air masses and fronts are also important weather-makers. An **air mass** is a huge volume of air covering hundreds of thousands of square kilometers with relatively uniform temperature and humidity properties horizontally. An air mass is typically associated with a large high pressure system and its specific characteristics depend on the types of surfaces over which the air mass forms (its *source region*) and travels. Cold air masses form at higher latitudes over surfaces that are often snow or ice covered, whereas warm air masses form in the lower latitudes where Earth's surface is relatively warm. Humid air masses form over moist maritime surfaces (e.g., Pacific Ocean, Gulf of Mexico), whereas dry air masses develop over dry continental surfaces (e.g., Desert Southwest, northwestern Canada). The four basic types of air masses are cold and dry, cold and humid, warm and dry, and warm and humid.

A **front** is a transition zone between air masses that differ in temperature, humidity, or both. Fronts form where contrasting air masses meet, and the associated air movements often give rise to cloudiness and precipitation. The most common fronts are stationary, cold, and warm; weather map symbols for all three are shown in Figure 1.6. As the name implies, a *stationary front* is just that, stationary (or nearly so). On both sides of a stationary front, winds blow roughly parallel to the front but in opposite directions. A shift in wind direction may cause a portion of a stationary front to advance northward (becoming a warm front) or southward (becoming a cold front).

At the same pressure, warm air is less dense than cold air so a warm air mass advances by gliding up and over a retreating cold air mass. The cold air mass forms a wedge under the warm air mass. The leading edge of warm air at the Earth's surface is plotted on a weather map as a *warm front* (Figure 1.8A). On the other hand, cold air advances by sliding under and pushing up the less dense warm air and the leading edge of cold air at the Earth's surface is plotted on a weather map as a *cold front* (Figure 1.8B). Consequently, the boundary between warm and cold air associated with a warm front slopes more gently with altitude than does the boundary between warm and cold air associated with a cold front.

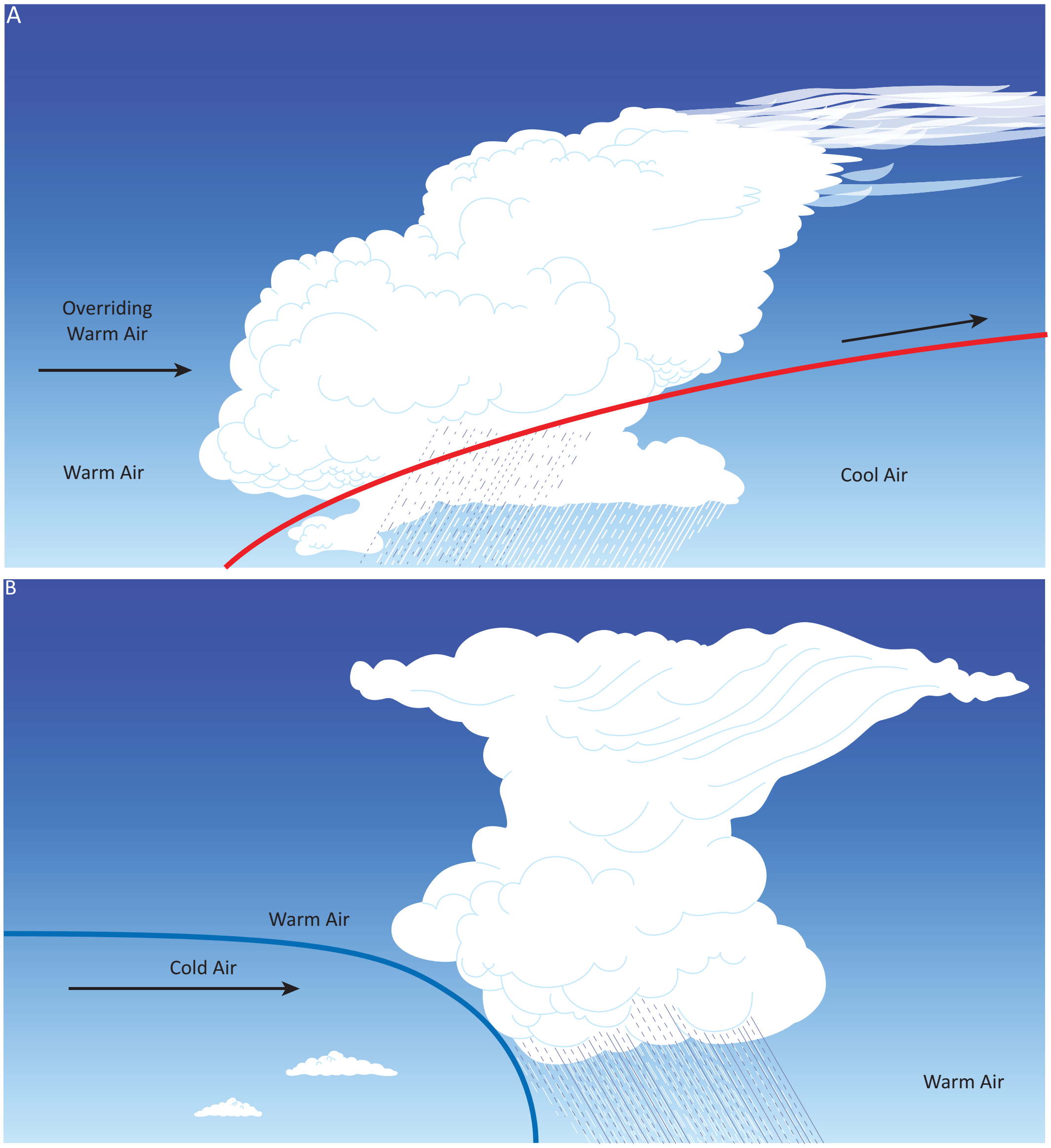


Figure 1.8
The two most common types of fronts are (A) a warm front that marks the boundary between advancing relatively warm (less dense) air and retreating cold (more dense) air, and (B) a cold front that marks the boundary between advancing cold air and retreating warm air. In both diagrams the fronts are shown in vertical cross-section with the vertical scale greatly exaggerated. The vertical scale in each diagram is approximately 10 km and the horizontal scale on the order of 1000 km.

Forecast maps

Topic in Depth **1.6**

As you examine surface weather maps, note the following about air masses and fronts:

- In response to regular seasonal changes in the duration and intensity of sunlight, polar air masses are much colder in winter and milder in summer. By contrast, in the tropics, sunlight is nearly uniform in duration and intensity throughout the year so tropical air masses are warm and exhibit less seasonal variation in temperature.
- An air mass modifies (becomes warmer, colder, more humid, drier) as it moves away from its source region. The degree of modification depends on the properties of the surface over which the air mass travels. For example, a cold air mass warms more if it travels over ground that is bare rather than snow-covered.
- Fronts are three-dimensional and the map symbol for a front is plotted where the frontal surface intersects Earth's surface (as shown in Figure 1.6).
- Most cloudiness and precipitation associated with a warm front occur over a broad band, often hundreds of kilometers wide, in advance of where the front intersects Earth's surface. Widespread precipitation ahead of a warm front generally is light to moderate in intensity and may persist at a particular location for 12–24 hrs or longer.
- Most cloudiness and precipitation associated with a cold front occur as a narrow band along or just ahead of where the front intersects Earth's surface. Although precipitation often is showery and may last from a few minutes to a few hours, it can be very intense.
- Wind direction (and at times wind speed) differs on opposite sides of a front.
- Some fronts are not accompanied by cloudiness or precipitation. A shift in wind direction, together with changes in air pressure, temperature, and/or humidity typically accompany the passage of the front.
- In summer, air temperatures can be nearly the same ahead of and behind a cold front. In that case, the air masses on opposite sides of the front differ primarily in humidity, the air mass ahead of the advancing front is more humid (and therefore less dense) and the air mass behind the front is less humid (denser). With passage of the front, refreshingly drier air replaces uncomfortably humid air.
- Cold and warm fronts are plotted on a weather map as heavy lines usually anchored at the center of a low-pressure system. The counterclockwise and inward circulation about a low brings contrasting air masses together to form fronts. By contrast, the outward flow of relatively homogeneous air from a high precludes development of fronts.
- A low-pressure system may develop along a stationary front and travel rapidly like a large ripple from west to east along the front.
- Thunderstorms and associated severe weather (e.g., tornadoes, hail) most often develop south and south-

east of the center of a low-pressure system in the warm, humid air mass located between the cold front and the warm front.

As you monitor national and regional weather maps, also watch for the following:

- Cool sea breezes or lake breezes may push inland perhaps 10–50 km (6–30 mi.), lowering summer afternoon temperatures in coastal areas.
- Beginning in late fall and continuing through much of the winter, lake-effect snows fall in narrow bands on the downwind (eastern and southern) shores of the Great Lakes and Utah's Great Salt Lake. Such snowfalls are highly localized and can be very heavy.
- Severe thunderstorms and tornadoes are most common in spring and early summer across the central United States, especially from east Texas northward to Nebraska and from Iowa eastward to central Indiana.
- Thunderstorms are most frequent in Florida, on the western High Plains and eastern slopes of the Rockies, but are rare along the Pacific coast and on the Hawaiian Islands.
- Tropical storms and hurricanes occasionally impact the Atlantic and Gulf coasts, primarily from August through October. However, these tropical weather systems are rare on the West Coast.

1.6 Describing the State of the Atmosphere

Devices, computers, television, and newspaper weather reports include statistical summaries of present and past weather conditions compiled to form a climatology (description of the climate) of a locale. The meaning of the most common weather parameters:

- *Maximum temperature*. The highest air temperature recorded over a 24-hr period, usually between midnight of one day and midnight of the next day. Typically, but not always, the day's maximum temperature occurs in the early to mid-afternoon. In the United States, surface air temperatures are reported in degrees Fahrenheit (°F) and other countries in degrees Celsius (°C).
- *Minimum temperature*. The lowest air temperature recorded over a 24-hr period, usually between midnight of one day and midnight of the next day. Typically, but not always, the minimum temperature occurs around sunrise.
- *Dewpoint* (or *frost point*). The temperature to which air must be cooled at constant pressure to become saturated with water vapor and for dew (or frost) to begin forming on relatively cold surfaces.
- *Relative humidity*. A measure of the actual concentration of the water vapor component of air compared to the concentration the air would have if saturated with water vapor. Relative humidity is always expressed as a percentage. Because the saturation concentration varies with air temperature so too does the relative humidity. On most days, the relative humidity is highest during the coldest time of day (around sunrise) and lowest during the warmest time of day (early to mid-afternoon).
- *Precipitation amount*. Depth of rainfall or melted snowfall over a 24-hr period, usually from midnight of one day to midnight of the next, measured to one-hundredth of an inch in the United States and in millimeters elsewhere. On average, 10 inches of freshly fallen snow melt down to about 1 inch of water.
- *Air pressure*. The weight of a column of air over a unit area of Earth's surface. With a mercury barometer, the initial instrument for measuring air pressure, the pressure exerted by the atmosphere supports a column of mercury to a certain height and the mercury column fluctuates up and down as the air pressure rises and falls. This is the reason air pressure is commonly reported in inches or millimeters of mercury. In the United States, meteorologists express air pressure in millibars (mb), a unit of pressure equal to a hectopascal (hPa). The average air pressure at sea level is 1013.25 mb, corresponding to the

pressure exerted by a 29.92 in. (760 mm) column of mercury. Falling air pressure over a span of several hours often signals an approaching low-pressure system and a turn to stormy weather. Rising air pressure, on the other hand, indicates an approaching high-pressure system, with clearing skies or continued fair weather.

- *Wind direction* and *wind speed*. According to meteorological tradition, wind direction is the compass direction from which the wind blows (Figure 1.9). For example, a southeast wind blows from the southeast toward the northwest and a west wind blows from the west toward the east. As a general rule, at middle latitudes a wind shift from east to northeast to north to northwest is accompanied by falling air temperatures. On the other hand, a wind shift from east to southeast to south usually brings warmer weather. Over a broad area about the center of a high-pressure system calm air or light winds prevail. Wind speed increase as a cold front passes a location and winds are particularly strong and gusty in the vicinity of thunderstorms.
- *Sky cover*. Based on the fraction of the sky that is cloud covered, the sky is described as clear (no clouds), a few clouds (1/8 to 2/8 cloud cover), scattered clouds (3/8 to 4/8), broken clouds (5/8 to 7/8), and overcast (completely cloud-covered). All other factors being equal, nights are coldest when the sky is clear and the air is relatively dry. An overcast sky prevents the day's minimum temperature from falling and the day's maximum temperature from rising more than otherwise.
- *Weather watch*. Issued by the National Weather Service when hazardous weather (e.g., tornadoes, heavy snowfall) is considered possible based on current or anticipated atmospheric conditions, but its occurrence, timing, or exact location is uncertain.
- *Weather warning*. Issued by the National Weather Service when hazardous weather is happening, imminent, or has a very high probability of occurring.

Figure 1.9
Wind vane atop the Smithsonian Institution Building in Washington, DC. The arrow of the wind vane points in the direction from which the wind is blowing, as confirmed by the flags that are stretched out in the downwind direction. [Photo by R. S. Weinbeck]

1.7 Weather Satellite Imagery

Satellite images and video loops (composed of successive images) are routine components of many televised and online weather reports. Some newspaper weather pages also feature satellite images. Sensors on weather satellites orbiting Earth provide a unique and valuable perspective on the state of the atmosphere over broad areas and enable meteorologists to remotely measure temperature and humidity as well as to locate and track weather systems.

The weather satellite images most familiar are obtained by sensors onboard a **Geostationary Operational Environmental Satellite (GOES)** orbiting Earth about 36,000 km (22,300 mi.) above the planet's equator. A GOES satellite revolves around Earth at the same rate and in the same direction as the planet rotates so it is always positioned over the same spot on Earth's surface and its sensors have a consistent field of view (Figure 1.10). The *sub-satellite point*, the location on Earth's surface directly below the satellite, is essentially on the equator. Two geostationary satellites, one over South America (near 75°W longitude) and the other over the eastern Pacific (approximately 135°W longitude), provide a complete view of much of North America and adjacent portions of the Pacific and Atlantic Oceans. Images of the entire western hemisphere are also available on a regular basis to latitudes of about 60°. In order to best observe the poles, polar-orbiting satellites are also used to complement geostationary satellites in monitoring the planet.

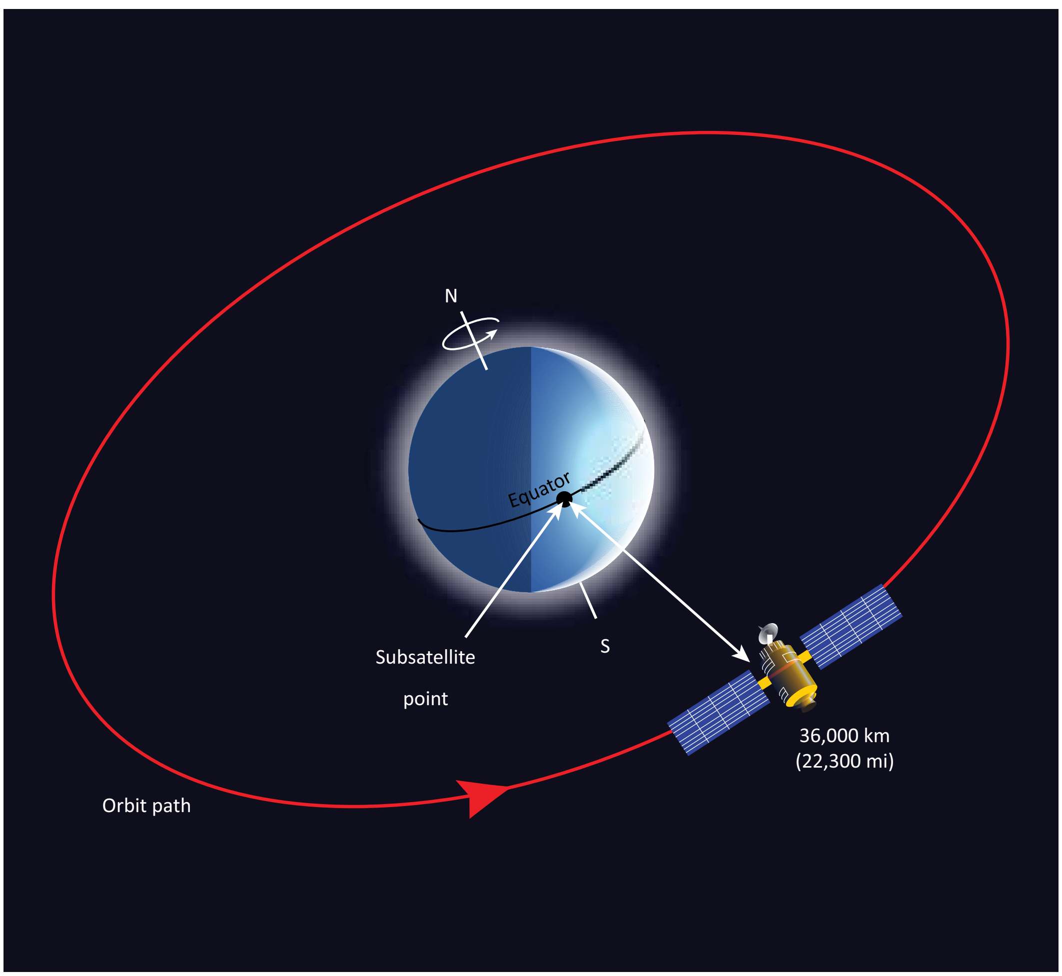


Figure 1.10
A Geostationary Operational Environmental Satellite (GOES) orbits Earth so that it is always positioned over the same equatorial spot on Earth's surface.

Weather satellites in orbit

Topic in Depth **1.7**

A **Polar-orbiting Operational Environmental Satellite (POES)** travels in a relatively low altitude (800 to 1000 km or 500 to 600 mi.) nearly north-south orbit passing close to the poles (Figure 1.11). The satellite's orbit traces out a plane in space while the planet continually rotates on its axis through the plane of the satellite's orbit. With each orbit, points on Earth's surface (except near the poles) move eastward so that onboard sensors sweep out successive overlapping north/south strips. A polar-orbiting satellite that follows the Sun (sun-synchronous) passes over the same area twice each 24-hr day. Other polar-orbiting satellites are positioned so they require several days before passing over the same point on Earth's surface.

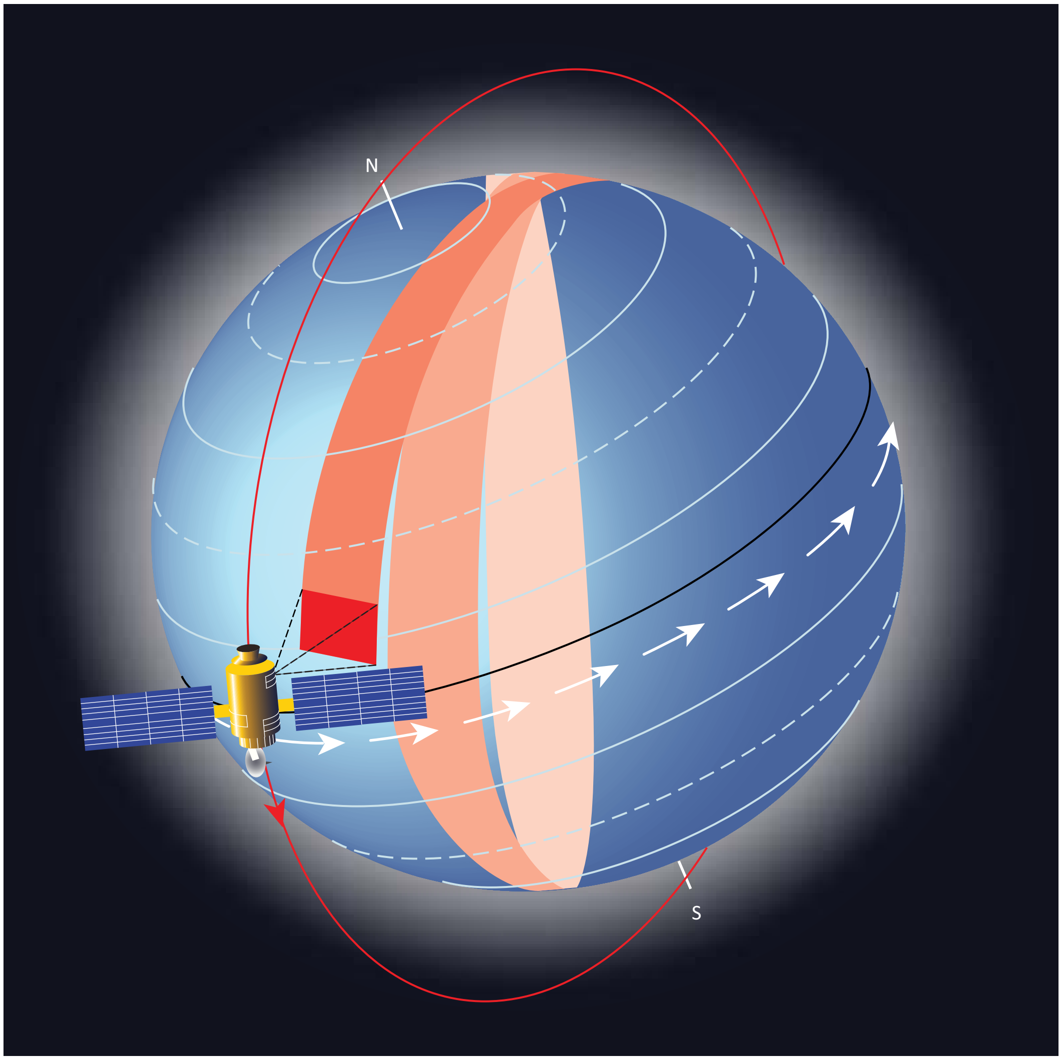


Figure 1.11
A Polar-orbiting Operational Environmental Satellite (POES) orbits Earth in a nearly north-south direction passing near the poles.

Polar orbit principle

Topic in Depth 1.8

Satellite-borne sensors are either passive or active. Passive sensors measure radiation coming from the Earth-atmosphere system, both visible solar radiation reflected by the planet and invisible infrared radiation emitted by the planet. Sunlight reflected by Earth's surface and atmosphere produces images that are essentially black and white photographs of the planet. Sun-lit, highly reflective surfaces, such as cloud tops and snow-covered ground, appear bright white whereas less reflective surfaces, such as evergreen forests and the ocean, appear much darker. Cloud patterns on a **visible satellite image** are of particular interest to atmospheric scientists (Figure 1.12). From analysis of cloud patterns displayed on the image, they identify not only a specific type of weather system (such as a hurricane), but also the stage of its life cycle and direction of movement once a sequence of images is animated.

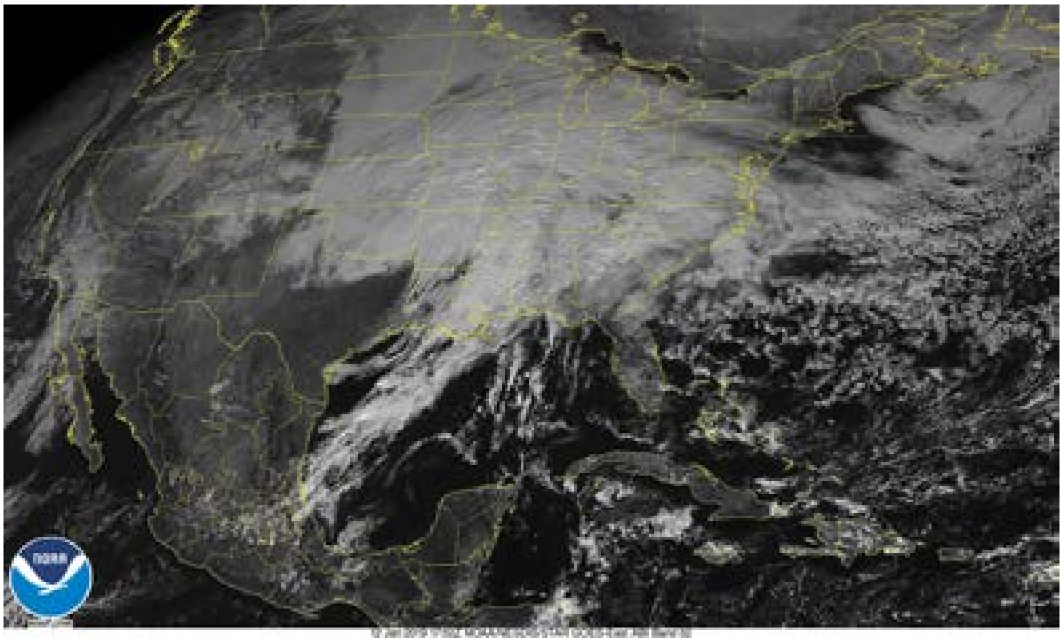
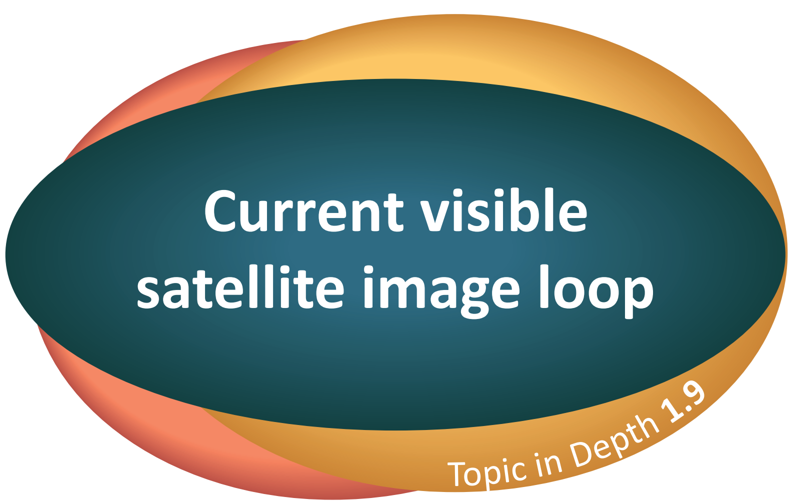


Figure 1.12
A sample visible satellite image from sensors onboard GOES-16. The cloud swirl over the central U.S. is a low pressure system that brought the first significant snowfall of 2019. [Courtesy of NOAA/NWS National Centers for Environmental Prediction]



A second type of sensor onboard a weather satellite detects infrared (IR) radiation. IR radiation is an invisible form of radiation emitted by all objects continually, both day and night. Hence, an **infrared satellite image** of the planet can provide information at any time whereas visible satellite images are available only during daylight hours. (Because of around-the-clock availability, IR satellite images are usually shown on television weathercasts.) Infrared signals are routinely calibrated to give the temperature of objects in the sensor's field of view. This is possible because the intensity of IR radiation emitted by an object depends on its surface temperature; relatively warm objects emit more intense IR radiation than relatively cold objects. IR-derived temperatures are calibrated on a gray scale such that the brightest white indicates the lowest temperature and dark gray indicates the highest temperature. A color scale can also be used to enhance certain temperatures.

The temperature dependency of IR emission makes it possible, for example, to distinguish low clouds from high clouds on an IR satellite image. In the part of the atmosphere where most clouds occur (the lowest 10 km or 6 mi. or so), air temperature usually decreases with increasing altitude. The tops of high clouds are colder than the tops of low clouds and emit less intense IR radiation. In the sample IR satellite image in Figure 1.13, taken at the same time as Figure 1.12, high clouds appear bright white (with the highest clouds color enhanced with progressive blue, green, yellow, and red shadings to depict colder temperatures) whereas low clouds are darker and warmer. IR sensors are also tuned to detect those wavelength bands where, in cloud-free areas, some of the radiation emitted from Earth's surface passes directly out to space. In this way, scientists can determine the surface temperature of the ground, snow cover, fog, ocean, or lake where the sky is cloud-free.

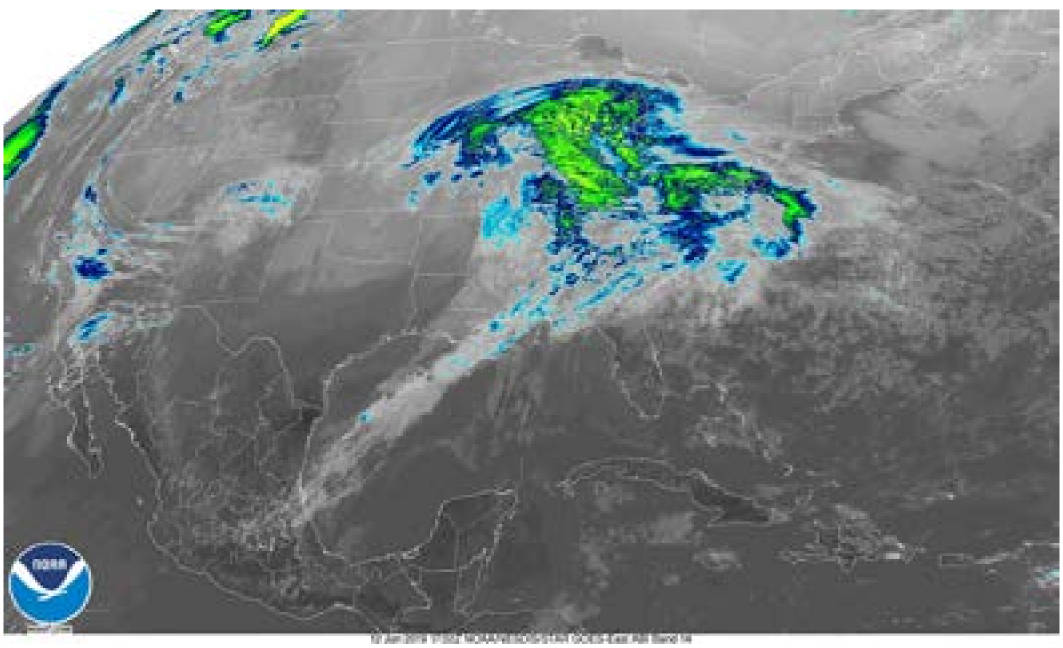


Figure 1.13
An infrared satellite image from sensors onboard GOES-16, taken at the same time as Figure 1.12. [Courtesy of NOAA/NWS National Centers for Environmental Prediction]

Current infrared satellite image loop

Topic in Depth 1.10

Water vapor satellite images enable meteorologists to identify and track the movement of moisture plumes within the atmosphere over thousands of kilometers. Water vapor is invisible and not detectable on visible or infrared satellite images. But water vapor efficiently absorbs and emits certain wavelength bands of IR radiation so that sensors onboard weather satellites sensitive to these wavelengths detect water vapor. Water vapor imagery displays the water vapor concentration at altitudes between about 5000 and 12,000 m (16,000 and 40,000 ft.). This can be shown on a gray scale, where at one extreme, dark gray indicates almost no water vapor whereas at the other extreme, milky white signals a relatively high concentration of water vapor. Upper-atmospheric clouds appear milky to bright white on water vapor images, masking water vapor concentrations in the image. As in Figure 1.14, a color scale can also be used for enhancement of certain water vapor concentrations. In this figure, blues, whites, and greens progressively represent higher concentrations of water vapor, whereas yellows, oranges, and reds progressively represent lower concentrations. Water vapor animations can reveal the air circulation pattern in weather systems prior to widespread cloud formation.

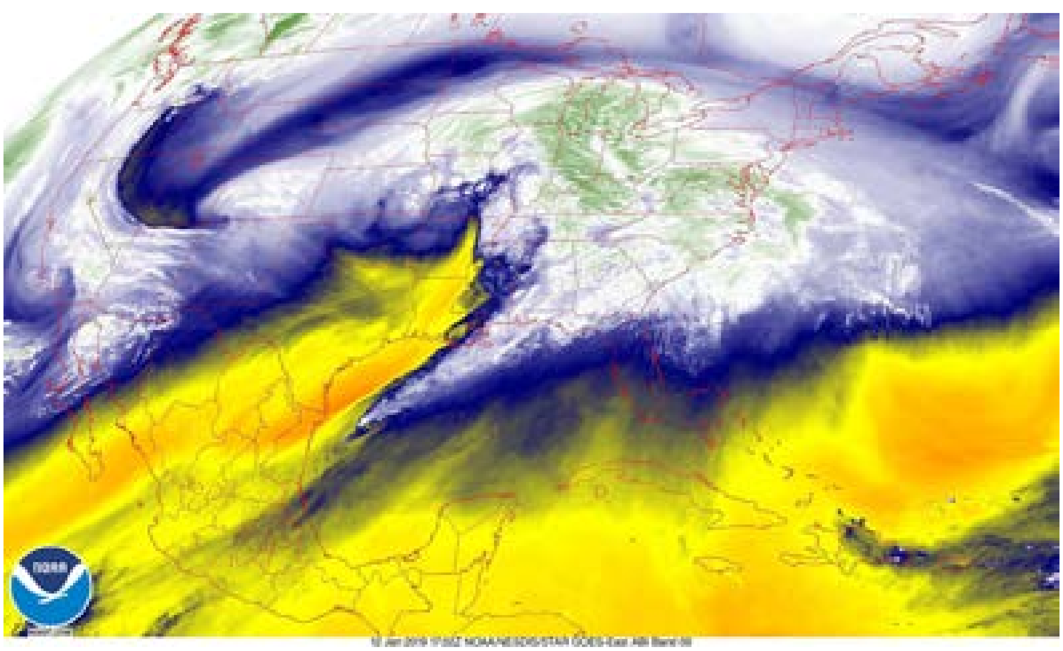
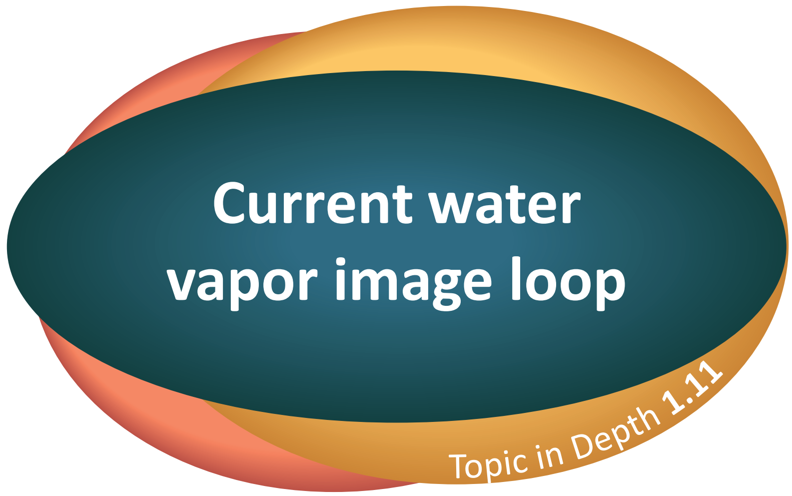


Figure 1.14
A sample water vapor satellite image from sensors onboard GOES-16, taken at the same time as Figure 1.12 and Figure 1.13. [Courtesy of NOAA/NWS National Centers for Environmental Prediction]



In addition to monitoring the weather, satellites have countless applications crucial to today's society, including the *Global Positioning System (GPS)*, which allows for precise location and navigation. Meteorologists use GPS to track instrumentation probing the atmosphere and slight variations in GPS signals can provide insight into atmospheric variables such as water vapor. To learn how GPS works, see *For Further Exploration* Essay 1.2.

1.8 Weather Radar

Weather radar complements satellite surveillance of the atmosphere by locating and tracking the movement of areas of precipitation and monitoring the circulation within small-scale weather systems such as thunderstorms. Weather radar continually emits pulses of microwave energy reflected by atmospheric targets such as raindrops, snowflakes, or hailstones. The reflected signal is displayed as blotches (radar echoes) on computer displays with a superimposed map of the region surrounding the radar. The heavier the precipitation, the more intense echo. Echo intensity is calibrated on a color scale so light green indicates light rain whereas dark red signals heavy rain or hail.

Some radar images appearing on weather broadcasts or online are color coded according to precipitation type to help distinguish between snow, rain, and freezing rain. From analysis of radar echoes, meteorologists can determine the intensity of thunderstorms, track the movement of areas of precipitation, and predict when precipitation is likely to begin or end. Composite maps of radar echoes from a number of weather radars around the nation are useful in following the progress of large-scale weather systems (Figure 1.15). By overlaying radar echoes on satellite images, areas of precipitation and clouds can be displayed simultaneously, thereby helping to locate the most active portion of a weather system (Figure 1.16). These composites are often animated.

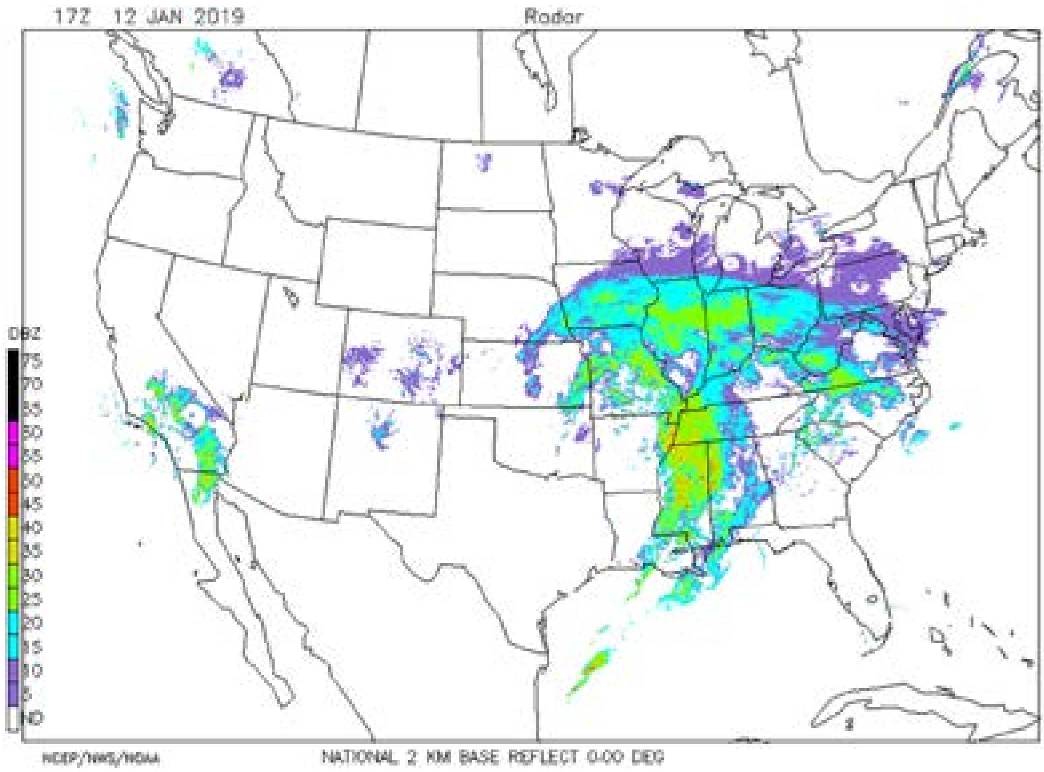


Figure 1.15
A sample composite national radar image from about the same time as the satellite images in Figures 1.12–1.14. [Courtesy of NOAA/NWS National Centers for Environmental Prediction]

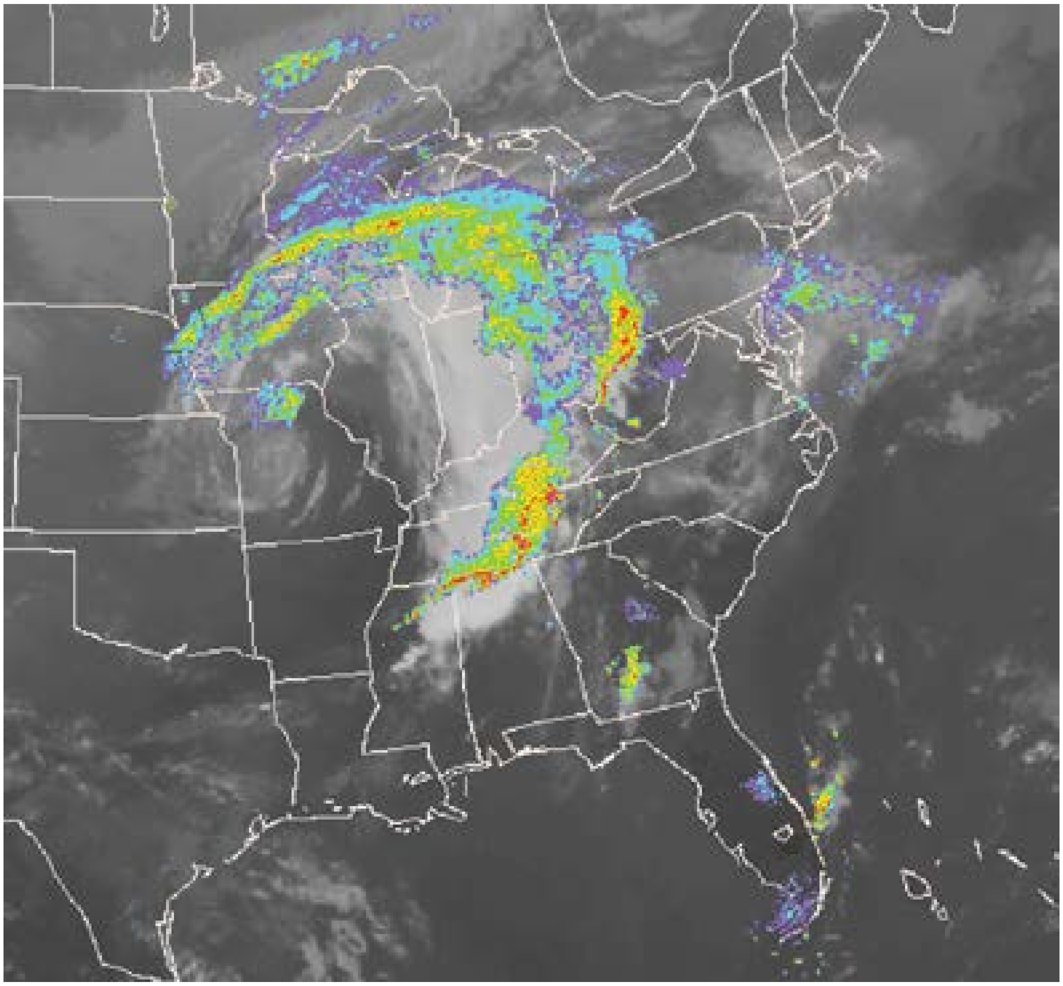
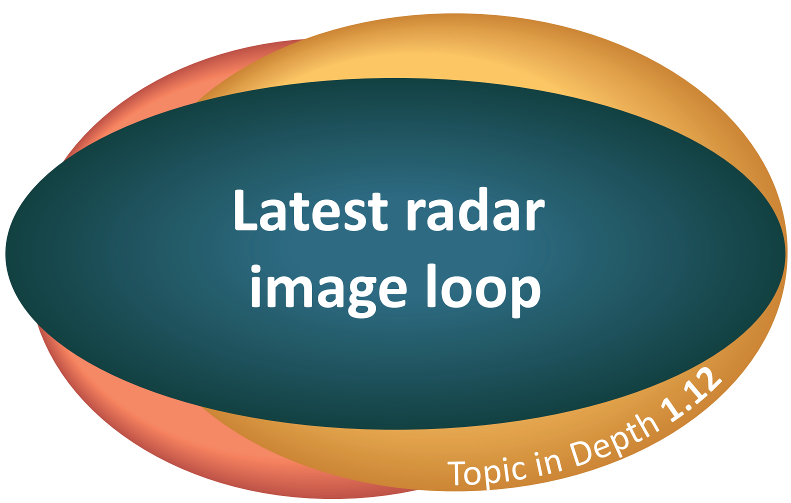


Figure 1.16
A sample infrared satellite image of the eastern United States, overlaid with radar echoes. This type of image allows areas of precipitation and clouds to be displayed simultaneously.



Weather radar also monitors the movement of raindrops, snowflakes, and hailstones within a storm system. Using the same operating principle as the device that measures the speed of a pitched baseball (*Doppler effect*), weather radar detects the motion of precipitation particles within the storm system and can indicate the system's circulation. Early identification of the circulation within a thunderstorm cloud that is a precursor of a developing tornado is a potentially life-saving application of Doppler weather radar. With advance warning of a tornadic circulation before a funnel cloud touches the ground, people have time to seek shelter or move out of its path. Radar is discussed in greater detail in Chapter 7.

1.9 Sky Watching

At the beginning stage the atmosphere and weather, develop a habit of observing the sky for changes in clouds and cloud cover. As generations before us knew, sky watching makes us more aware of the dynamic nature of the atmosphere and reveals clues to future weather. Here are some things to watch for:

- Clouds are aggregates of tiny water droplets, ice crystals, or some combination of both. Ice-crystal clouds, such as cirrus clouds, occur at high altitudes where air temperatures are relatively low and they have a fibrous or wispy appearance (Figure 1.17). Water-droplet clouds, such as cumulus clouds, occur at lower altitudes where temperatures are higher and their edges are more sharply defined (Figure 1.18).

Figure 1.17
These high thin cirrus clouds appear fibrous because they are composed of mostly tiny ice crystals. [Photo by Captain Albert E. Theberge Jr., NOAA Corps (ret.), NOAA NWS Collection]

Figure 1.18
These relatively low cumulus clouds are composed of tiny water droplets and have more sharply defined edges than ice-crystal clouds. [Photo by Stephen Corfidi, NOAA/NWS/SPC/OB]

- A cloud that is very near or in contact with Earth's surface is fog (Figure 1.19). By convention, *fog* is a suspension of tiny water droplets or ice crystals in air that reduces horizontal visibility to less than 1000 m (0.621 mi.).

Figure 1.19
Fog reduces visibility along a highway. [NOAA]

- Some clouds form in horizontal layers (*stratiform clouds*) whereas others appear puffy (*cumuliform clouds*). Stratiform clouds develop where air ascends gently over a broad region whereas cumuliform clouds are produced by vigorous ascent of air over a much smaller area. Often stratiform clouds develop ahead of a warm front while cumuliform clouds, especially those having great vertical development, form along or just ahead of a cold front.
- Arrival of high, thin clouds in the western sky at a middle latitude location is often the first sign of an approaching warm front. In time, clouds gradually lower and thicken until they eventually block the Sun during the day or the Moon at night.
- The day may begin with clear skies, but after several hours of bright sunshine, small white clouds appear, resembling puffs of cotton floating in the sky (Figure 1.20). These fair-weather *cumulus clouds* usually vaporize rapidly near sunset.

Figure 1.20
Fair weather cumulus clouds in Hawaii. These clouds are most common during the warmest time of the day.
[NOAA NWS Collection]

- During certain atmospheric conditions, cumulus clouds build vertically and merge laterally, eventually forming a thunderstorm cloud, called a *cumulonimbus cloud* (Figure 1.21). All thunderstorms are accompanied by lightning and thunder. Severe thunderstorms can produce torrential rains, large hail, strong, gusty winds, and even tornadoes.

Figure 1.21
Cumulonimbus clouds always produce lightning and sometimes heavy rain, hail, and gusty surface winds. This hail-producing supercell thunderstorm was photographed over the Colorado high plains just east of the foothills of the Rockies. [Photo Credit:Walt Lyons/WeatherVideoHD.TV]

- Clouds at different altitudes sometimes move horizontally in different directions and even at different speeds (Figure 1.22). Because most clouds move with the wind, such motion indicates that the horizontal wind shifts direction (and speed) with increasing altitude.

Figure 1.22
Clouds at different altitudes may move horizontally in different directions indicating a change in wind direction with altitude. [Courtesy of NASA S'COOL Project]

Conclusions

There is much to be learned about the atmosphere and weather by keeping track of local, regional, and national weather patterns via television, radio, newspapers or online. Weather maps, satellite images, and radar displays are particularly valuable in obtaining the "big picture" when following the development and movement of weather systems across a broad region. In addition, it is useful to develop the habit of watching the sky for changing conditions locally and to monitor weather instruments if available. These practices make course learning more meaningful and practical. The study of the atmosphere, weather, and climate continues in the next chapter with an examination of the evolution, composition, and structure of the atmosphere.

Basic Understandings

- From the experiences of everyday life, everyone has acquired basic understandings of the workings of the atmosphere, weather, and climate.
- Weather is the state of the atmosphere at a place and time, described quantitatively in terms of such variables as temperature, humidity, and wind speed. Climate, traditionally defined as the average of weather and the extremes at a particular location over a period of time, has expanded to describe the state of the climate system as a whole.
- Weather information can be accessed online as well as from television, newspapers, and radio, including the NOAA Weather Radio.
- A weather map portrays graphically the state of the atmosphere over a broad geographical region at a specified time. On a weather map, H or High symbolizes a locale where air pressure is relatively high compared to the surrounding area. Viewed from above in the Northern Hemisphere, surface winds blow clockwise and outward about the center of a high. A high (or anticyclone) features generally fair weather.
- On a weather map, L or Low symbolizes a locale where air pressure is relatively low compared to the surrounding area. Viewed from above in the Northern Hemisphere, surface winds blow counterclockwise and inward about the center of a low. A low (or cyclone) often features stormy weather.
- An air mass is a huge volume of air covering hundreds of thousands of square kilometers that is relatively uniform horizontally in temperature and humidity. The temperature and humidity of an air mass depend on the properties of its source region and the nature of the surface over which the air mass travels.
- A front is a narrow transition zone between air masses that contrast in temperature and/or humidity. Fronts form where air masses meet and associated air movements often give rise to cloudiness and precipitation depending on the type of front. The most common types of fronts are stationary, warm, and cold.
- Sensors onboard weather satellites orbiting the planet provide a unique and valuable perspective on the state of the atmosphere and enable meteorologists to remotely measure temperature and humidity and track weather systems. These sensors measure two types of radiation: sunlight that is reflected or scattered by Earth and infrared radiation that is emitted by Earth. Weather satellites are in either geostationary or polar orbits and generate data processed into visible and infrared images.
- Weather radar continually emits pulses of microwave radiation reflected by raindrops, snowflakes, or hailstones. The reflected signal appears as blotches, known as radar echoes, on a screen. From analysis of radar echoes, meteorologists determine the intensity and track the movement of areas of precipitation. Using the Doppler effect, weather radar can also monitor the circulation of air within a storm system and provide advance warning of severe weather.
- Observing the development, type, and movement of clouds may provide clues as to future weather.

Enduring Ideas

- Weather is described in terms of variables of state, including temperature, dewpoint, wind, and air pressure. Near real-time information about weather around the world is readily available online, on television, and from AM/FM radio. The NOAA Weather Radio is an important medium for receiving immediate watches, warnings, and advisories regarding extreme weather and other hazards proximate to your locality.

- Weather maps commonly plot air pressure and/or temperature as these variables help illustrate the principal weather-makers, pressure systems and fronts. High pressure systems, representing specific air mass types, are separated by low pressure systems and their associated fronts. The atmosphere is in continuous motion with air sinking and flowing clockwise and outward near Earth's surface in Highs and flowing counterclockwise and inward near the surface and rising in Lows. Rising air often leads to cloud and precipitation development.
- Satellite and radar imagery are valuable tools in weather analysis and forecasting. Visible, infrared, and water vapor imagery monitor the ever-changing state of the atmosphere and weather systems moving across the globe. Radar imagery offers a detailed look into the structure, movement, and circulation within precipitation systems.
- Sky watching helps discern the current state of the atmosphere and often reveals clues to future weather. Clouds are defined by their height (low, middle, or high), nature of appearance (stratiform or cumuliform), and whether they are producing precipitation.

Key Terms

weather
meteorology
climate
climatology
NOAA Weather Radio All Hazards (NWR)
pressure systems
air pressure
air mass
front
GOES
POES
visible satellite image
infrared satellite image
water vapor satellite image
weather radar

Review

1. Distinguish between weather and climate.
2. What parameters are most commonly used to describe the climate of some locality?
3. Identify the various sources of weather information that are available to the public.
4. Describe the type of weather that usually accompanies a high (anticyclone) and a low (cyclone) in middle latitudes.
5. What is an air mass? What governs the temperature and humidity of an air mass?
6. Explain why clouds and precipitation are often associated with fronts.
7. Distinguish between GOES and POES weather satellites.
8. What advantages does an infrared satellite image offer over a visible satellite image for monitoring the state of the atmosphere?

9. Describe how weather radar detects the location and movement of areas of precipitation.
10. Distinguish between a fair-weather cumulus cloud and a cumulonimbus cloud.

Critical Thinking

1. Identify several of the technological advances of the 20th century that significantly improved weather observation and forecasting.
2. Why are near-simultaneous weather observations essential for drawing weather maps?
3. How does the local air pressure change as a cyclone approaches your location?
4. A location experiences an approaching warm front and then a cold front. Describe the changing nature (e.g., cumuliform) of the clouds in the sky.
5. Explain how it is possible for stratiform clouds at different altitudes to move in different directions.
6. Speculate on why the highest temperature of the day usually occurs in mid-afternoon rather than noon.
7. Describe how the composition and appearance of a cloud change with increasing altitude.
8. On a visible satellite image, why do cloud tops and snow-covered surfaces appear bright white while forest-covered land and oceans appear relatively dark?
9. Why would a local TV weather broadcast typically rely on GOES satellite data?
10. An intense low pressure system tracks northeastward just offshore from Cape Hatteras, NC to just east of Cape Cod, MA. Describe the general direction of surface winds over New England as the center of the storm moves toward Nova Scotia (just northeast of New England).

For Further Exploration

ESSAY 1.1: Weather Maps, Historical Perspective

Weather maps shown online, on television, or in newspapers are graphical models that display weather observations and analyses. The purpose of a weather map is to represent the state of the atmosphere over a broad geographical area at a specific time, permitting the identification of weather systems such as fronts, cyclones, and anticyclones. Analyzing a chronological sequence of weather maps enables meteorologists to determine the movement of weather systems, a key component of weather forecasting.

In meteorology, *weather analysis* refers to the sequence of steps involved in the interpretation of a graphical (e.g., weather map) display of the distribution of one or more weather elements (e.g., temperature, air pressure). Typically, an important part of the analysis consists of drawing isopleths. An *isopleth* is a contour line that joins places with the same value of a weather element. Examples include *isotherms*, connecting locales with the same air temperature, and *isobars*, joining places with the same air pressure. Isopleths plotted on a weather map form patterns meteorologists interpret.

During the 18th century, European and North American scientists made weather observations because of their interest in weather for its own sake and weather's influence on agriculture and human health. By the early 19th century, some weather observers had assembled reasonably continuous weather records, but typically were not part of an organized reporting network. Their observations were primarily for the purpose of describing the climate. Lacking any means for rapid communication of weather observations, these data were not useful for weather analysis and forecasting.

The first weather maps appeared in the early 19th century but took years to assemble because of sparse data, non-standard observation practices, and poor communications systems. Heinrich Wilhelm Brandes (1777–1834), a professor at the University of Breslau (in modern Poland), was one of the first to recognize the value of the spatial display of weather data in depicting the state of the atmosphere. Credit goes to Brandes for drawing the first weather map in 1819 showing an intense storm centered over the English Channel on 6 March 1783. However, the 36-year time delay meant that his analysis was not useful for weather forecasting. In 1819, Brandes also plotted 365 daily weather maps for the year 1785.

The source of data for Brandes' weather maps was the network of 39 volunteer weather observers in 18 nations (mostly European) operated by the Meteorological Society of the Palatinate in Mannheim. This first attempt at organized international weather observation lasted from 1781–1792. The Society published the data on wind, temperature, pressure, humidity, and precipitation but no maps in a series of a dozen volumes from 1783 to 1795. Brandes plotted departures (anomalies) from normal air pressure and drew isopleths joining locations having the same departure value. He also plotted winds on the same map and observed how air rotated around a storm and converged inward toward the storm center. By viewing a sequence of weather maps based on simultaneous observations, Brandes concluded that reduced air pressure was associated with a storm system.

In the United States, the first weather maps appeared in the fourth and fifth decades of the 19th century. In 1837, James P. Espy (1785–1860) published the first U.S. weather map based on observations from widely spaced locales. Espy's map had no isobars and used arrows to represent wind directions associated with a storm system centered near Silver Lake, NY, on 20 June 1836. Elias Loomis (1811–1889), professor of mathematics at Western Reserve College in Cleveland, OH, employed a similar approach as Brandes in his 1843 study of a storm that occurred on 16 February 1842. Loomis analyzed a series of maps with plotted simultaneous observations from 131 locations to determine the circulation and track of the storm. In so doing, Loomis produced the first *synoptic weather map* with pressure, temperature, wind, sky condition, and precipitation on the same map.

Until the mid-1800s, the utility of weather maps for forecasting purposes was stymied by a lack of a rapid communication. That changed with the invention of the electric telegraph in 1844. Weather observations could be transmitted quickly over long distances, making possible up-to-date weather maps and the first practical system of weather analysis and forecasting (Essay 1.1 Figure 1). The first telegraph-linked weather observation networks in the U.S. were operated by Cleveland Abbe (1838–1916) at Cincinnati's Mitchell Astronomical Observatory, Joseph Henry (1797–1878) at the Smithsonian Institution, and the U.S. Army Signal Corps (predecessor to the U.S. Weather Bureau and National Weather Service). Through the years, with technological advances in instrumentation and communications, weather maps more accurately portrayed the state of the atmosphere and thus more useful for weather analysis and forecasting (Chapter 2).

Essay 1.1 Figure 1
U.S. Army Signal Corps weather map dated 1 September 1872 based on observations telegraphed to Washington, DC. The Signal Corps weather network was the predecessor to the U.S. Weather Bureau and National Weather Service. [Courtesy of NOAA Photo Library]

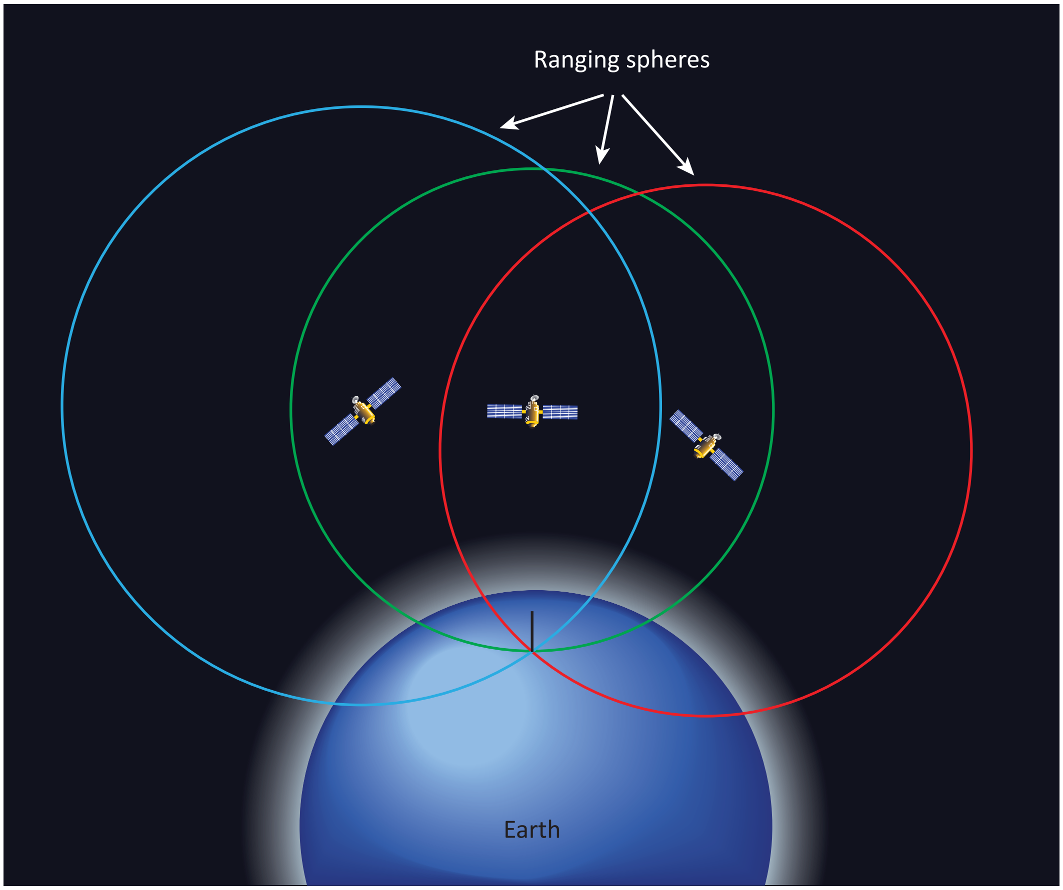
ESSAY 1.2: Global Positioning System

Satellite navigation was the brainchild of the U.S. Department of Defense. Similar to 18th century governments offering prize money to whoever solved the longitude problem (creating a reliable means of determining the longitude of a ship at sea), the U.S. government spent over $12 billion to develop a satellite-based system that could specify a location to near pinpoint accuracy at all times and in all types of weather. Originally intended for U.S. Armed Forces, with continuous positioning and navigation data available worldwide, the *Global Positioning System (GPS)* dates to the 1978 launch of the first Navstar satellite. In the 1980s, the government made the system available for civilian use, mostly used on large ships, and completed the original satellite network in 1994. The U.S. government owns and operates GPS as a national resource.

Not to be outdone by its Cold War adversary, the Soviet Union developed a similar system known as the GLObal NAvigation Satellite System (GLONASS), which Russia made publicly available in 2007. Other satellite navigation systems include the European Union's Galileo (with 24 primary operational satellites and 6 active spares), The People's Republic of China's BeiDou Satellite Navigation Experimental System (expected to have 35 satellites providing global coverage), and regional systems operated by India (operational name Navigation with Indian Constellation or NAVIC) covering India and the Northern Indian Ocean, as well as one by Japan (Quasi-Zenith Satellite System or QZSS) encompassing Asia and Oceania.

At least 24 Navstar satellites are needed to provide continuous service for GPS, and the U.S. currently operates more than 30 of these satellites. Once the 24-satellite base was achieved in the early 1990s, inexpensive, small portable receivers were developed and civilian use soared. GPS is widely used for navigation by ships, planes, delivery trucks, automobiles, and smartphones. Today non-military sectors (consumers and commercial customers) account for the majority of GPS equipment sales. In 2017 the global GPS market size was estimated at $37.9 billion (USD) and is expected to grow exponentially, driven by continued use into smartphones and GPS-enabled vehicles.

The principle behind GPS is *trilateration* (related to triangulation) from satellites that are in unobstructed view of the receiver (Essay 1.2 Figure 1). At least four satellites are needed for maximum precision, with each satellite in orbit at about 20,200 km (12,550 mi.) and completing two orbits in less than 24 hrs. Ranging signals travel from satellites to GPS receivers by line of sight through the atmosphere, clouds, and materials such as glass, but not most solids such as buildings and mountains. Hence, GPS units do not function indoors or underground, or underwater. The time it takes a ranging signal to travel from satellite to receiver is used to determine distance to the location. Atomic clock times, taken from the satellite, are embedded in the code of the ranging signal and compared with a code generated by the clock of the receiver. Radio signals travel at a finite speed (300,000 km per sec, or 186,000 mi. per sec, the speed of light) so that elapsed time is easily converted to distance. All GPS satellites are identifiable by their coded signals and their orbits are regular, allowing refinement of triangulated distances.



Essay 1.2 Figure 1
To determine its location on Earth's surface, a GPS receiver measures the travel times of radio signals sent by three satellites of known orbital location. Travel times are converted to distances. This trilateration technique is more precise when a fourth satellite is used to synchronize the clocks on the GPS satellites and receiver.

With a single satellite, a location could be at any point on a sphere, centered about the satellite, with a radius equal to the distance between the location and the satellite. With a second satellite, the location must be where the spheres overlap. The two spheres have different radii so their intersection is a circle. A third satellite describes yet another sphere, intercepting the other two spheres, and narrowing the location to the two points where all three spheres intersect. Usually one point is in space or Earth's interior while the other is on Earth's surface. Computer algorithms in the GPS receiver can distinguish between correct and spurious locations.

The fourth (and any additional) satellite synchronizes the slight differences in timing between the precise atomic clocks onboard GPS satellites and the less accurate quartz clocks in GPS receivers. In practice, most receivers select the best signals from many satellites so that assumptions about the correct point of intersection are unnecessary. Also, the more satellites in the line of sight of a GPS receiver, the greater the accuracy. Using an inexpensive, widely available receiver, anyone can readily locate their position within a few meters. Since 2018, new receivers can achieve location accuracy in centimeters.

The accuracy of GPS has been increased by broadcasting new signals from the Navstar satellites. One of the anticipated benefits of these new signals is reduction in interference from Earth's ionosphere (a region of the upper atmosphere containing a relatively high concentration of electrically charged particles). GPS satellite radio signals slow as they pass first through the ionosphere and then the electrically neutral atmosphere, delaying the expected arrival of the ranging signal. It is possible to correct for ionospheric delay, as it is frequency dependent, by using dual-frequency GPS receivers. The delay due to the neutral atmosphere is not frequency dependent but depends on the components of the atmosphere (a mixture of dry gases and water vapor).

Interestingly, measurement of atmospheric delays in GPS signals allows atmospheric water vapor to be monitored. As discussed in detail elsewhere in this book, water vapor is one of the most important components of the atmosphere. Through the energy involved in the phase changes of water, heat is transferred within the Earth-atmosphere system and contributes to the weather. Water vapor is also a greenhouse gas that plays a critical role in Earth's climate system, not only absorbing and emitting infrared (heat) radiation, but also affecting cloud and aerosol formation and the chemistry of the lower atmosphere. Monitoring atmospheric water vapor is therefore a significant meteorological application of GPS technology.

GPS signals can also arrive at receivers from nearby reflecting surfaces, a phenomenon known as multipath signals. Normally, multipath signals interfere with those received directly from the satellites, reducing positioning accuracy. Researchers from the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL) Physical Sciences Division (PSD), however, use GPS multipath signals reflecting off ocean or land to learn about the ocean's state, soil moisture, snowpack, and sea ice. Land surface reflections of the radio wavelength emitted by GPS transmitters are especially sensitive to these environmental parameters.

Web Resources

GOES Image Viewer
– www.star.nesdis.noaa.gov/goes/

GOES Operational Status
– www.ospo.noaa.gov/Operations/GOES/status.html

Global Positioning System
– www.gps.gov

Lockheed Martin GOES-R Information
– www.lockheedmartin.com/en-us/products/goes-r-series.html

National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS)
– www.weather.gov

NOAA NWS Forecast Offices
– www.wrh.noaa.gov/wrh/forecastoffice_tab.php

NOAA Weather Radio
– www.nws.noaa.gov/nwr/

NOAA National Hurricane Center
– www.nhc.noaa.gov

NOAA Satellite Imagery
– www.weather.gov/satellite

NOAA Storm Prediction Center
– www.spc.noaa.gov

POES Operational Status
– www.nesdis.noaa.gov/polar-orbiting-satellites

University Corporation for Atmospheric Research (UCAR) MetEd: Teaching and Training Resources for the Geoscience Community
– www.meted.ucar.edu

Scientific Literature

Decker, S. G., 2012: Development and analysis of a probabilistic forecasting game for meteorology students. *Bull. Amer. Meteor. Soc.,* **93**, 1833-1843, https://doi.org/10.1175/BAMS-D-11-00100.1.

Goodman, S. J., and Coauthors, 2012: The GOES-R proving ground: Accelerating user readiness for the next-generation geostationary environmental satellite system. *Bull. Amer. Meteor. Soc.,* **93**, 1029–1040, https://doi.org/10.1175/BAMS-D-11-00175.1.

Illston, B. G., J. B. Basara, C. Weiss, and M. Voss, 2013: The WxChallenge: Forecasting competition, educational tool, and agent of cultural change. *Bull. Amer. Meteor. Soc.,* **94**, 1501-1506, https://doi.org/10.1175/BAMS-D-11-00112.1.

Klaes, K. D., and Coauthors, 2007: An introduction to the EUMETSAT Polar System. *Bull. Amer. Meteor. Soc.,* **88**, 1085–1096, https://doi.org/10.1175/BAMS-88-7-1085.

Lazo, J. K., R. E. Morss, and J. L. Demuth, 2009: 300 billion served: Sources, perceptions, uses, and values of weather forecasts, *Bull. Amer. Meteor. Soc.,* **90**, 785–798, https://doi.org/10.1175/2008BAMS2604.1.

Lindsey, D. T., L. Grasso, J. F. Dostalek, and J. Kerkmann, 2014: Use of the GOES-R split-window difference to diagnose deepening low-level water vapor. *J. Appl. Meteor. Climatol.,* **53**, 2005–2016, https://doi.org/10.1175/JAMC-D-14-0010.1.

Schmit, T. J., 2015. Rapid refresh information of significant events: Preparing users for the next generation of geostationary operational satellites. *Bull. Amer. Meteor. Soc.,* **96**, 561–576, https://doi.org/10.1175/BAMS-D-13-00210.1.

Schmit, T. J., P. Griffith, M. M. Gunshor, J. M. Daniels, S. J. Goodman, and W. J. Lebai, 2017: A closer look at the ABI on the GOES-R Series. *Bull. Amer. Meteor. Soc.,* **98**, 681–698, https://doi.org/10.1175/BAMS-D-15-00230.1.

Schmit, T. J., S. S. Lindstrom, J. J. Gerth, and M. M. Gunshor, 2018: Applications of the 16 spectral bands on the Advanced Baseline Imager (ABI). *J. Operational Meteor.,* **6** (4), 33–46, https://doi.org/10.15191/nwajom.2018.0604.

Squires, M. F., J. H. Lawrimore, R. R. Helm Jr., D. A. Robinson, M. R. Gerbush, and T. W. Estilow, 2014: The regional snowfall index. *Bull. Amer. Meteor. Soc.,* **95**, 1835–1848, https://doi.org/10.1175/BAMS-D-13-00101.1.

Troutman, T. W., L. J. Vannozzi, and J. T. Fleming, 2001: The importance of educating the public regarding NOAA Weather Radio reception and placement within a structure. *Bull. Amer. Meteor. Soc.,* **82**, 2769–2772, https://doi.org/10.1175/1520-0477(2001)082<2769:TIOETP>2.3.CO;2.