AIR MASSES

CHAPTER 8

In late December 2001, a major lake-effect snowstorm dropped about 2 meters (7 feet) of snow on the Buffalo, New York area over a five-day period. *(AP Photo/David Duprey)*

Most people living in the middle latitudes have experienced hot, "sticky" summer heat waves and frigid winter cold waves. In the first case, after several days of sultry weather, the spell may come to an abrupt end that is marked by thundershowers and followed by a few days of relatively cool relief. In the second case, thick stratus clouds and snow may replace the clear skies that had prevailed, and temperatures may climb to values that seem mild compared with what preceded them. In both examples, what was experienced was a period of generally uniform weather conditions followed by a relatively short period of change and the subsequent reestablishment of a new set of weather conditions that remained for perhaps several days before changing again.

What Is an Air Mass?

Basic Weather Patterns
▸ Air Masses

The weather patterns just described are the result of the movements of large bodies of air, called air masses. An **air mass,** as the term implies, is an immense body of air, usually 1600 kilometers (1000 miles) or more across and perhaps several kilometers thick, which is characterized by homogeneous physical properties (in particular, temperature and moisture content) at any given altitude. When this air moves out of its region of origin, it will carry these temperatures and moisture conditions elsewhere, eventually affecting a large portion of a continent (Figure 8–1).

An excellent example of the influence of an air mass is illustrated in Figure 8–2. Here a cold, dry mass from northern Canada moves southward. With a beginning temperature of −46°C (−51°F), the air mass warms 13°C (24°F), to −33°C (−27°F), by the time it reaches Winnipeg. It continues to warm as it moves southward through the Great Plains and into Mexico. Throughout its southward journey, the air mass becomes warmer, but it also brings some of the coldest weather of the winter to the places in its path. Thus, the air mass is modified, but it also modifies the weather in the areas over which it moves.

The horizontal uniformity of an air mass is not complete because it may extend through 20 degrees or more of latitude and cover hundreds of thousands to millions of square kilometers. Consequently, small differences in temperature and humidity from one point to another at the same level are to be expected. Still, the differences observed within an air mass are small in comparison to the rapid rates of change experienced across air-mass boundaries.

Because it may take several days for an air mass to traverse an area, the region under its influence will probably experience generally constant weather conditions, a situation called **air-mass weather.** Certainly, some day-to-day

FIGURE 8-1 When an air mass that forms in the desert Southwest in summer moves out from its region of origin, it will bring hot, dry conditions to other regions. This scene is in Arizona's Sonoran desert. *(Photo by Michael Collier)*

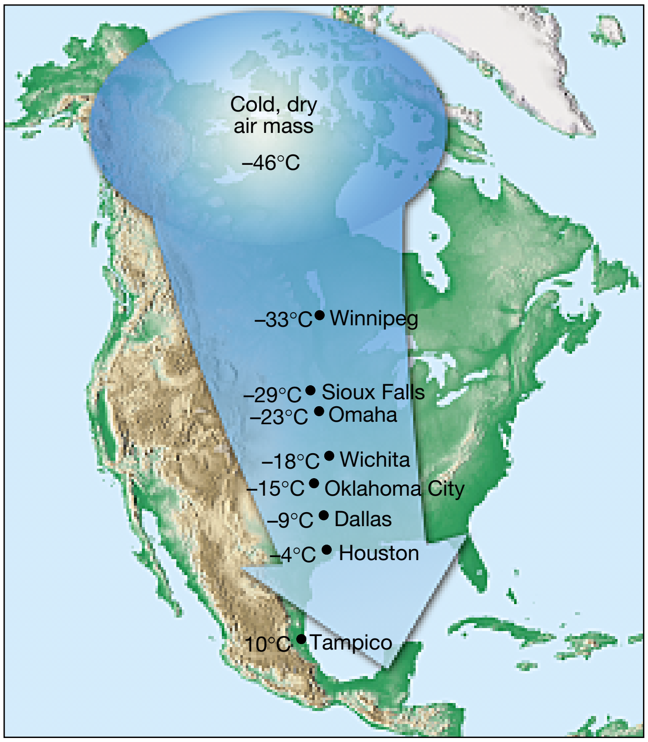


FIGURE 8-2 As this frigid Canadian air mass moved southward, it brought some of the coldest weather of the winter. *(After Tom L. McKnight,* Physical Geography, *5th ed. Upper Saddle River, NJ: Prentice Hall, 1996, p. 174)*

variations may exist, but the events will be very unlike those in an adjacent air mass.

The air-mass concept is an important one because it is closely related to the study of atmospheric disturbances. Many significant middle-latitude disturbances originate along the boundary zones that separate different air masses.

Source Regions

Basic Weather Patterns

▸ Air Masses

Where do air masses form? What factors determine the nature and degree of uniformity of an air mass? These two basic questions are closely related, because the site where an air mass forms vitally affects the properties that characterize it.

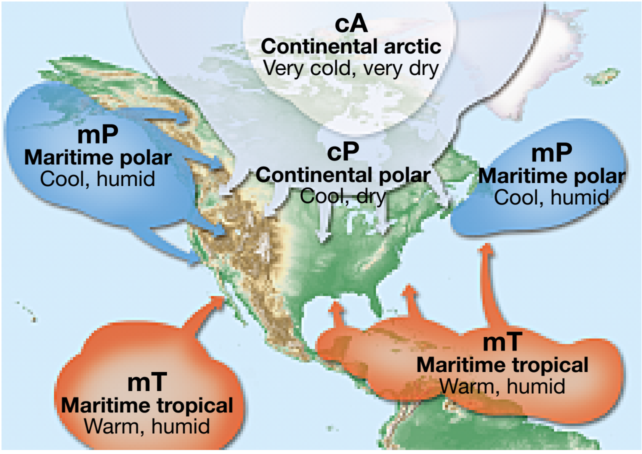
Areas in which air masses originate are called **source regions.** Because the atmosphere is heated chiefly from below and gains its moisture by evaporation from Earth's surface, the nature of the source region largely determines the initial characteristics of an air mass. An ideal source region must meet two essential criteria. First, it must be an extensive and physically uniform area. A region having highly irregular topography or one that has a surface consisting of both water and land is not satisfactory.

The second criterion is that the area be characterized by a general stagnation of atmospheric circulation so that air will stay over the region long enough to come to some measure of equilibrium with the surface. In general, it means regions dominated by stationary or slow-moving anticyclones with their extensive areas of calms or light winds.

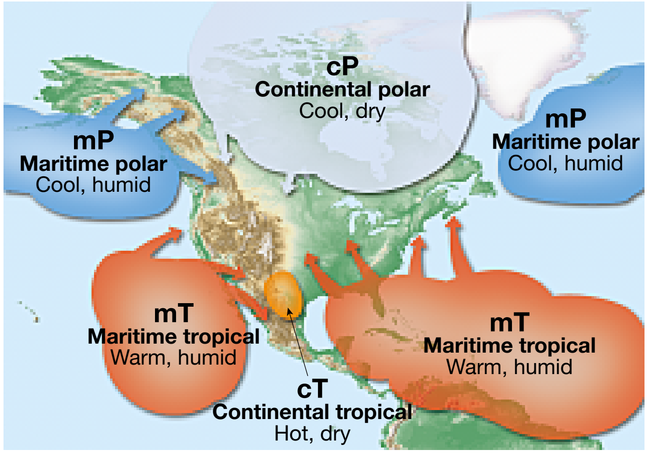
Regions under the influence of cyclones are not likely to produce air masses because such systems are characterized by converging surface winds. The winds in lows are constantly bringing air with unlike temperature and humidity properties into the area. Because the time involved is not long enough to eliminate these differences, steep temperature gradients result, and air-mass formation cannot take place.

Figure 8–3 shows the source regions that produce the air masses that most often influence North America. The waters

FIGURE 8-3 Air-mass source regions for North America. Source regions are largely confined to subtropical and subpolar locations. The fact that the middle latitudes are the site where cold and warm air masses clash, often because the converging winds of a traveling cyclone draw them together, means that this zone lacks the conditions necessary to be a source region. The differences between polar and arctic are relatively small and serve to indicate the degree of coldness of the respective air masses. By comparing the summer and winter maps, it is clear that the extent and temperature characteristics fluctuate.



(a) Winter pattern



(b) Summer pattern

of the Gulf of Mexico and Caribbean Sea and similar regions in the Pacific west of Mexico yield warm air masses, as does the land area that encompasses the southwestern United States and northern Mexico. In contrast, the North Pacific, the North Atlantic, and the snow- and ice-covered areas comprising northern North America and the adjacent Arctic Ocean are major source regions for cold air masses. It is also clear that the size and intensity of the source regions change seasonally.

Notice in Figure 8–3 that major source regions are not found in the middle latitudes but instead are confined to subtropical and subpolar locations. The fact that the middle latitudes are the site where cold and warm air masses clash, often because the converging winds of a traveling cyclone draw them together, means that this zone lacks the conditions necessary to be a source region. Instead, this latitude belt is one of the stormiest on the planet.

Classifying Air Masses

Basic Weather Patterns

▸ Air Masses

The classification of an air mass depends on the latitude of the source region and the nature of the surface in the area of origin—ocean or continent. The latitude of the source region indicates the temperature conditions within the air mass, and the nature of the surface below strongly influences the moisture content of the air.

Air masses are identified by two-letter codes. With reference to latitude (temperature), air masses are placed into one of three categories: **polar (P), arctic (A)**, or **tropical (T).** The differences between polar and arctic are usually small and simply serve to indicate the degree of coldness of the respective air masses.

The lowercase letter *m* (for **maritime**) or the lowercase letter *c* (for **continental**) is used to designate the nature of the surface in the source region and hence the humidity characteristics of the air mass. Because maritime air masses form over oceans, they have a relatively high water-vapor content compared to continental air masses that originate over landmasses (Figure 8–4).

When this classification scheme is applied, the following air masses can be identified:

cA	continental	arctic
cP	continental	polar
cT	continental	tropical
mT	maritime	tropical
mP	maritime	polar

Notice that the list does not include mA (maritime arctic). These air masses are not listed, because they seldom,

FIGURE 8-4 Air masses acquire their properties of temperature and moisture from extensive and physically uniform areas called *source regions*. When an air mass forms over the ocean, it is called *maritime*. Such air masses are relatively humid in contrast to continental air masses, which are dry. *(Photo by Norbert Wu/Peter Arnold, Inc.)*

if ever, form. Although arctic air masses form over the Arctic Ocean, this water body is ice-covered throughout the year. Consequently, the air masses that originate here consistently have the moisture characteristics associated with a continental source region.

Air-Mass Modification

After an air mass forms, it normally migrates from the area where it acquired its distinctive properties to a region with different surface characteristics. Once the air mass moves from its source region, it not only modifies the weather of the area it is traversing, but it is also gradually modified by the surface over which it is moving. Warming or cooling from below, the addition or loss of moisture, and vertical movements all act to bring about changes in an air mass. The amount of modification can be relatively small, or as the following example illustrates, the changes can be profound enough to alter completely the original identity of the air mass.

When cA or cP air moves over the ocean in winter, it undergoes considerable change. Evaporation from the water surface rapidly transfers large quantities of moisture to the once-dry continental air. Furthermore, because the underlying water is warmer than the air above, the air is also heated from below. This factor leads to instability and vertically ascending currents that rapidly transport heat and moisture to higher levels. In a matter of days, cold, dry, and stable continental air is transformed into an unstable mP air mass.

When an air mass is colder than the surface over which it is passing, as in the preceding example, the lowercase letter *k* is added after the air-mass symbol. If, however, an air mass is warmer than the underlying surface, the lowercase letter *w* is added. It should be remembered that the *k* or *w* suffix does not mean that the air mass itself is cold or warm. It means only that the air is *relatively* cold or warm in comparison with the underlying surface over which it is traveling. For example, an mT air mass from the Gulf of Mexico is usually classified as mTk as it moves over the southeastern states in summer. Although the air mass is warm, it is still cooler than the highly heated landmass over which it is passing.

The *k* or *w* designation gives an indication of the stability of an air mass and hence the weather that might be expected. An air mass that is colder than the surface is obviously going to be warmed in its lower layers. This fact causes greater instability that favors the ascent of the heated lower air and creates the possibility of cloud formation and precipitation. Indeed, a *k* air mass is often characterized by cumulus clouds, and should precipitation occur, it will be of the shower or thunderstorm variety. Also, visibility is generally good (except in rain) because of the stirring and overturning of the air.

Conversely, when an air mass is warmer than the surface over which it is moving, its lower layers are chilled. A surface inversion that increases the stability of the air mass often develops. This condition does not favor the ascent of air, and so it opposes cloud formation and precipitation. Any clouds that do form will be stratus, and precipitation, if any, will be light to moderate. Moreover, because of the lack of vertical movements, smoke and dust often become concentrated in the lower layers of the air mass and cause poor visibility. During certain times of the year, fogs, especially the advection type, may also be common in some regions.

In addition to modifications resulting from temperature differences between an air mass and the surface below, upward and downward movements induced by cyclones and anticyclones or topography can also affect the stability of an air mass. Such modifications are often called *mechanical* or *dynamic* and are usually independent of the changes caused by surface cooling or heating. For example, significant modification can result when an air mass is drawn into a low. Here convergence and lifting dominate and the air mass is rendered more unstable. Conversely, the subsidence associated with anticyclones acts to stabilize an air mass. Similar alterations in stability occur when an air mass is lifted over highlands or descends the leeward side of a mountain barrier. In the first case, the air's stability is reduced; in the second case, the air becomes more stable.

Properties of North American Air Masses

Air masses frequently pass over us, which means that the day-to-day weather we experience often depends on the temperature, stability, and moisture content of these large bodies of air. In this section, we briefly examine the properties of the principal North American air masses. In addition, Table 8–1 serves as a summary.

Continental Polar (cP) and Continental Arctic (cA) Air Masses

Continental polar and continental arctic air masses are, as their classification implies, cold and dry. Continental polar air originates over the often snow-covered interior regions of Canada and Alaska, poleward of the 50th parallel. Continental arctic air forms farther north, over the Arctic Basin and the Greenland ice cap (Figure 8–3).

Continental arctic air is distinguished from cP air by its generally lower temperatures, although at times the differences may be slight. In fact, some meteorologists do not differentiate between cP and cA.

During the winter, both air masses are bitterly cold and very dry. Winter nights are long, and the daytime Sun is short-lived and low in the sky. Consequently, as winter advances, Earth's surface and atmosphere lose heat that, for the most part, is not replenished by incoming solar energy. Therefore, the surface reaches very low temperatures and the air near the ground is gradually chilled to heights of 1 kilometer (0.6 mile) or more. The result is a strong and

TABLE 8-1 Weather characteristics of North American air masses

Air mass	Source region	Temperature and moisture characteristics in source region	Stability in source region	Associated weather
cA	Arctic basin and Greenland ice cap	Bitterly cold and very dry in winter	Stable	Cold waves in winter
cP	Interior Canada and Alaska	Very cold and dry in winter	Stable entire year	a. Cold waves in winter b. Modified to cPk in winter over Great Lakes bringing "lake-effect" snow to leeward shores
mP	North Pacific	Mild (cool) and humid entire year	Unstable in winter Stable in summer	a. Low clouds and showers in winter b. Heavy orographic precipitation on windward side of western mountains in winter
				c. Low stratus and fog along coast in summer; modified to cP inland
mP	Northwestern Atlantic	Cold and humid in winter Cool and humid in summer	Unstable in winter Stable in summer	a. Occasional "nor'easter" in winter b. Occasional periods of clear, cool weather in summer
cT	Northern interior Mexico and southwestern U.S. (summer only)	Hot and dry	Unstable	a. Hot, dry, and cloudless, rarely influencing areas outside source region b. Occasional drought to southern Great Plains
mT	Gulf of Mexico, Caribbean Sea, western Atlantic	Warm and humid entire year	Unstable entire year	a. In winter it usually becomes mTw moving northward and brings occasional widespread precipitation or advection fog b. In summer, hot and humid conditions, frequent cumulus development and showers or thunderstorms
mT	Subtropical Pacific	Warm and humid entire year	Stable entire year	a. In winter it brings fog, drizzle, and occasional moderate precipitation to N.W. Mexico and S.W. United States b. In summer this air mass occasionally reaches the western United States and is a source of moisture for infrequent convectional thunderstorms.

persistent temperature inversion with the coldest temperatures near the ground. Marked stability is, therefore, the rule. Because the air is very cold and the surface below is frozen, the mixing ratio of these air masses is necessarily low, ranging from perhaps 0.1 gram per kilogram in cA up to 1.5 grams per kilogram in some cP air.

As wintertime cP or cA air moves outward from its source region, it carries its cold, dry weather to the United States, normally entering between the Great Lakes and the Rockies. Because there are no major barriers between the high-latitude source regions and the Gulf of Mexico, cP and cA air masses can sweep rapidly and with relative ease far southward into the United States. The winter cold waves experienced in much of the central and eastern United States are closely associated with such polar outbreaks. One such cold wave is described in Box 8–1. Usually, the last freeze in spring and the first in autumn can be correlated with outbreaks of polar or arctic air.

Because cA air is present principally in the winter, only cP air has any influence on our summer weather, and this effect is considerably reduced when compared with winter. During summer months, the properties of the source region for cP air are very different from those during winter. Instead of being chilled by the ground, the air is warmed from below as the long days and higher Sun angle warm the snow-free land surface. Although summer cP air is warmer and has a higher moisture content than its wintertime counterpart, the air is still cool and relatively dry compared with areas farther south. Summer heat waves in the northern portions of the eastern and central United States are often ended by the southward advance of cP air, which for a day or two brings cooling relief and bright, pleasant weather.

Students Sometimes Ask…

When a cold air mass moves south from Canada into the United States, how rapidly can temperatures change?

When a fast-moving frigid air mass advances into the northern Great Plains, temperatures have been known to plunge 20° to 30°C (40°–50°F) in a matter of just a few hours. One notable example is a drop of 55.5°C (100°F), from 6.7°C to −48.8°C (44° to −56°F), in 24 hours at Browning, Montana, on January 23–24, 1916. Another remarkable example occurred on Christmas Eve, 1924, when the temperature at Fairfield, Montana, dropped from 17°C (63°F) at noon to −29°C (−21°F) at midnight—an amazing 46°C (83°F) change in just 12 hours.

Lake-Effect Snow: Cold Air over Warm Water

Continental polar air masses are not, as a rule, associated with heavy precipitation. Yet during late autumn and winter a unique and interesting weather phenomenon takes place along the downwind shores of the Great Lakes.* Periodically, brief, heavy snow showers issue from dark clouds that move onshore from the lakes (see Box 8–2). Seldom do these storms move more than about 80 kilometers (50 miles) inland from the shore before the snows come to an end. These highly localized storms, occurring along the leeward shores of the Great Lakes, create what are known as **lake-effect snows.**

Lake-effect storms account for a high percentage of the snowfall in many areas adjacent to the lakes. The strips of land that are most frequently affected, called *snowbelts,* are shown in Figure 8–5. A comparison of average snowfall totals at Thunder Bay, Ontario, on the north shore of Lake Superior, and Marquette, Michigan, along the southern shore, provides another excellent example. Because Marquette is situated on the leeward shore of the lake, it receives substantial lake-effect snow and therefore has a much higher snowfall total than does Thunder Bay (Table 8–2).

What causes lake-effect snow? The answer is closely linked to the differential heating of water and land (Chapter 3) and to the concept of atmospheric instability. During the summer months, bodies of water, including the Great Lakes, absorb huge quantities of energy from the Sun and from the warm air that passes over them. Although these water bodies do not reach particularly high temperatures, they nevertheless represent huge reservoirs of heat. The surrounding land, in contrast, cannot store heat nearly as effectively. Consequently, during autumn and winter, the temperature of the land drops quickly, whereas water bodies lose their heat more gradually and cool slowly.

From late November through late January the contrasts in average temperatures between water and land range from about 8°C in the southern Great Lakes to 17°C farther north. However, the temperature differences can be much greater (perhaps 25°C) when a very cold cP or cA air mass pushes southward across the lakes. When such a dramatic temperature contrast exists, the lakes interact with the air to produce major lake-effect storms. Figure 8–6 depicts the movement of a cP air mass across one of the Great Lakes. During its journey, the air acquires large quantities of heat and moisture from the relatively warm lake surface. By the time it reaches the opposite shore, this cPk air is humid and unstable and heavy snow showers are likely.

Students Sometimes Ask…

I know that Buffalo, New York, is famous for its lake-effect snows. Just how bad can it get?

Because of Buffalo's location along the eastern shore of Lake Erie, it does indeed receive a great deal of lake-effect snow (see Figure 8–5). One of the most memorable events took place between December 24, 2001, and January 1, 2002. This storm, which set a record as the longest-lasting lake-effect event, buried Buffalo with 207.3 centimeters (81.6 inches) of snow. Prior to this storm, the record for the *entire month* of December had been 173.7 centimeters (68.4 inches)! The eastern shore of Lake Ontario was also hard hit, with one station recording more than 317 centimeters (125 inches) of snow.

Maritime Polar (mP) Air Masses

Maritime polar air masses form over oceans at high latitudes. As the classification would indicate, mP air is cool to cold and humid, but compared with cP and cA air masses in winter, mP air is relatively mild because of the higher temperatures of the ocean surface as contrasted to the colder continents.

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*Actually, the Great Lakes are just the best-known example. Other large lakes can also experience this phenomenon.

BOX 8-1 The Siberian Express

The surface weather map for December 22, 1989, shows a high-pressure center covering the eastern two-thirds of the United States and a substantial portion of Canada (Figure 8–A). As is usually the case in winter, a large anticyclone such as this is associated with a huge mass of dense and bitterly cold arctic air. After

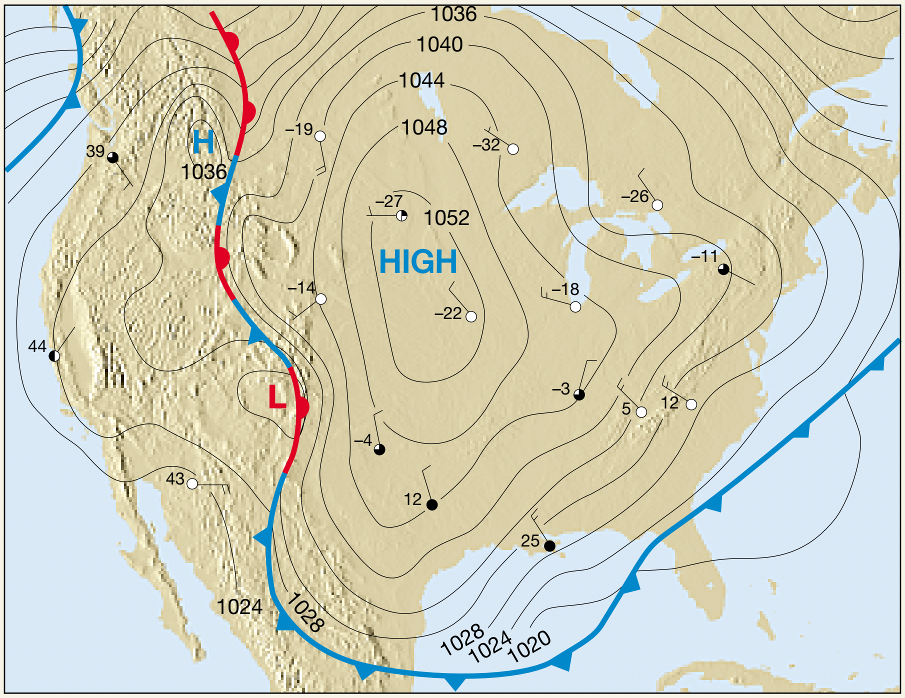
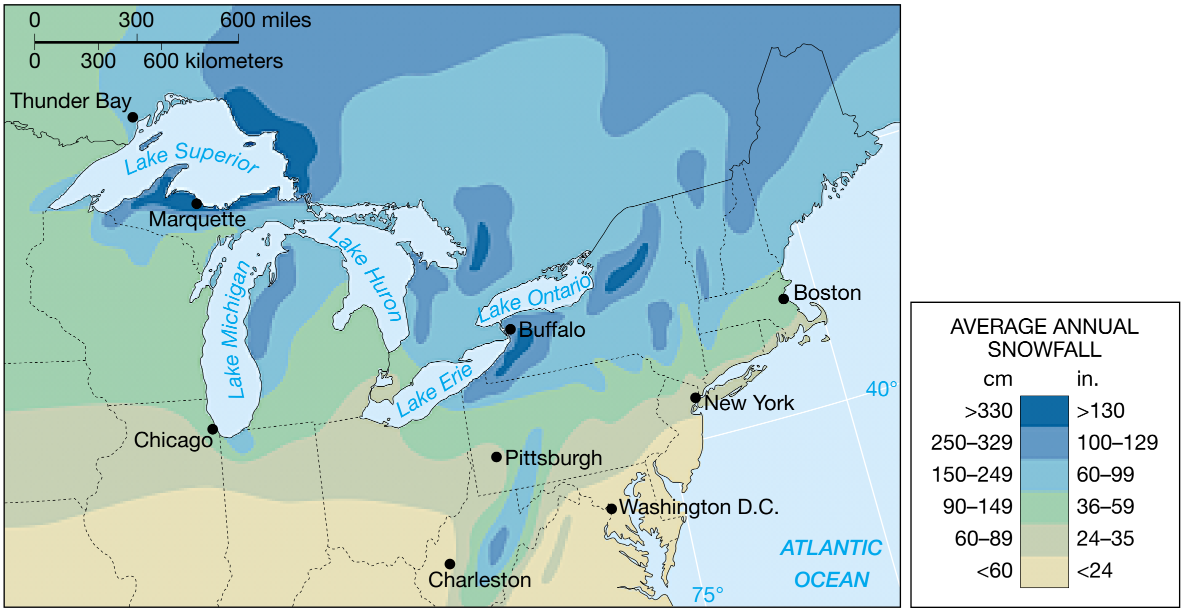


FIGURE 8-A A surface weather map for 7 A.M. EST, December 22, 1989. This simplified National Weather Service (NWS) map shows an intense winter cold wave caused by an outbreak of frigid continental arctic air. This event brought subfreezing temperatures as far south as the Gulf of Mexico. Temperatures on NWS maps are in degrees Fahrenheit.

FIGURE 8-5 The snowbelts of the Great Lakes region are easy to pick out on this snowfall map. *(Data from NOAA)*



such an air mass forms over the frozen expanses near the Arctic Circle, the winds aloft sometimes direct it toward the south and east. When an outbreak takes place, it is popularly called the "Siberian Express" by the news media.

November 1989 was unusually mild for late autumn. In fact, across the United States, over 200 daily high-temperature records were set. December, however, was different. East of the Rockies, the month's weather was dominated by two arctic outbreaks. The second brought record-breaking cold.

Between December 21–25, as the frigid dome of high pressure advanced southward and eastward, more than 370 record low temperatures were reported. On December 21, Havre, Montana, had an overnight low of −42.2°C (−44°F), breaking a record set in 1884. Meanwhile, Topeka's −32.2°C (−26°F) was that city's lowest temperature for any date since record keeping started 102 years earlier.

The three days that followed saw the arctic air migrate toward the south and east. By December 24, Tallahassee, Florida, had a low temperature of −10°C (14°F). In the center of the state the daily minimum at Orlando was −5.6°C (22°F). It was actually warmer in North Dakota on Christmas Eve than in central and northern Florida!

As we would expect, utility companies in many states reported record demand. When the arctic air advanced into Texas and Florida, agriculture was especially hard hit. Some Florida citrus growers lost 40 percent of their crop, and many vegetable crops were wiped out completely (Figure 8–B).

After Christmas the circulation pattern that brought this record-breaking Siberian Express from the arctic deep into the United States changed. As a result, temperatures for much of the country during January and February 1990 were well above normal. In fact, January 1990 was the second warmest January in 96 years. Thus, despite frigid December temperatures, the winter of 1989–1990 "averaged out" to be a relatively warm one.

FIGURE 8-B When an arctic air mass invades the citrus regions of Florida and Texas, even modern freeze controls may not be able to prevent significant losses. *(Photo courtesy of Florida Department of Citrus)*

Two regions are important sources for mP air that influences North America: the North Pacific and the northwestern Atlantic from Newfoundland to Cape Cod (Figure 8–3). Because of the general west-to-east circulation in the middle latitudes, mP air masses from the North Pacific source region have a more profound influence on North American weather than do mP air masses generated in the northwestern Atlantic. Whereas air masses that form in the Atlantic generally move eastward toward Europe, mP air from the

FIGURE 8-6 (a) As continental polar air crosses the Great Lakes in winter, it acquires moisture and is made unstable because of warming from below. A "lake-effect" snow shower on the lee side of the lakes is often the consequence of this air-mass modification. (b) This satellite image from December 27, 2001, shows thick bands of clouds extending from the eastern tip of Lake Erie to east of Buffalo. Thick cloud bands also extend from the eastern margin of Lake Huron over southern Ontario. The arrows show the wind direction, which was blowing across the length of the lake. *(Image courtesy of NASA GOES Project Science Office)*

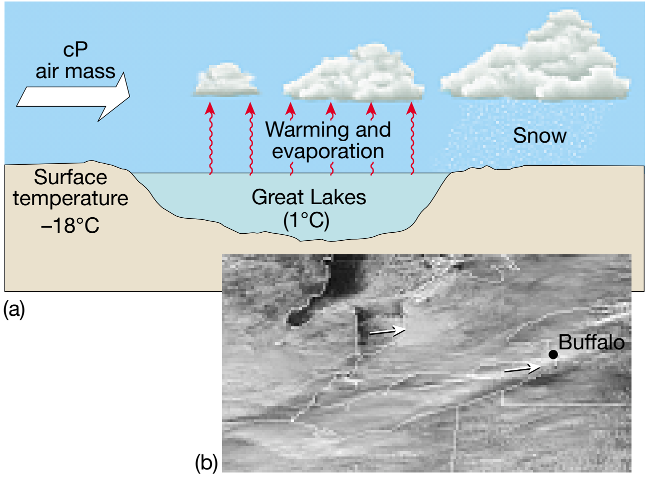


TABLE 8-2 Monthly snowfall at Thunder Bay, Ontario, and Marquette, Michigan

Thunder Bay, Ontario			
October	November	December	January
3.0 cm	14.9 cm	19.0 cm	22.6 cm
(1.2 in.)	(5.8 in.)	(7.4 in.)	(8.8 in.)
Marquette, Michigan			
October	November	December	January
5.3 cm	37.6 cm	56.4 cm	53.1 cm
(2.1 in.)	(14.7 in.)	(22 in.)	(20.7 in.)

BOX 8-2 Atmospheric Hazard: An Extraordinary Lake-Effect Snowstorm

Northeastern Ohio is part of the Lake Erie snowbelt, a zone that extends eastward into northwestern Pennsylvania and western New York (see Figure 8–5). Here snowfall is enhanced when cold winds blow from the west or northwest across the relatively warm unfrozen waters of Lake Erie. Average annual snowfall in northeastern Ohio is between 200 and 280 centimeters (80 to 110 inches) and increases to 450 centimeters (175 inches) in western New York.

Although residents here are accustomed to abundant snows, even they were surprised in November 1996 by an especially early and strong storm. During a six-day span, from November 9–14, northeastern Ohio experienced record-breaking lake-effect snows. Rather than raking fall leaves, people were shoveling sidewalks and clearing snow from overloaded roofs (Figure 8–C).

Persistent snow squalls (narrow bands of heavy snow) frequently produced accumulation rates of 5 centimeters (2 inches) per hour during the six-day siege. The snow was the result of especially deep and prolonged lower atmospheric instability created by the movement of cold air

FIGURE 8-C A six-day lake-effect snowstorm in November 1996 dropped 175 centimeters (nearly 69 inches) of snow on Chardon, Ohio, setting a new state record. *(Photo by Tony Dejak/AP/Wide World Photos)*

North Pacific has a strong influence on the weather along the western coast of North America, especially in the winter.

Pacific mP Air Masses. During the winter, mP air masses from the Pacific usually begin as cP air in Siberia (Figure 8–7). Although air rarely stagnates over this area, the source region is extensive enough to allow the air moving across it to acquire its characteristic properties. As the air advances eastward over the relatively warm water, active evaporation and heating occur in the lower levels. Consequently, what was once a very cold, dry, and stable air mass is changed into one that is mild and humid near the surface and relatively unstable. As this mP air arrives at the western coast of North America, it is often accompanied by low clouds and shower activity. When the mP air advances inland against the western mountains, orographic uplift produces heavy rain or snow on the windward slopes of the mountains (see Figure 15–12).

Maritime Polar Air from the North Atlantic. As is the case for mP air from the Pacific, air masses forming in the northwestern Atlantic source region were originally cP air masses that moved from the continent and were transformed over the ocean. However, unlike air masses from the North Pacific, mP air from the Atlantic only occasionally affects the weather of North America. Nevertheless, across a relatively warm Lake Erie. The surface temperature of the lake was 12°C (54°F), several degrees above normal. The air temperature at a height of 1.5 kilometers (nearly 5000 feet) was −5°C (23°F).

The northwest flow of cold air across Lake Erie and the 17°C lapse rate generated lake-effect rain and snow almost immediately.* During some periods loud thunder accompanied the snow squalls!

Data from the Cleveland National Weather Service Snow Spotters Network show 100 to 125 centimeters (39 to 49 inches) of snow through the core of the Ohio snowbelt (Figure 8–D). The deepest accumulation was measured near Chardon, Ohio. Here the six-day total of 175 centimeters (68.9 inches) far exceeded the previous Ohio record of 107 centimeters (42 inches) set in 1901. In addition, the November 1996 snowfall total of 194.8 centimeters (76.7 inches) at the same site set a new monthly snowfall record for Ohio. The previous one-month record had been 176.5 centimeters (69.5 inches).

The impact of the storm was considerable. Ohio's governor declared a state of emergency on November 12, and National Guard troops were dispatched to assist in snow removal and aid in the rescue of snowbound residents. There was widespread damage to trees and shrubs across northeastern Ohio because the snow was particularly wet and dense and readily clung to objects. Press reports indicated that about 168,000 homes were without electricity, some for several days. Roofs of numerous buildings collapsed under the excessive snow loads. Although residents of the northeast Ohio snowbelt are winter storm veterans, the six-day storm in November 1996 will be long remembered as an extraordinary event.

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*Thomas W. Schmidlin and James Kasarik, "A Record Ohio Snowfall during 9–14 November 1996," *Bulletin of the American Meteorological Society*, Vol. 80, No. 6, June 1999, p. 1109.

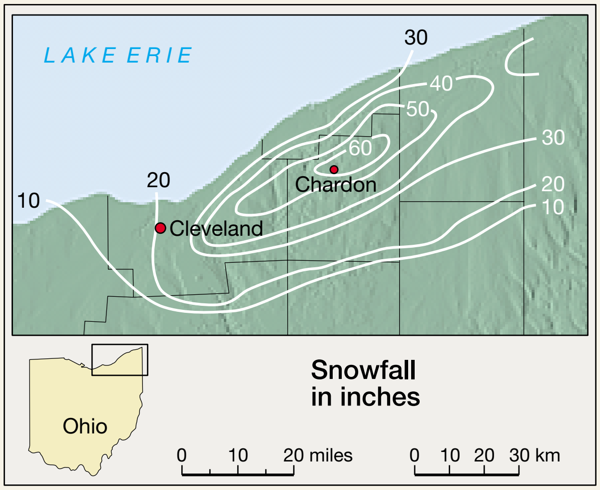
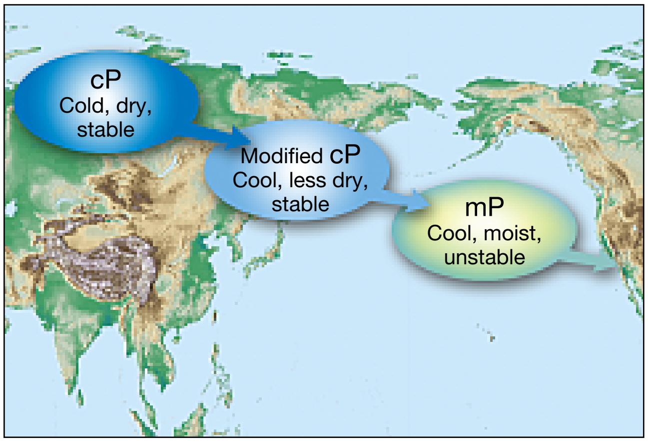


FIGURE 8-D Snowfall totals (in inches) for northeastern Ohio for the November 9–14, 1996, lake-effect storm. The deepest accumulation, nearly 69 inches (175 centimeters), occurred near Chardon. *(After National Weather Service)*

this air mass does have an effect when the northeastern United States is on the northern or northwestern edge of a passing low-pressure center. On these occasions, cyclonic winds draw mP air into the region. Its influence is generally confined to the area east of the Appalachians and north of Cape Hatteras, North Carolina. The weather associated with an invasion of mP air from the Atlantic is known locally as a **nor'easter.** Strong northeast winds, freezing or near freezing temperatures, high relative humidity, and the likelihood of precipitation make this weather phenomenon an unwelcome event.

Summer brings a change in the characteristics of mP air masses from the North Pacific. During the warm season, the

FIGURE 8-7 During winter, maritime polar (mP) air masses in the North Pacific usually begin as continental polar (cP) air masses in Siberia. The cP air is modified to mP as it slowly crosses the ocean.



ocean is cooler than the surrounding continents. In addition, the Pacific high lies off the western coast of the United States (see Figure 7–10). Consequently, there is almost continuous southward flow of air having moderate temperatures. Although the air near the surface may often be conditionally unstable, the presence of the Pacific high means that there is subsidence and stability aloft. Thus, low stratus clouds and summer fogs characterize much of the western coast. Once summer mP air from the Pacific moves inland, it is heated at the surface over the hot and dry interior. The heating and resulting turbulence act to reduce the relative humidity in the lower layers, and the clouds dissipate.

Although mP air masses from the Atlantic may produce an occasional unwelcome nor'easter during the winter, summertime incursions of this air mass often bring pleasant weather. Like the Pacific source region, the northwestern Atlantic is dominated by high pressure during the summer (see Figure 7–10). Thus, the upper air is stable because of subsidence and the lower air is essentially stable because of the chilling effect of the relatively cool water. As the circulation on the southern side of the anticyclone carries this stable and relatively dry mP air into New England, and occasionally as far south as Virginia, the region enjoys clear, cool weather and good visibility.

Students Sometimes Ask…

I once heard a weather report refer to some storms in California as being associated with the "Pineapple Express." What were they talking about?

Much of the precipitation along the western margin of North America occurs in winter when unstable mP air originating in the vicinity of the Gulf of Alaska is drawn into a cyclonic system and/or lifted orographically. Occasionally, however, storms approach the West Coast from the subtropical Pacific in the vicinity of the Hawaiian Islands. Because these storms advance from the direction of Hawaii, they are sometimes called the "Pineapple Express." These systems, with their associated mT air, sometimes yield torrential flood-producing rains.

Maritime Tropical (mT) Air Masses

Maritime tropical air masses affecting North America most often originate over the warm waters of the Gulf of Mexico, the Caribbean Sea, or the adjacent western Atlantic Ocean (Figure 8–3). The tropical Pacific is also a source region for mT air. However, the land area affected by this latter source is small compared with the size of the region influenced by air masses produced in the Gulf of Mexico and adjacent waters.

As expected, mT air masses are warm to hot, and they are humid. In addition, they are often unstable. It is through invasions of mT air masses that the subtropics export much heat and moisture to the cooler and drier areas to the north. Consequently, these air masses are important to the weather whenever present because they are capable of contributing significant precipitation.

North Atlantic mT Air. Maritime tropical air masses from the Gulf–Caribbean–Atlantic source region greatly affect the weather of the United States east of the Rocky Mountains. Although the source region is dominated by the North Atlantic subtropical high, the air masses produced are not stable but are neutral or unstable because the source region is located on the weak western edge of the anticyclone where pronounced subsidence is absent.

During winter, when cP air dominates the central and eastern United States, mT air only occasionally enters this part of the country. When an invasion does occur, the lower portions of the air mass are chilled and stabilized as it moves northward. Its classification is changed to mTw. As a result, the formation of convective showers is unlikely. Widespread precipitation does occur, however, when a northward-moving mT air mass is pulled into a traveling cyclone and forced to ascend. In fact, much of the wintertime precipitation over the eastern and central states results when mT air from the Gulf of Mexico is lifted along fronts in traveling cyclones.

Another weather phenomenon associated with a northward-moving wintertime mT air mass is advection fog. Dense fogs can develop as the warm, humid air is chilled as it moves over the cold land surface.

During the summer, mT air masses from the Gulf, Caribbean, and adjacent Atlantic affect a much wider area of North America and are present for a greater percentage of the time than during the winter. As a result, they exert a strong and often dominating influence over the summer weather of the United States east of the Rocky Mountains. This influence is due to the general sea-to-land (monsoonal) airflow over the eastern portion of North America during the warm months, which brings more frequent incursions of mT air that penetrate much deeper into the continent than during the winter months. Consequently, these air masses are largely responsible for the hot and humid conditions that prevail over the eastern and central United States.

Initially, summertime mT air from the Gulf is unstable. As it moves inland over the warmer land, it becomes an mTk air mass as daytime heating of the surface layers further increases the air's instability. Because the relative humidity is high, only modest lifting is necessary to bring about active convection, cumulus development, and thunderstorm or shower activity (Figure 8–8). This is, indeed, a common warm-weather phenomenon associated with mT air.

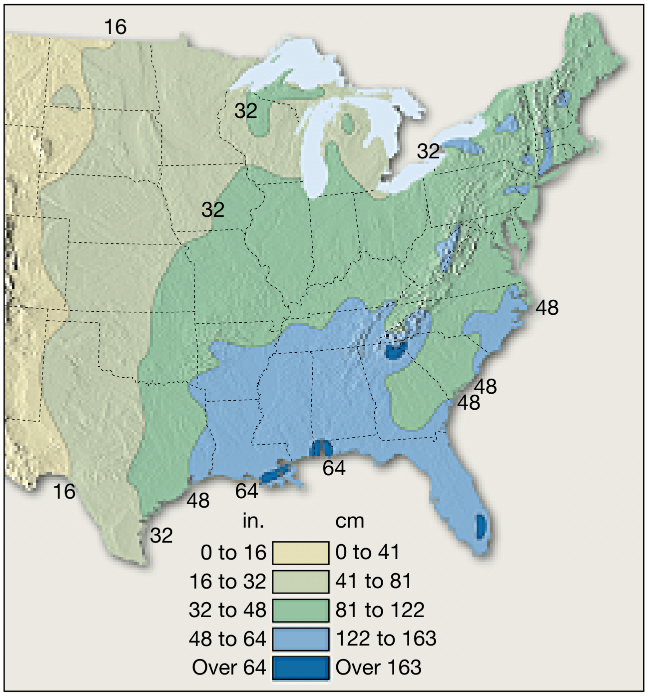
It should be also noted here that air masses from the Gulf–Caribbean–Atlantic region are the primary source of much, if not most, of the precipitation received in the eastern two-thirds of the United States. Pacific air masses con-

FIGURE 8-8 As mT air from the Gulf of Mexico moves over the heated land in the summer, cumulus development and afternoon showers frequently result. *(Photo by Rod Planck/Photo Researchers, Inc.)*

tribute little to the water supply east of the Rockies because the western mountains effectively "drain" the moisture from the air by numerous episodes of orographic uplift.

Figure 8–9, which shows the distribution of average annual precipitation for the eastern two-thirds of the United States by using **isohyets** (lines connecting places having equal rainfall), illustrates this situation nicely. The pattern of isohyets shows the greatest rainfall in the Gulf region and a decrease in precipitation with increasing distance from the mT source region.

FIGURE 8-9 Average annual precipitation for the eastern two-thirds of the United States. Note the general decrease in yearly precipitation totals with increasing distance from the Gulf of Mexico, the source region for mT air masses. Isohyets are labeled in inches. *(Courtesy of Environmental Data Service, NOAA)*



North Pacific mT Air. Compared to mT air from the Gulf of Mexico, mT air masses from the Pacific source region have much less of an impact on North American weather. In winter, only northwestern Mexico and the extreme southwestern United States are influenced by air from the tropical Pacific. Because the source region lies along the eastern side of the Pacific anticyclone, subsidence aloft produces upper-level stability. When the air mass moves northward, cooling at the surface also causes the lower layers to become more stable, often resulting in fog or drizzle. If lifted along a front or forced over mountains, moderate precipitation results.

For many years the summertime influence of air masses from the tropical Pacific source region on the weather of the southwestern United States and northern Mexico was believed to be minimal. It was thought that the moisture for the infrequent summer thunderstorms that occur in the region came from occasional westward thrusts of mT air from the Gulf of Mexico. However, the Gulf of Mexico is no longer believed to be the primary supplier of moisture for the area west of the Continental Divide. Rather, it has been demonstrated that the tropical North Pacific west of central Mexico is a more important source of moisture for this area.

In summer the mT air moves northward from its Pacific source region up the Gulf of California and into the interior of the western United States. This movement, which is confined largely to July and August, is essentially monsoonal in character. That is, the inflow of moist air is a response to the thermally produced low pressure that develops over the heated landmass. The July–August rainfall maximum for Tucson is a response to this incursion of Pacific mT air (Figure 8–10).

Continental Tropical (cT) Air Masses

North America narrows as it extends southward through Mexico; therefore, the continent has no extensive source region for continental tropical air masses. By checking the maps in Figure 8–3, you can see that only in summer do northern interior Mexico and adjacent parts of the arid

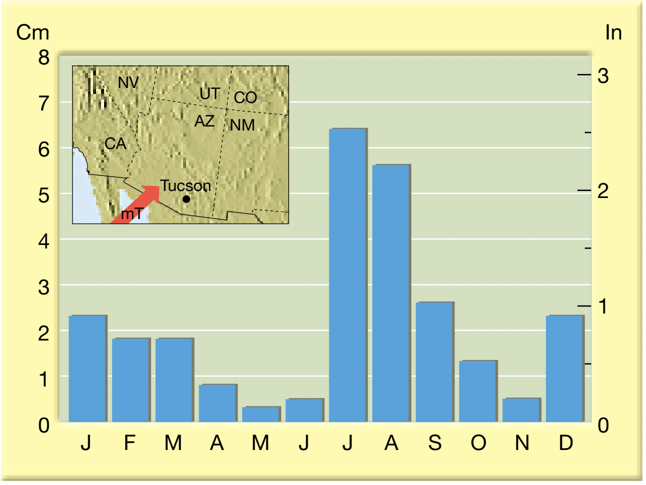


FIGURE 8-10 Monthly precipitation data for Tucson, Arizona. The July–August rainfall maximum in the desert Southwest results from the monsoonal flow of Pacific mT air into the region.

southwestern United States produce hot, dry cT air. Because of the intense daytime heating at the surface, both a steep environmental lapse rate and turbulence extending to considerable heights are found. Nevertheless, although the air is unstable, it generally remains nearly cloudless because of extremely low humidity. Consequently, the prevailing weather is hot, with an almost complete lack of rainfall. Large daily temperature ranges are the rule. Although cT air masses are usually confined to the source region, occasionally they move into the southern Great Plains. If the cT air persists for long, drought may occur.

Chapter Summary

- In the middle latitudes many weather events are associated with the movements of air masses. An *air mass* is a large body of air, usually 1600 kilometers (1000 miles) or more across and perhaps several kilometers thick, that is characterized by homogeneous physical properties (in particular temperature and moisture content) at any given altitude. A region under the influence of an air mass will probably experience generally constant weather conditions, a situation referred to as *air-mass weather.*
- Areas in which air masses originate are called *source regions*. An ideal source region must meet two criteria. First, it must be an extensive and physically uniform area. The second criterion is that the area is characterized by a general stagnation of atmospheric circulation so that air will stay over the region long enough to come to some measure of equilibrium with the surface.
- The classification of an air mass depends on (1) the latitude of the source region, and (2) the nature of the surface in the area of origin—ocean or continent. Air masses are identified by two-letter codes. With reference to latitude (temperature), air masses are placed into one of three categories: *polar (P), arctic (A),* or *tropical (T).* A lowercase letter (*m,* for *maritime,* or *c* for *continental*) is placed in front of the uppercase letter to designate the nature of the surface in the source region and therefore the humidity characteristics of the air mass. Using this classification scheme, the following air masses are identified: cA, cP, cT, mT, and mP.
- Once an air mass moves from its source region, it not only modifies the weather of the area it is traversing, but it is also gradually modified by the surface over which it is moving. Changes to the stability of an air mass can result from temperature differences between an air mass and the surface and/or vertical movements induced by cyclones, anticyclones or topography.
- The day-to-day weather we experience depends on the temperature, stability, and moisture content of the air mass we are experiencing. *Continental polar* (cP) and *continental arctic* (cA) air masses are, as their classification implies, cold and dry. Although cP air masses are not, as a rule, associated with heavy precipitation, those that cross the Great Lakes during late autumn and winter sometimes bring *lake-effect snows* to the leeward shores. *Maritime polar* air masses (mP) form over oceans at high latitudes and are cool to cold and humid. The stormy winter weather associated with an invasion of mP air from the Atlantic into an area east of the Appalachians and north of Cape Hatteras is known as a *nor'easter. Maritime tropical* (mT) air masses affecting North America most often originate over the warm water of the Gulf of Mexico, the Caribbean Sea, or the adjacent western Atlantic Ocean. As expected, mT air masses are warm to

hot, and they are humid. During winter, when cP air dominates the central and eastern United States, mT air only occasionally enters this part of the country. However, during the summer, mT air masses from the Gulf, Caribbean, and adjacent Atlantic are more common and cover a much wider area of the continent. The mT air masses from the Gulf–Caribbean–Atlantic source region are also the source of much, if not most, of the precipitation received in the eastern two-thirds of the United States. *Isohyets,* lines of equal rainfall drawn on a map, show that the greatest rainfall occurs in the Gulf region and decreases with increasing distance from the mT source region. Hot and dry *continental tropical* (cT) air is produced only in the summer in northern interior Mexico and adjacent parts of the arid southwestern United States.

Vocabulary Review

air mass (p. 234)
air-mass weather (p. 324)
arctic (A) air mass (p. 326)
continental (c) air mass (p. 326)
isohyet (p. 245)
lake-effect snow (p. 239)
maritime (m) air mass (p. 236)
nor'easter (p. 242)
polar (P) air mass (236)
source region (p. 235)
tropical (T) air mass (p. 236)

Review Questions

1. Define the terms *air mass* and *air-mass weather.*
2. What two criteria must be met for an area to be an air-mass source region?
3. Why are regions that have a cyclonic circulation generally not conducive to air-mass formation?
4. On what bases are air masses classified? Compare the temperature and moisture characteristics of the following air masses: cP, mP, mT, and cT.
5. Why is mA left out of the air-mass classification scheme?
6. What do the lowercase letters *k* and *w* indicate about an air mass? List the general weather conditions associated with *k* and *w* air masses.
7. During winter, polar air masses are cold. Which should be coldest, a wintertime mP air mass or a wintertime cP air mass? Explain your choice.
8. How might vertical movements induced by a pressure system or topography act to modify an air mass?
9. What two air masses are most important to the weather of the United States east of the Rocky Mountains? Explain your choice.
10. What air mass influences the weather of the Pacific Coast more than any other?
11. Why do cA and cP air masses often sweep so far south into the United States?
12. Describe the modifications that occur as a cP air mass moves across one of the Great Lakes in the winter.
13. Why do mP air masses from the North Atlantic source region seldom affect the eastern United States?
14. What air mass and source region provide the greatest amount of moisture to the eastern and central United States?
15. For each statement below, indicate which air mass is most likely involved and from what source region it came:
    - **a.** summer drought in the southern Great Plains
    - **b.** wintertime advection fog in the Midwest
    - **c.** heavy winter precipitation in the western mountains
    - **d.** summertime convectional showers in the Midwest and East
    - **e.** a nor'easter

Problems

1. Figure 8–11 shows the distribution of air temperatures (top number) and dew-point temperatures (lower number) for a December morning. Two well-developed air masses are influencing North America at this time. The air masses are separated by a broad zone that is not affected by either air mass. Draw lines on the map that show the boundaries of each air mass. Label each air mass with the proper classification.
2. The Great Lakes are not the only water bodies associated with lake-effect snow. For example, large lakes in Canada also experience this phenomenon. Shown here are snowfall data (in centimeters) for two Canadian stations that receive significant lake-effect snow. Fort Resolution is on the southeastern shore of Great Slave Lake, and Norway House is at the northern end of Lake Winnipeg. During what month does each station have its snowfall maximum? Suggest an explanation as to why the maximum occurs when it does.

	Sept.	**Oct.**	**Nov.**	**Dec.**	**Jan.**
Fort Resolution	2.5	13.7	36.6	19.6	15.4
Norway House	3.8	6.9	29.5	20.1	16.3

3. Refer to Figure 8–5. Notice the narrow, north–south-oriented zone of relatively heavy snowfall east of Pittsburgh and Charleston. This region is too far from the Great Lakes to receive lake-effect snows. Speculate on a likely reason for the higher snowfalls here. Does your explanation explain the shape of this snowy zone?
4. Albuquerque, New Mexico, is situated in the desert Southwest. Its annual precipitation is just 21.2 centimeters (8.3 inches). Month-by-month data (in centimeters) are as follows:

J	F	M	A	M	J	J	A	S	O	N	D
1.0	1.0	1.3	1.3	1.3	1.3	3.3	3.8	2.3	2.3	1.0	1.3

What are the two rainiest months? The pattern here is similar to other southwestern cities, including Tuscon, Arizona. Briefly explain why the rainiest months occur when they do.

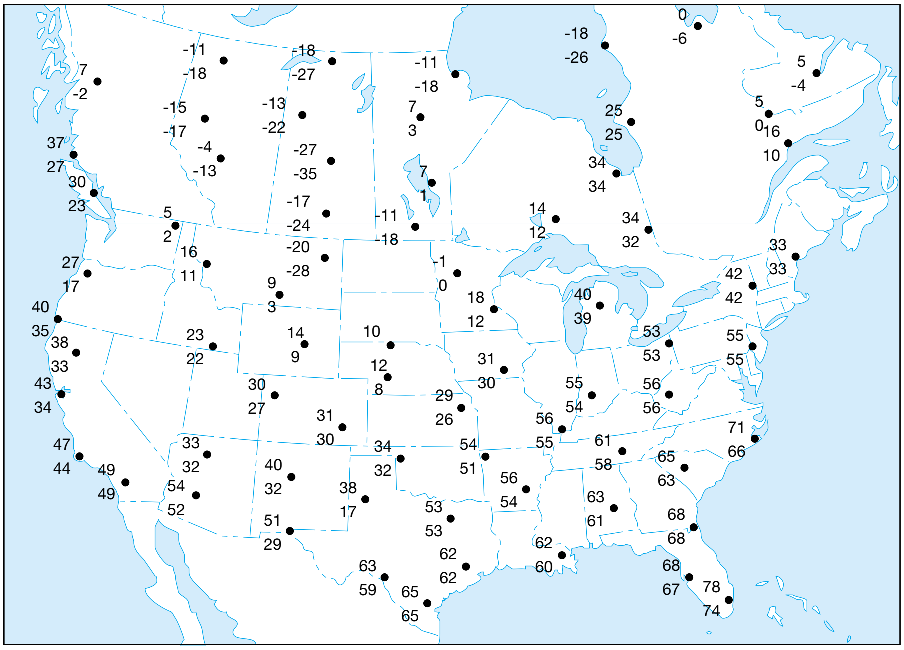


FIGURE 8-11 Map to accompany Problem 1.

Atmospheric Science Online

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