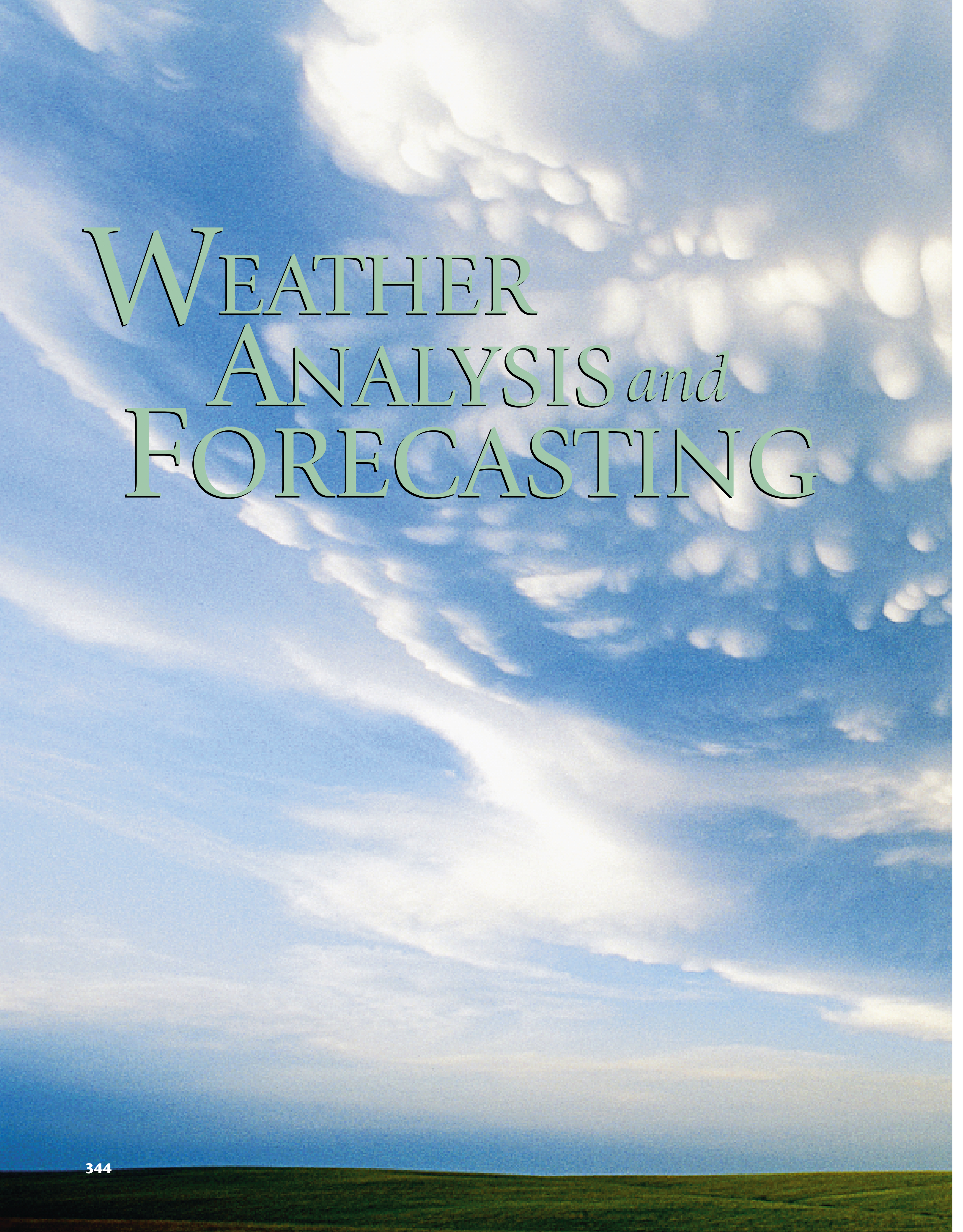
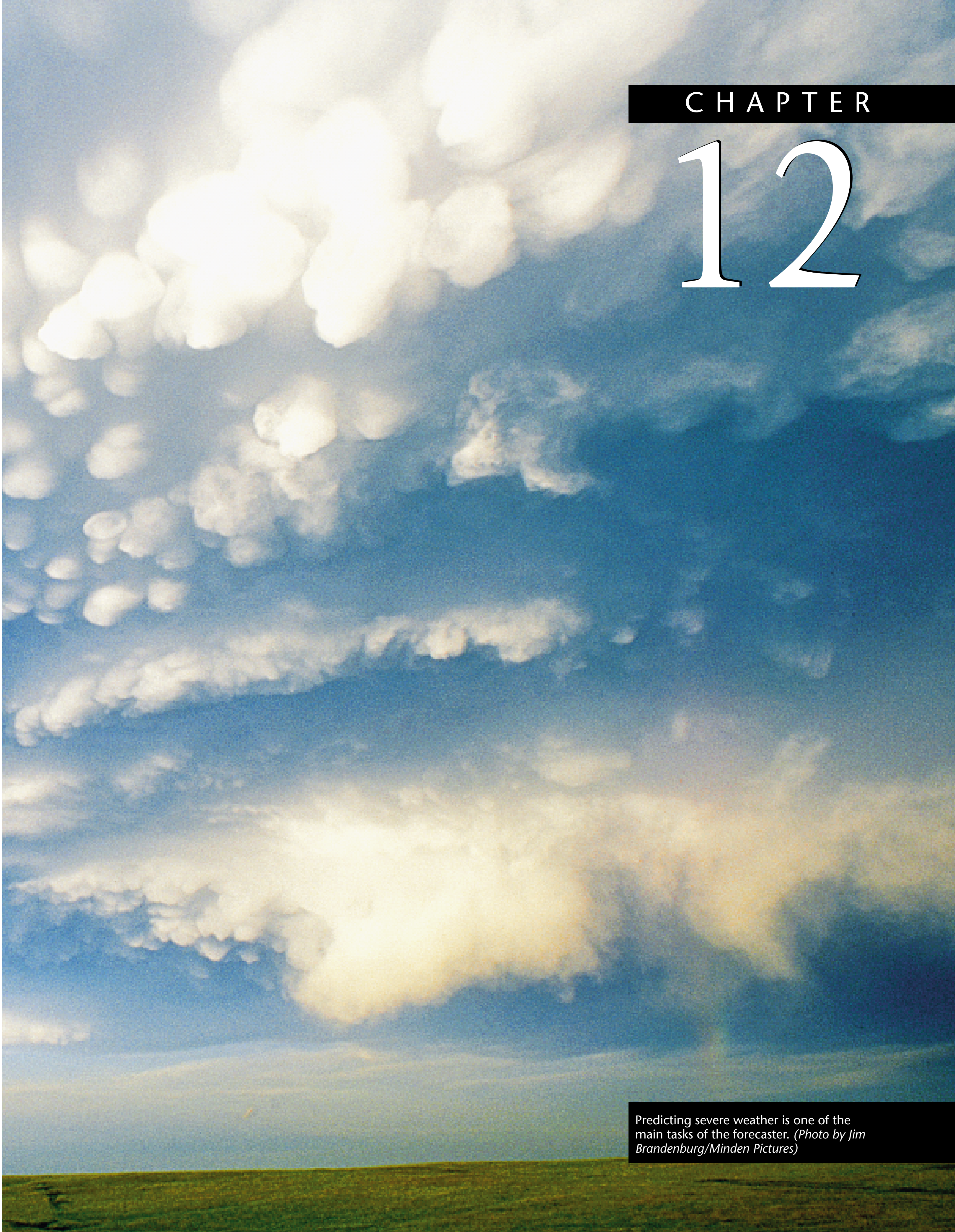
WEATHER ANALYSIS and FORECASTING



CHAPTER

12



Predicting severe weather is one of the main tasks of the forecaster. *(Photo by Jim Brandenburg/Minden Pictures)*

Each year modern society demands more accurate weather forecasts. The desire for sound weather predictions ranges from wanting to know if the weekend's weather will permit a beach outing to NASA's need to evaluate conditions on a space shuttle launch date (Figure 12–1). Such diverse industries as airlines and fruit growers depend heavily on accurate weather forecasts. In addition, the designs of buildings, oil platforms, and many industrial facilities rely on a sound knowledge of the atmosphere in its most extreme forms, including thunderstorms, tornadoes, and hurricanes. We are no longer satisfied with short-range predictions, but instead demand accurate long-range predictions. Such a question as "Will the Northeast experience an unseasonably cold winter?" has become common.

What is a weather forcast? Simply, a **weather forecast** is a scientific estimate of the weather conditions at some future time. Forecasts are usually expressed in terms of the most significant weather variables, which include temperature, cloudiness, humidity, precipitation, wind speed, and wind direction. As the following quote illustrates, weather forecasting is a formidable task.

> Imagine a system on a rotating sphere that is 8000 miles wide, consists of different materials, different gases that have different properties (one of the most important of which, water, exists in different concentrations), heated by a nuclear reactor 93 million miles away. Then, just to make life interesting, this sphere is oriented such that, as it revolves around the nuclear reactor, it is heated differently at different times of the year. Then, someone is asked to watch the mixture of gases, a fluid only 20 miles deep, that covers an area of 250 million square miles, and to predict the state of the fluid at one point on the sphere 2 days from now. This is the problem weather forecasters face.*

The Weather Business: A Brief Overview

In the United States the governmental agency responsible for gathering and disseminating weather-related information is the **National Weather Service (NWS),** a branch of the *National Oceanic and Atmospheric Administration* (*NOAA*). The mission of the NWS is as follows:

> The National Weather Service (NWS) provides weather, hydrologic and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure that can be used by other governmental agencies, the private sector, the public and the global community.

*Robert T. Ryan, "The Weather Is Changing . . . or Meteorologists and Broadcasters, the Twain Meet, " *Bulletin of the American Meteorological Society,* 63, no. 3 (March 1982), 308.

FIGURE 12-1 Fog can be a significant airport hazard. (*AP Photo/Natcha Pisarenko*)

Perhaps the most important services provided by the NWS are forecasts and warnings of hazardous weather including thunderstorms, flooding, hurricanes, tornadoes, winter weather, and extreme heat. According to the Federal Emergency Management Agency, 80 percent of all declared emergencies are weather related (see Box 12–1). In a similar vein, the Department of Transportation reports that more than 6000 fatalities per year can be attributed to the weather. Heat waves claim approximately 1000 lives annually in the United States. Further, 2005 was the most costly hurricane season on record. Major storms, which included Katrina, Rita, and Wilma, inflicted hundreds of billions of dollars worth of damage and killed an estimated 1300 people along the Gulf and Atlantic coasts

As global population increases, the economic impact of weather-related phenomena also escalates. During the years 1986 through 1995, for example, property damage in the United States due to wind, hail, snow, and tornadoes increased by 500 percent. As a result, the NWS is under greater pressure to provide more accurate and longer-range forecasts.

To produce even a short-range forecast is an enormous task. It involves complicated and detailed procedures, including collecting weather data, transmitting it, and compiling it on a global scale. These data must then be analyzed so that an accurate assessment of the current conditions can be made. In the United States, weather information from around the world is collected by the **National Centers for Environmental Prediction,** located in Camp Springs, Maryland, near Washington, D.C. This branch of the National Weather Service prepares weather maps, charts, and forecasts on a global and national scale. These forecasts are disseminated to regional **Weather Forecast Offices,** where they are used to produce local and regional weather forecasts.

The final phase in the weather business is the disseminatin of a wide variety of forecasts. Each of the 119 Weather Forecast Offices regularly issues regional and local forecasts, aviation forecasts, and warnings covering their forecast area. The *local forecast* seen on The Weather Channel or your local TV station is derived from a forecast issued by one of the offices operated by the NWS. Further, all the data and products (maps, charts, and forecasts) provided by the NWS are available at no cost to the general public and to private forecasting services such as AccuWeather and WeatherData (Figure 12–2).

The demand for highly visual forecasts containing computer-generated graphics has grown along with the use of personal computers and the Internet. Because it is outside the mission of the National Weather Service, this publicly funded entity is not the source of the animated depictions of the weather that appear on most local newscasts. Instead, the private sector has taken over this task. In addition, private forecast services customize the NWS products to create a variety of specialized weather reports that are tailored for specific audiences. In a farming community, for example, the weather reports might include frost warnings, while winter forecasts in Denver, Colorado, include the snow conditions at ski resorts.

FIGURE 12-2 Weather broadcaster previewing graphics. *(Photo by Bob Daemmrich/Stock Boston)*

It is important to note that despite the valuable role that the private sector plays in disseminating weather-related information to the public, the NWS is the *official* voice in the United States for issuing warnings during life-threatening weather situations. Two major weather centers operated by the NWS serve critical functions in this regard. The Storm Prediction Center in Norman, Oklahoma, maintains a constant vigil for severe thunderstorms and tornadoes (see Chapter 10). Hurricane watches and warnings for the Atlantic, Caribbean, Gulf of Mexico, and eastern Pacific are issued by the National Hurricane Center/Tropical Prediction Center in Miami, Florida (see Chapter 11).

In summary, the process of providing weather forecasts and warnings throughout the United States occurs in three stages. First, to provide a picture of the current state of the atmosphere, data are collected and analyzed on a global scale. Second, the NWS employs a variety of techniques to establish the future state of the atmosphere; a process called *weather forecasting.* Third, forecasts are disseminated to the public, mainly through the private sector. The National Weather Service serves as the sole entity responsible for issuing watches and warnings of extreme weather events.

Weather Analysis

GEODe ATMOSPHERE **Introduction to the Atmosphere**

▶ In the Lab: Reading Weather Maps

Before weather can be predicted, the forecaster must have an accurate picture of current atmospheric conditions. This enormous task, called **weather analysis,** involves collecting,

BOX 12-1 Atmospheric Hazard: Debris Flows in the San Francisco Bay Region*

When prolonged, intense rain falls on steep hillsides, the saturated soils can become unstable and move rapidly downslope (see Figure 1–1c, p. 2). Such land movements, called *debris flows,* are capable of destroying homes, washing out roads and bridges, knocking down trees, and obstructing streams and roadways with thick deposits of mud and rocks (Figure 12–A). An especially destructive event occurred in 1982 when thousands of debris flows caused nearly $70 million in damages and took 25 lives. Since then, several serious but less severe events have occurred. As more and more people build in the hills around the Bay region, the potential impact of debris flows on life and property is increasing.

FIGURE 12-A On January 25, 1997, a debris flow literally buried this one-story home in Mill Valley, California. Heavy rains from a powerful Pacific storm triggered the event. *(Justin Sullivan/AP Wide World Photos)*

transmitting, and compiling millions of pieces of observational data. Because the atmosphere is ever changing, this job must be accomplished quickly. High-speed supercomputers have greatly aided the weather analyst.

Gathering Data

A vast network of weather stations is required to provide enough data for a weather chart that is useful for generating even short-range forecasts. On a global scale the **World Meteorological Organization (WMO),** an agency of the United Nations, is responsible for the international exchange of weather data. Included in this task is the oversight of observational procedures to insure the comparability of data coming from the more than 185 participating nations and territories.

Surface Observations. Worldwide, over 10,000 observation stations on land, 7000 ships at sea, and hundreds of data buoys and oil platforms report atmospheric conditions four times each day at 0000, 6000, 1200, and 1800 Greenwich Mean Time (Figure 12–3). These data are rapidly sent around the globe using a telecommunications system dedicated to weather information.

In the United States, 119 Weather Forecast Offices, in addition to their role as regional forecast centers, are responsible for gathering and transmitting weather information to a central database. The Federal Aviation Administration (FAA), in cooperation with the NWS, also operates observation stations at most metropolitan airports. Together, the NWS and the FAA operate nearly 900 **Automated Surface Observing Systems (ASOS).** These automated systems provide weather observations that include temperature, dew point, wind, visibility, sky conditions, and can even detect present weather such as rain or snow (Figure 12–4). Automation often assists or, in some cases, replaces human observers because it can provide information from inhospitable and remote areas.

Observations Aloft Because the atmosphere is three dimensional, upper-air observations are essential (see Figure 1–8, p. 9). Worldwide, nearly 900 balloon-borne instrument packages, called *radiosondes,* are launched twice daily at 0000 and 1200 Greenwich Mean Time (6:00 PM and 6:00 AM Central Standard Time). Most of the upper-air observation stations are located in the Northern Hemisphere, with 92 stations operated by the National Weather Service.

A radiosonde is a light instrument package containing sensors that measure temperature, humidity, and pressure as

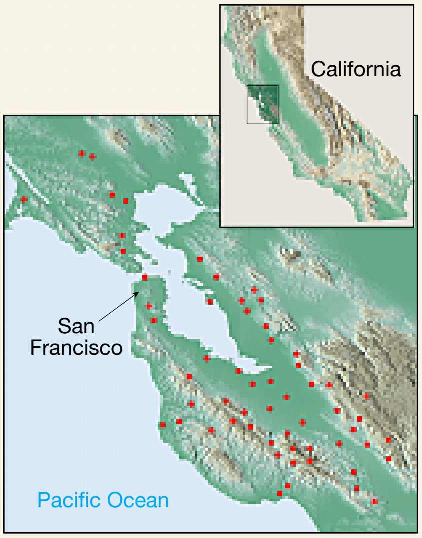


FIGURE 12-B San Francisco Bay region, showing hilly areas where debris flows are possible. Dots show locations of ALERT rain gauges. During storms, these gauges radio-transmit rainfall data to the U.S. Geological Survey and the National Weather Service. Scientists analyze the data to determine debris-flow danger. If danger is high, a Debris-Flow Watch or Warning is issued.

The Debris-Flow Warning System

Debris flows can begin suddenly, often with little warning. Loss of lives during the intense 1982 storm prompted the National Weather Service (NWS) and the U.S. Geological Survey (USGS) to develop a debris-flow warning system for the San Francisco Bay area.

During the rainy season (October through April), this warning system measures rainfall using more than 50 radio-telemetered rain gauges, called the ALERT network (Figure 12–B). Early in each rainy season, these rainfall measurements, along with measurements of soil moisture from a study site in the hills south of San Francisco, are used to estimate the moisture level of soils throughout the Bay region. Soils must reach a sufficient moisture level each year before slopes become susceptible to debris flows during intense rainstorms. Once soils reach this moisture level, the USGS monitors weather forecasts and uses up-to-the-minute data from the ALERT network to determine the potential for imminent debris flows during each subsequent rainstorm. Warnings are then broadcast by the National Weather Service.

How Much Rain Is Needed to Trigger Debris Flows?

Once soils have reached sufficient moisture levels during a rainy season, it is the rainfall rate, rather than total rainfall amount, that is most important for determining whether debris flows will occur. For example, 4 inches of rain in 24 hours is generally not sufficient to trigger debris flows in the San Francisco Bay region. However, 4 inches of rain in 6 hours generally will trigger numerous debris flows. On burned slopes that have lost their anchoring vegetation, and altered slopes, such as road cuts, greater caution is needed because debris flows can be triggered by less severe rainfall conditions.

*Based on material prepared by the U.S. Geological Survey

the balloon (normall filled with hydrogen or helium) rises. Also, by tracking the radiosonde, wind speed and direction at various altitudes can be calculated. A radiosonde flight typically lasts about 90 minutes, during which it may ascend to over 35 kilometers (about 115,000 feet). Because pressure decreases with altitude, the balloon eventually stretches to its breaking point and bursts. When this occurs, a small parachute opens and the instrument package slowly descends to Earth. If you find a radiosonde, follow the mailing instructions as they can be reused.

Acquiring upper-air data over the ocean is problematic. Only a few ships launch radiosondes. Some commercial aircraft contribute upper-air information over the ocean by regularly reporting wind, temperature and, occasionally, turbulence along their flight routes.

A number of technical advances have been made that improve our ability to make observations aloft. Special radar units called **wind profilers** are used to measure wind speed and direction up to 10 kilometers (6 miles) above the surface. These measurements can be taken every six minutes in contrast to the 12-hour interval between balloon launches. In addition, satellites and weather radar have become invaluable tools for making weather observations. The importance of these modern technologies are considered later in this chapter.

Despite the advances being made in the collection of weather data, two difficulties remain. First, observations may be inaccurate due to instrument malfunctions or data transmission errors. Second, there are some regions, particularly over oceans and in mountainous areas, where there are too few observations.

Weather Maps: Pictures of the Atmosphere

Once this large body of data has been collected, the analyst displays it in a form that can be comprehended easily by the forecaster. This step is accomplished by placing the information on a number of **synoptic weather maps** (see Box 12–2). They are called synoptic, which means “coincident in time,” because they display a synopsis of the weather conditions at a given moment. These weather charts are a symbolic representation of the state of the atmosphere. Thus, to the trained eye, a weather map is a snapshot that shows the status of the atmosphere, including data on temperature, humidity, pressure, and airflow. (Forecast maps that depict the future state of the

FIGURE 12-3 Data buoy used to record atmospheric conditions over a section of the global ocean. These data are transmitted via satellite to a land-based station. *(Photo by Matthew Neal McVay/Stock Boston)*

atmosphere are also produced, a topic we will consider later in this chapter.)

Over 200 surface maps and charts covering several levels of the atmosphere are produced each day by the NWS and its forecast centers. A task once done by hand, computers are now employed to analyze and plot the data in a systematic fashion. Typically, lines and symbols are used to depict the weather patterns. Once a map is generated, an analyst fine-tunes it, correcting any errors or omissions. Figure 12–5 shows a simplified version of a surface map, as well as a 500-millibar-height contour chart covering the same time period.

In addition to the surface map, twice-daily upper-air charts are drawn at 850-, 700-, 500-, 300-, and 200-millibar levels. Recall that on these charts, height contours (in meters or tens of meters) instead of isobars are used to depict the pressure field. These charts also contain isotherms (equal temperature lines) shown as dashed lines labeled in degrees Celsius. This series of upper-air charts provides a three-dimensional view of the atmosphere.

Students Sometimes Ask…

Who was the first weather forecaster?

In the United States, Benjamin Franklin is often credited with making the first long-term weather predictions in his *Poor Richard's Almanac,* beginning in 1732. However, these forecasts were based primarily on *folklore* rather than weather data. Nevertheless, Franklin may have been the first to document that storm systems move. In 1743, while living in Philadelphia, rainy weather prevented Franklin from viewing an eclipse. Through later correspondence with his brother, he learned that the eclipse had been visible in Boston, but within a few hours that city also experienced rainy weather conditions. These observations led Franklin to the conclusion that the storm, which prevented his viewing of the eclipse in Philadelphia, moved up the East Coast to Boston.

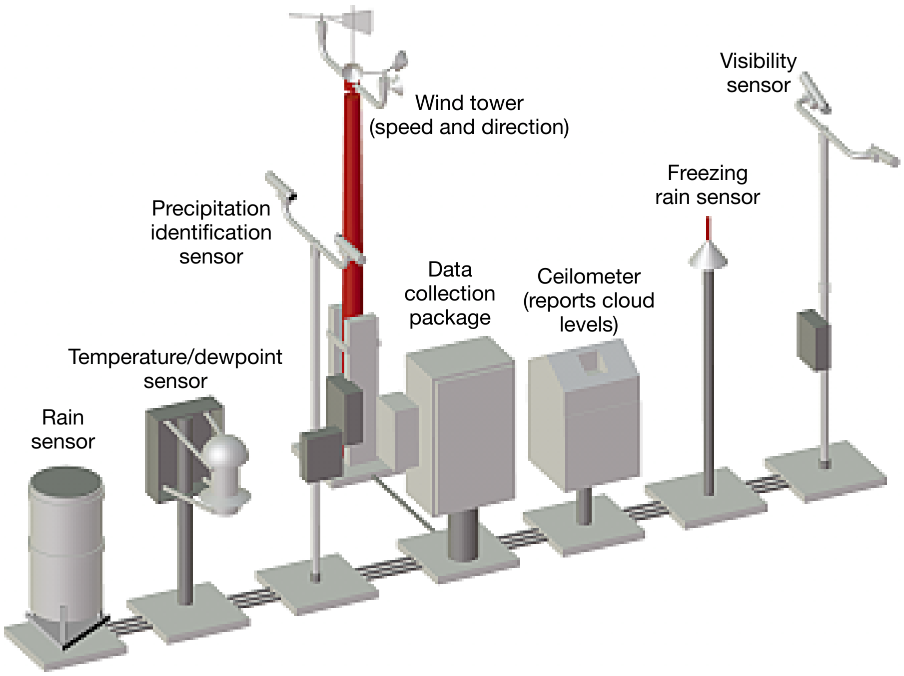
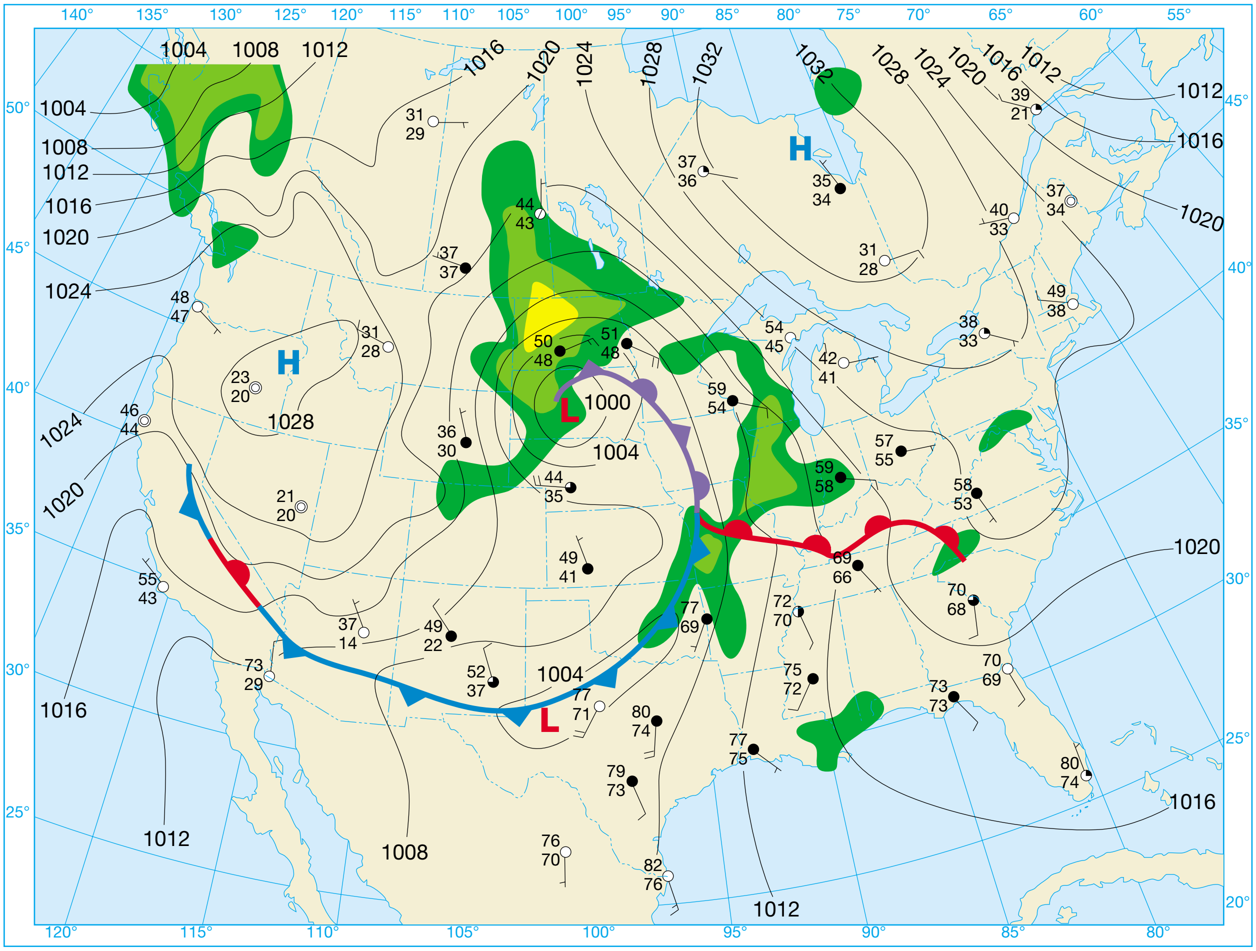
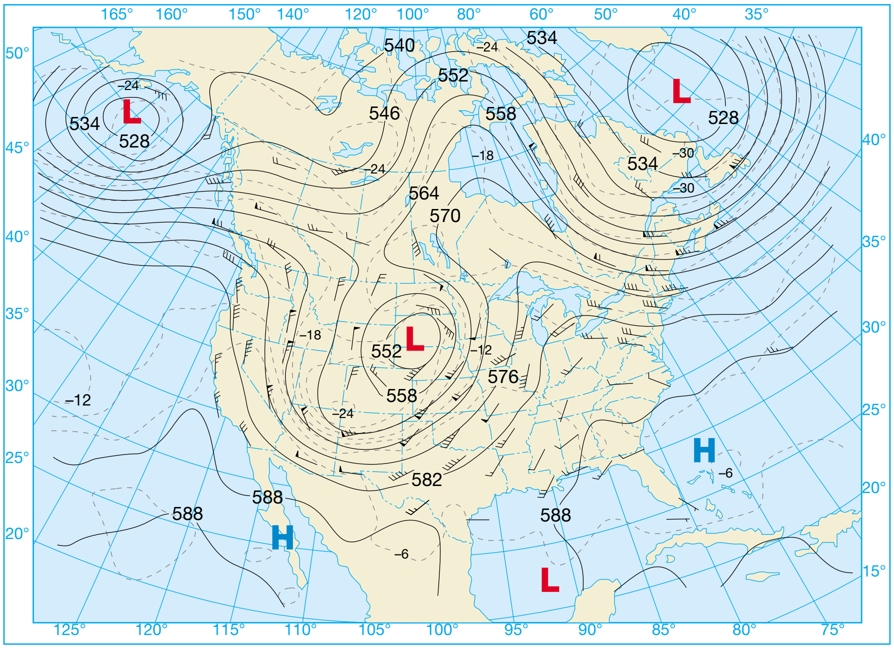


FIGURE 12-4 Diagram of an Automated Surface Observing System (ASOS) equipped to sample the sky for cloud coverage; take temperature and dew-point measurements; determine wind speed and direction; and even detect present weather—if it is raining or snowing. Also see Figure 1–7, p. 8.



(a) Surface weather map.



(b) 500-millibar level chart.

FIGURE 12-5 Simplified synoptic weather maps. (a) Surface weather map for 7:00 A.M. Eastern Standard Time depicting a well-developed middle-latitude cyclone. (b) A 500-millibar-level map, with height contours in tens of meters, for the same time period.

BOX 12-2 Constructing a Synoptic Weather Chart

Production of surface weather charts first involves plotting the data from selected observing stations. By international agreement, data are plotted using the symbols illustrated in Figure 12–C. Normally, data that are plotted include temperature, dew point, pressure and its tendency, cloud cover (height, type, and amount), wind speed and direction, and weather, both current and past. These data are always plotted in the same position around the station symbol for consistent reading. Using Figure 12–C, for example, you can see that the temperature is plotted in the upper-left corner of the sample model, and it will always appear in that location. (The only exception to this arrangement is the wind arrow, because it is oriented with the direction of airflow.) A more complete weather station model and a key for decoding weather symbols are in Appendix B.

The data are plotted as shown in Figure 12–D (left). Once data have been plotted, isobars and fronts are added to the weather chart (Figure 12–D on right). Isobars are usually plotted on surface maps at intervals of 4 millibars (1004, 1008, 1012, etc.). The positions of the isobars are estimated as accurately as possible from the pressure readings available. Note in Figure 12–D (right) that the 1012-millibar isobar is about halfway

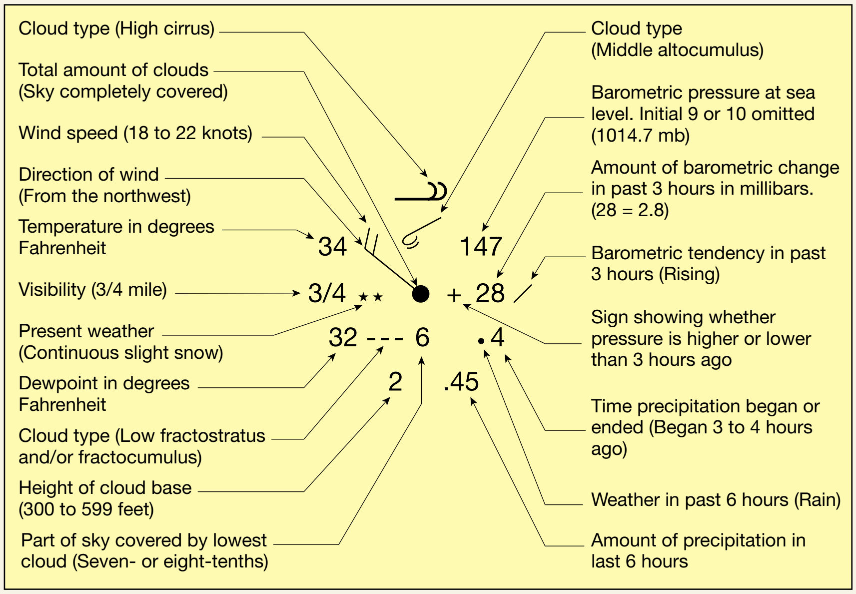


FIGURE 12-C A specimen station model showing the placement of commonly plotted data. *(Abridged from the International Code)*

between two stations that report 1010 millibars and 1014 millibars. Frequently, observational errors and other complications require the analyst to smooth the isobars so that they conform to the overall picture. Many irregularities in the pressure field are caused by local influences that have little bearing on the larger circulation depicted on the charts. Once the isobars are drawn, centers of high and low pressure are designated.

Because fronts are boundaries that separate contrasting air masses, they can often be identified on weather charts by locating zones exhibiting abrupt changes in conditions. Because several elements change across a front, all are examined so that the frontal position is located most accurately. Some of the more easily recognized changes that can aid in identifying a front on a surface chart are as follows:

1. Marked temperature contrast over a short distance.

In summary, the analysis phase involves collecting and compiling millions of pieces of observational data describing the current state of the atmosphere. These data are then displayed on a number of different weather maps that show current weather patterns at selected levels throughout the depth of the atmosphere, not just at the surface.

Weather Forecasting

Until the late 1950s, all weather maps and charts were plotted manually and served as the primary tools for making weather forecasts. Various techniques were utilized by forecasters to extrapolate future conditions from the patterns depicted on the most recent weather charts. One method involved matching current conditions with similar, well-established patterns from the past. From such comparisons, meteorologists predicted how current systems might change in the hours and days to come. As this practice evolved, "rules of thumb" were established to aid forecasters. Applying these rules to current weather charts became the backbone of weather forecasting and still plays an important role in making short-range (24 hours or less) predictions.

Later, computers were used to plot data and produce surface and upper-air charts. As technologies improved,

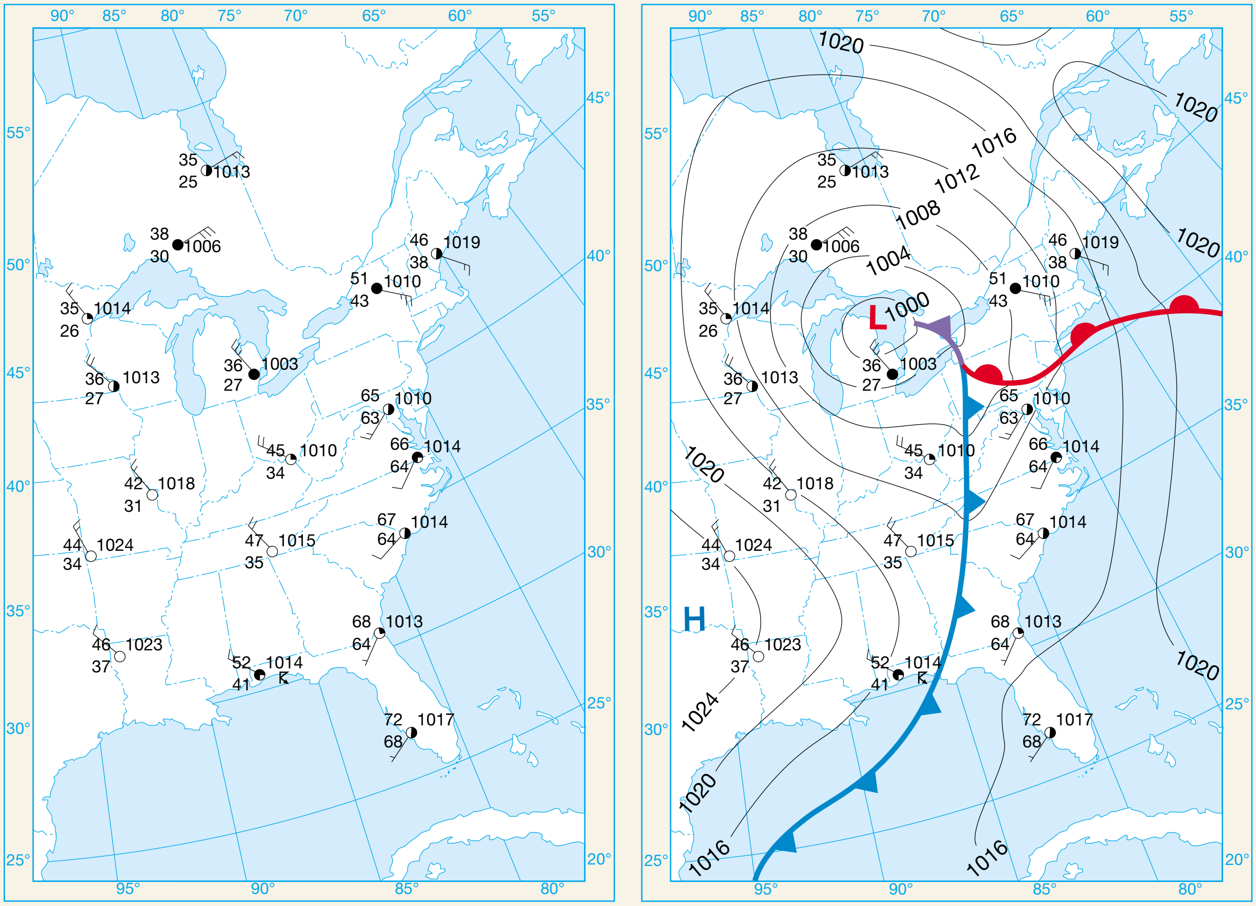


FIGURE 12-D Simplified weather charts. (left) Stations, with data for temperature, dew point, wind direction, wind speed, sky cover, and barometric pressure. (right) Same chart showing isobars and fronts.

2. Wind shift (in a clockwise direction) over a short distance by as much as 90°.
3. Humidity variations commonly occurring across a front that can be detected by examining dew-point temperatures.
4. Clouds and precipitation patterns giving clues to the position of fronts.

Notice in Figure 12–D that all the conditions listed are easily detected across the frontal zone. However, not all fronts are as easily defined as the one on our sample map. In some cases, surface contrasts on opposite sides of the front are subdued. When this happens, charts of the upper air, where flow is less complex, become an important tool for detecting fronts.

computers eventually were used to make weather forecasts. Computers have played a key role in improving the accuracy and detail of weather forecasts, and in lengthening the period for which useful guidance can be given.

Numerical Weather Prediction: Forecasting by Computer

Numerical weather prediction is the technique used to forecast weather using numerical models designed to represent atmospheric processes. (The word "numerical" is somewhat misleading, because all types of weather forecasting are based on some quantitative data and therefore could fit under this heading.) Numerical weather prediction relies on the fact that the behavior of atmospheric gases is governed by a set of physical principles that can be expressed as mathematical equations (see Box 12–3). If we can solve these equations, we will have a description of the future state (a forecast) of the atmosphere, derived from the current state, which we can interpret in terms of weather—temperature, moisture, cloud cover, and wind. This method is analogous to using a computer to predict the future positions of Mars, using Newton's laws of motion and knowing the planet's current position.

Highly refined computer models that attempt to mimic the behavior of the "real" atmosphere are used in numeri-

BOX 12-3 Numerical Weather Prediction

*Gregory J. Carbone**

During the past several centuries, the physical laws governing the atmosphere have been refined and expressed through mathematical equations. In the early 1950s, meteorologists began using computers, which provided an efficient means of solving these mathematical equations, to forecast the weather. The goal of such numerical weather prediction is to predict changes in large-scale atmospheric flow patterns. The equations relate to many of the processes already discussed in this book. Two *equations of motion* describe how horizontal air motion changes over time, taking into account pressure gradient, Coriolis, and frictional forces. The *hydrostatic equation* describes vertical motion in the atmosphere. The *first law of thermodynamics* is used to predict changes in temperature that result from the addition or subtraction of heat or from expansion and compression of air. Two equations refer to the conservation of mass and water. Finally, the *ideal gas law* or *equation of state* shows the relationship among three fundamental variables—temperature, density, and pressure.

Weather-prediction models begin with observations describing the current state of the atmosphere. They use the equations to compute new values for each variable of interest, usually at 5- to10-minute intervals, called the *time step.* Predicted values serve as the initial conditions for the next series of computations and are made for specific locations and levels of the atmosphere. Each model has a spatial resolution that describes the distance between prediction points. Solving the model's fundamental equations repeatedly predicts the future state of the atmosphere. The model output is provided to weather forecasters for fixed intervals, such as 12, 24, 36, 48, and 72 hours in the future.

Despite the sophistication of numerical weather-prediction models, most still produce forecast errors. Three factors in particular restrict their accuracy—inadequate representation of physical processes, errors in initial observations, and inadequate model resolution. Whereas the models are grounded on sound physical laws and capture the major characteristics of the atmosphere, they necessarily simplify the workings of a very complex system. The representation of land–surface processes and topography are just two examples of features that are incompletely treated in current numerical models. Errors in the initial observations fed into the computer will be amplified over time because numerical weather prediction models include many nonlinear relationships. Finally, physical conditions at all spatial scales can influence atmospheric changes. Yet the spatial resolution of numerical models is too coarse to capture many important processes. In fact, the atmospheric system moves at scales too small to ever be observed and incorporated explicitly into models.

A simple example illustrates how misrepresentation of physical processes or observation error might lead to inaccurate predictions. Figure 12–E is based on an equation used to predict future values of a given variable *Y*. The equation is written as

$$Y_t = (a \times Y_t) - Y_t^2,$$

where *Y* represents the value of some variable at time *t*, Y_{t+1} represents the same variable at the next time step, and *a* represents a constant coefficient.

Notice that each predicted value serves as the initial value for the next calculation, the same way in which output from a numerical weather-prediction model provides input for subsequent computations. The solid line in Figure 12–E shows the equation

cal weather prediction. All numerical simulations are based on the same governing equations but differ in the way the equations are applied and in the parameters that are used. For example, some models use a very closely spaced set of data points and cover a specific concentrated area, whereas others describe the atmosphere more broadly on a global scale. In the United States, several different numerical models are in use.

The process begins by entering current atmospheric variables (temperature, wind speed, humidity, and pressure) into a computer simulation. This set of values represents the atmosphere at the start of the forecast. After literally billions of calculations, a forecast of how these basic elements are expected to change over a short time frame (perhaps only 15 minutes) is generated. Once all the new values have been calculated, the process starts over again with the next 15-minute forecast being established. By repeating this procedure many times over, a forecast for six or more days can be built.

Using mathematical models, the NWS produces a variety of generalized forecast charts at the National Centers for Environmental Predictions near Washington, D.C. Because these machine-generated maps predict atmospheric conditions at some future time, they are called **prognostic charts,** or simply **progs.** Most numerical models are designed to generate prognostic charts that predict changes in the flow pattern aloft. In addition, some models create forecasts for other conditions, including maximum and minimum temperatures, wind speeds, and precipitation probabilities. Even the simplest models require such a vast number of calculations that they could not have been

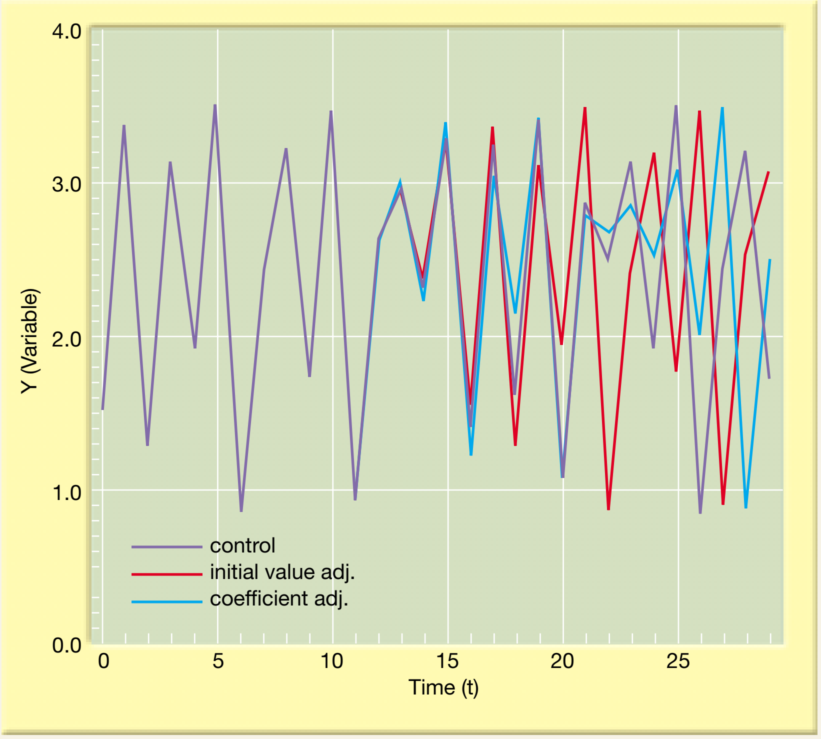


FIGURE 12-E Tiny errors may not significantly influence the early stages of a prediction, but with time, such errors amplify dramatically.

solution over a number of time steps, given an initial value of (e.g., a meteorological observation), $Y_{t=0} = 1.5$, and a coefficient value, $a = 3.75$. The graph illustrates how the precision of our equations describing the evolving state of the atmosphere may affect predictions. The blue line represents values of Y that result from the adjustment of a from 3.75 to 3.749. Similarly, we can demonstrate how a very small observation error could amplify over time by adjusting $Y_{t=0}$ from 1.5 to 1.499. The red line in the graph shows how an incremental change in the initial value affects predictions. Small errors may make very little difference in the early stages of our prediction, but such errors amplify dramatically over time. Because we cannot observe many small-scale features of the atmosphere, nor incorporate all of its processes into computer models, weather forecasts have a theoretical limit.

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used prior to the development of high-speed supercomputers.

Once generated, a statistical analysis is used to modify these machine-generated forecasts by making comparisons of how accurate previous forecasts have been. This approach, known as **Model Output Statistics (MOS,** pronounced “moss”), corrects for errors the model tends to make consistently. For example, certain forecast models may predict too much rain, overly strong winds, or temperatures that are too high or too low. MOS forecasts form the baseline that forecasters from the NWS, as well as private forecast companies, try to improve upon. This final step is performed by humans, using their knowledge of meteorology and making allowances for known model shortcomings (Figure 12–6).

To summarize, meteorologists use equations to create mathematical models of the atmosphere. Thus, by utilizing data on initial atmospheric conditions, they solve these equations to predict a future state. Of course, this is easier said than done. Earth’s atmosphere is a very complex, dynamic system that can only be roughly approximated using mathematical models. Further, because of the nature of the equations, tiny differences in the data can yield huge differences in outcomes. Nevertheless, these models produce surprisingly good results—much better than those made without them.

Ensemble Forecasting. One of the most significant challenges for weather forecasters is the apparently chaotic behavior of the atmosphere. Specifically, two very

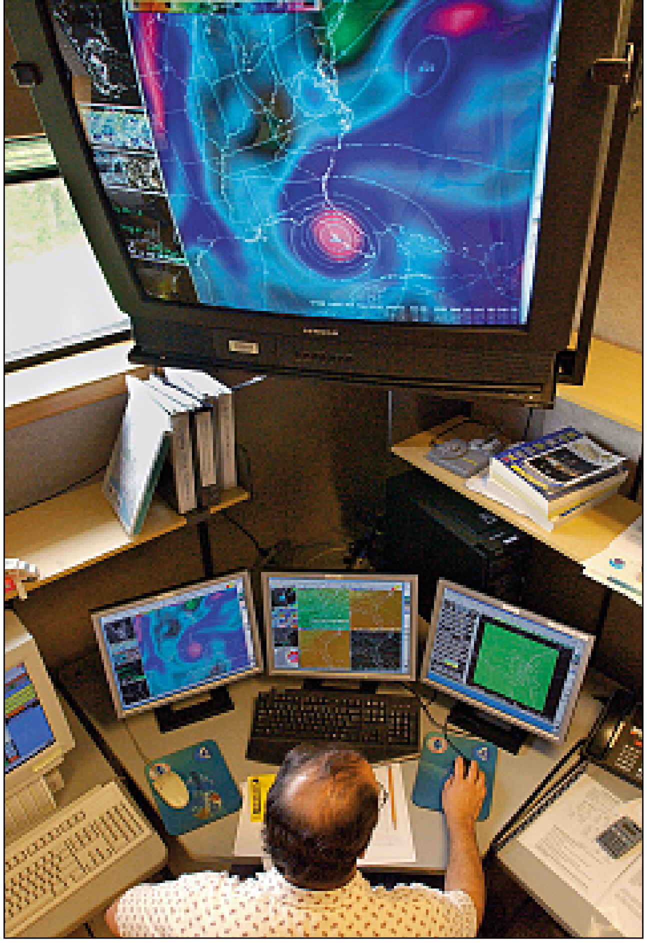


FIGURE 12-6 Forecasters at the National Weather Service provide nearly 2 million predictions annually to the public and commercial interests. *(Photo by* Florida Times-Union, *Will Dickey/AP Wide World Photos.)*

similar atmospheric disturbances may, over time, develop into two very different weather patterns. One may intensify, becoming a major disturbance, while the other withers and dissipates. To demonstrate this point, Edward Lorenz at the Massachusetts Institute of Technology employed a metaphor that became known as the *butterfly effect*. Lorenz described a butterfly in the Amazon rain forest fluttering its wings and setting into motion a subtle breeze that travels and gradually magnifies over time. According to Lorenz's metaphor, two weeks later this faint breeze has grown into a tornado over Kansas. Obviously, by stretching the point considerably, Lorenz tried to illustrate that a very small change in initial atmospheric conditions can dramatically affect the resulting weather pattern.

To deal with the inherent chaotic behavior of the atmosphere, forecasters rely on a technique known as **ensemble forecasting.** Simply, this method involves producing a number of forecasts using the same computer model but slightly altering the initial conditions, while remaining within an error range of the observational instruments. Essentially, ensemble forecasting attempts to assess how the inherent errors and omissions in weather measurements might affect the result.

One of the most important outcomes of ensemble forecasts is the information they provide about forecast uncertainty. For example, assume that a prognostic chart that was generated using the best available weather data predicts the occurrence of precipitation over a wide area of the southeastern United States within 24 hours. Now let's say that the same calculations are performed several times in succession, each time making minor adjustments to the initial conditions. If most of these progs also predict a pattern of precipitation in the Southeast, the forecaster would place a high degree of confidence in the forecast. On the other hand, there is far less confidence in a forecast when the prognostic charts generated by the ensemble method differ significantly.

Role of the Forecaster. Despite faster computers, constant improvements in numerical models, and significant technological advances, prognostic charts provide only a generalized picture of atmospheric behavior. As a result, human forecasters, using their knowledge of meteorology as well as judgments based on experience, continue to serve a vital role in creating weather forecasts, particularly short-range forecasts.

Once generated, a variety of prognostic charts are sent to the 119 regional weather forecast offices of the NWS. The responsibility of the forecasters is to blend numerical predictions with local conditions and regional weather quirks to produce site-specific forecasts. This task is further complicated by the availability of multiple prognostic charts. For example, generally two different numerical models are employed to predict the minimum temperature for a given day. One method works better on some days than on others and performs better in some locales than in others. It is up to the forecaster to select the "best" model each day, or perhaps to blend the data from both models.

Often, forecasters add extra detail to the model forecast. Isolated summer thunderstorms, for example, are on a scale too small for the computer models to adequately resolve. In addition, weather phenomena such as tornadoes and thunderstorm microbursts cannot be predicted using available forecasting techniques (Figure 12–7). Therefore, emphasis is placed on using satellites and weather radar to detect and track these features.

In summary, computer-generated numerical models have greatly improved our ability to forecast the weather. Because the prognostic charts obtained by these techniques are somewhat general, detailed aspects of weather must still be added by an experienced human forecaster, utilizing various other forecasting methods.

Other Forecasting Methods

Although machine-generated prognostic charts form the basis of modern forecasting, other methods are available to meteorologists. These methods, which have "stood the test of time," include persistence forecasting, climatological forecasting, analog methods, and trend forecasting.

Persistence Forecasting. Perhaps the simplest forecasting technique, called **persistence forecasting,** is

FIGURE 12-7 Mesoscale phenomena such as this tornado are too small to appear on computer-generated prognostic charts. Detection of such events relies heavily on weather radar and geostationary satellites. *(Photo by A.T. Wilett/Alamy)*

based on the tendency of weather to remain unchanged for several hours or even days. If it is raining at a particular location, for example, it might be reasonable to assume that it will still be raining in a few hours. Persistence forecasts do not account for changes that might occur in the intensity or direction of a weather system, nor can they predict the formation or dissipation of storms. Because of these limitations and the rapidity with which weather systems change, persistence forecasts usually diminish in accuracy within 6–12 hours, or one day at the most.

Climatological Forecasting. Another relatively simple way of generating forecasts uses climatological data—average weather statistics accumulated over many years. This method is known as **climatological forecasting.** Consider, for example, that Yuma, Arizona, experiences sunshine approximately 90 percent of its daylight hours; thus, forecasters predicting sunshine every day of the year would be correct about 90 percent of the time. Nearly the opposite situation exists during December in Portland, Oregon, where forecasters would be correct about 90 percent of the time by predicting overcast skies.

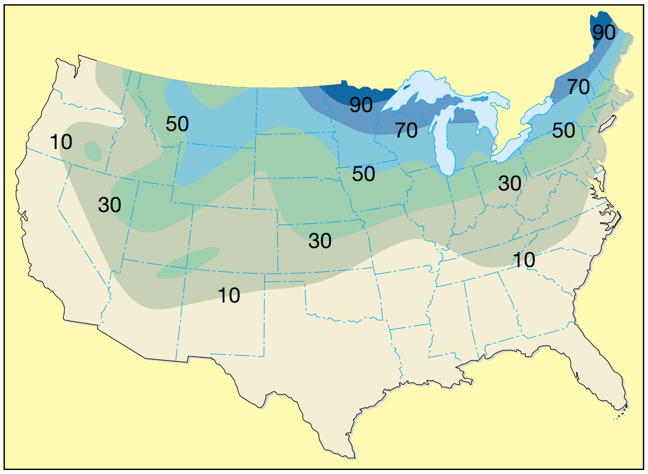
Climatological forecasting is particularly useful when making agricultural business decisions. For example, in the relatively dry north-central portion of Nebraska known as the Sand Hills, the implementation of center-pivot irrigation made growing corn more feasible. However, the farmers were faced with the question of which corn hybrid to plant. A high-yield variety widely used in southeastern Nebraska (its warmest region) seemed to be the logical choice. However, review of local climatological data showed that because of the cooler temperatures in the Sand Hills, corn planted in late April would not mature until late September, when there is a 50 percent probability of an autumn frost. Farmers used this important climate information to select a hybrid that better fit the growing season in the Sand Hills.

One interesting use of climatological data is the prediction of a "White Christmas"—that is, a Christmas with one inch or more of snow on the ground. As Figure 12–8 illustrates, northern Minnesota and northern Maine have more than a 90 percent chance of experiencing a "White Christmas." By contrast, those who are in southern Florida for the holidays have a minuscule chance of experiencing snow.

Analog Method. A somewhat more complex way to predict the weather is the **analog method,** which is based on the assumption that weather repeats itself, at least in a general way. Thus, forecasters attempt to find well-established weather patterns from the past that match (are analogous to) a current event. From such a comparison forecasters predict how the current weather might evolve.

Prior to the advent of computer modeling, the analog method was the backbone of weather forecasting. Even today, an analog method called *pattern recognition* is used to improve upon short-range machine-generated forecasts.

FIGURE 12-8 Probability (in percent) of a "White Christmas," that is, a Christmas in which at least 1 inch of snow is on the ground. *(Data from the U.S. Department of Commerce)*



Trend Forecasting. Another related method, **trend forecasting,** involves determining the speed and direction of features such as fronts, cyclones, and areas of clouds and precipitation. Using this information, forecasters attempt to extrapolate the future position of these weather phenomena. For example, if a line of thunderstorms is moving toward the northeast at 35 miles per hour, a trend forecast would predict that the storm will reach a community located 70 miles to the northeast in about two hours.

Because weather events tend to increase or decrease in speed and intensity or change direction, trend forecasting is most effective over periods of just a few hours. Thus, it works particularly well for forecasting severe weather events that are expected to be short-lived, such as hailstorms, tornadoes, and microbursts, because warnings for such events must be issued quickly and be site-specific. The techniques used for this work, often called **nowcasting,** are heavily dependent on weather radar and geostationary satellites. These tools are important in detecting areas of heavy precipitation or clouds that are capable of triggering severe conditions. Nowcasting techniques use highly interactive computers capable of integrating data from a variety of sources. Prompt forecasting of tornadic winds is one example of the critical nature of nowcasting techniques.

In summary, weather forecasts are produced using several methods. The National Weather Service uses numerical weather prediction to generate prognostic charts for large regions. These charts are then disseminated to regional forecast centers that apply various forecasting techniques as well as the experienced judgment of meteorologists to generate area-specific forecasts.

Upper Airflow and Weather Forecasting

In Chapter 9 we demonstrated that a strong connection exists between cyclonic disturbances at the surface and the wavy flow of the westerlies aloft. The importance of this connection cannot be overstated, particularly as it applies to weather forecasting. In order to understand the development of thunderstorms or the formation and movement of mid-latitude cyclones, meteorologists must know what is occurring aloft as well as at the surface.

Upper-Level Maps

By convention, upper-air maps are generated twice daily, at 0000 and 1200 GMT (midnight and noon GMT). Recall that these charts are drawn at 850-, 700-, 500-, 300-, and 200-millibar (mb) levels as height contours (in meters or tens of meters), which are analogous to isobars used on surface maps. These maps also contain isotherms, depicted as dashed lines, and some show humidity as well as wind speed and direction.

850- and 700-millibar Maps. Figure 12–9a illustrates a standard 850-mb map, which is similar in general layout to a 700-mb map. Both maps show height contours using solid black lines at 30-meter intervals and isotherms labeled in degrees Celsius. If relative humidity is depicted, levels above 70 percent are shown in green. Wind data is plotted using black arrows.

The 850-mb map depicts the atmosphere at an average height of about 1500 meters (1 mile) above sea level. In nonmountainous areas, this level is above the layer where daily temperature fluctuations are strongly influenced by the warming and cooling of Earth's surface. (In areas where elevations are high, such as Denver, Colorado, the 850-mb level represents surface conditions.)

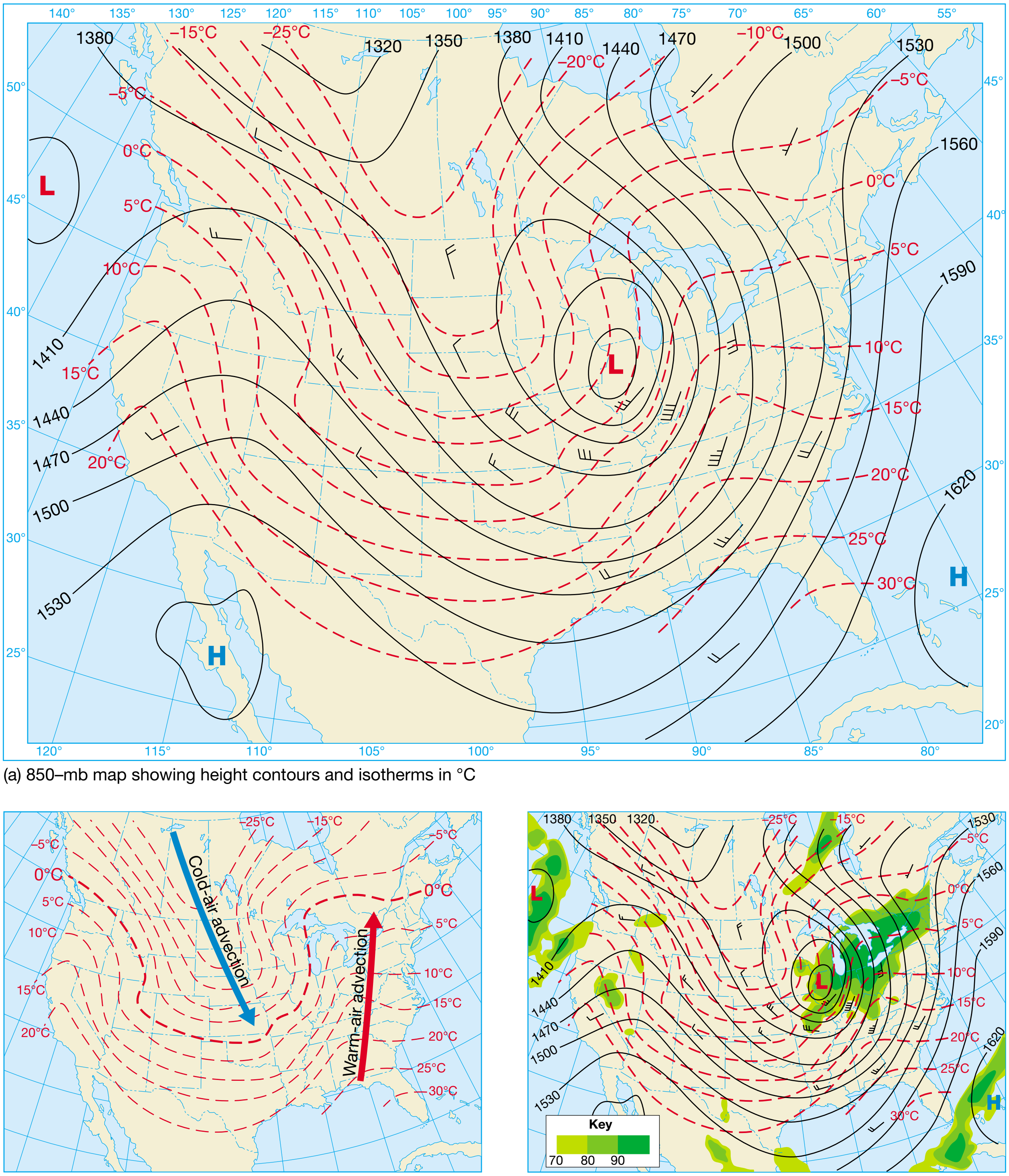
Forecasters regularly examine the 850-mb map to find areas of *cold-air and warm-air advection*. Cold-air advection occurs where winds blow across isotherms from colder areas toward warmer areas. The 850-mb map in Figure 12–9b shows a blast of cold air moving south from Canada into the Mississippi Valley. Notice that the isotherms (red dashed lines) in this region of the country are packed tightly together, which means the affected area will experience a rapid drop in temperature.

By contrast, warm-air advection is occurring along the Eastern Seaboard of the United States. In addition to moving warm air into a cooler region, warm-air advection is generally associated with widespread lifting in the lower troposphere. If the humidity in the region of warm-air advection is relatively high, then lifting could result in cloud formation and possibly precipitation (Figure 12–9c).

The temperatures occurring at the 850-mb level also provide useful information. During the winter, for example, forecasters use the 0°C isotherm as the boundary between areas of rain and areas of snow or sleet. Further, because air at the 850 mb level does not experience the daily cycle of temperature changes that occurs at the surface, these maps provide a way to estimate the daily maximum surface temperature. In summer, the maximum surface temperature is usually 15°C (27°F) higher than the temperature at the 850-mb level. In winter, maximum surface temperatures tend to be about 9°C (16°F) warmer than at the 850-mb level.

In addition to serving as a proxy for the 850-mb map in areas of high elevation, the 700-mb map has other uses as well. The 700-mb flow, which occurs about 3 kilometers (2 miles) above sea level, serves as the steering mechanism for air-mass thunderstorms. Thus, winds at this level are used to predict the movement of these weather producers. One rule of thumb used with these charts is that when temperatures at the 700-mb level are 14°C (57°F) or higher, thunderstorms will not develop. A warm 700-mb layer acts as a lid inhibiting the upward movement of warm, moist surface air that might otherwise rise to generate towering cumulonimbus clouds. The cause of these warm conditions aloft is generally subsidence associated with a strong high-pressure center.

500-millibar Maps. The 500-mb level is found approximately 5.5 kilometers (18,000 feet) above sea level. Here, about half of Earth's atmosphere is below and half is



(a) 850–mb map showing height contours and isotherms in °C

(b) Isotherms at 850–mb level

(c) Relative humidity at 850–mb level

FIGURE 12-9 A typical 850-mb map. (a) The solid lines are height contours spaced at 30-meter intervals, and the dashed lines are isotherms in degrees Celsius. (b) Areas of warm- and cold-air advection are shown with colored arrows. (c) Regions where the relative humidity is greater than 70 percent are depicted in shades of green.

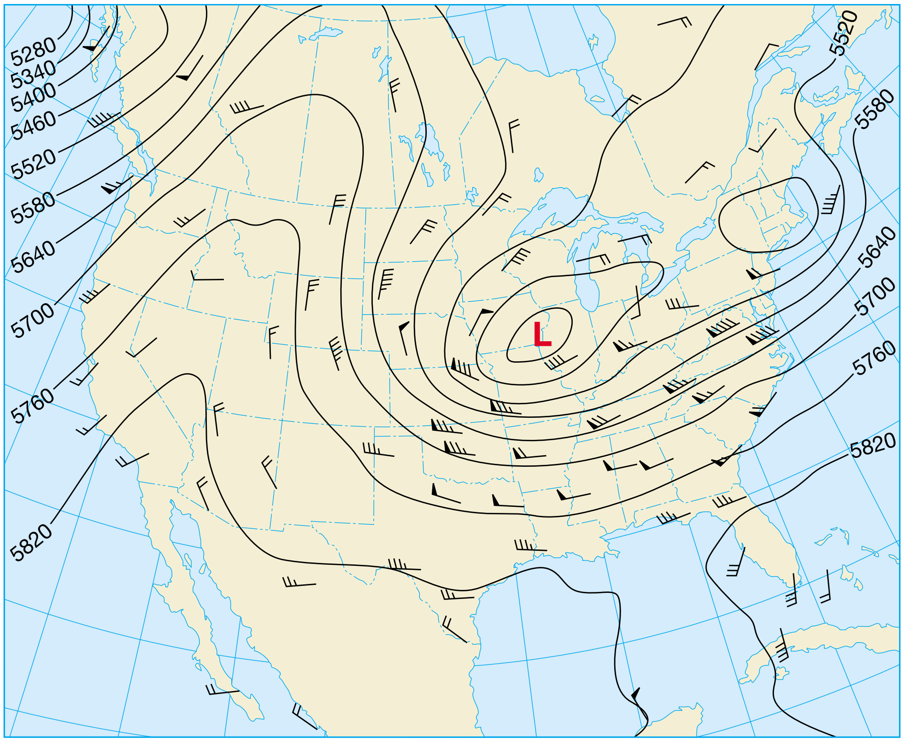


FIGURE 12-10 A 500-mb map. Notice the well developed trough in the central and eastern United States. Height contours are spaced at 60 meter intervals.

above. Notice in the example shown in Figure 12–10 that a large trough overlies much of the eastern United States, whereas a ridge is influencing the West. Troughs indicate the presence of a storm at mid-tropospheric levels, whereas ridges are associated with calm weather. When a prog (forecast chart) predicts a trough will increase in magnitude, it is an indication that a storm will intensify.

To estimate the movement of surface cyclonic storms, which tend to travel in the direction of the flow at the 500-mb level but at roughly a quarter to half the speed, forecasters find it useful to rely on 500-mb maps. Sometimes an upper-level low (shown as a closed contour in Figure 12–10) forms within a trough. When present, these features are associated with counterclockwise rotation and significant vertical lifting that typically results in heavy precipitation.

300- and 200-millibar Maps Two of the regularly generated upper-level maps, the 300-mb and the 200-mb charts, represent zones near the top of the troposphere. Here, at altitudes above 10 kilometers (6 miles), temperatures can reach a frigid –60°C (–75°F). It is at these levels that the details of the polar jet stream can best be observed. Because the jet stream is lower in winter and higher in summer, 300-mb maps are most useful during winter and early spring, whereas the 200-mb maps are best during the warm season.

In order to show airflow aloft, these maps often plot **isotachs,** which are lines of equal wind speed. Areas exhibiting the highest wind speeds may also be colored, as shown in Figure 12–11. These segments of higher-velocity winds found within the jet stream are called **jet streaks.**

The 200- and 300-mb charts are important to forecasters for several reasons. Recall that jet streams have regions where upper-level divergence is dominant. Divergence aloft leads to rising air, which supports surface convergence and cyclonic development (see Figure 9–14 p. 288). When a jet streak is strong, it tends to energize a trough, causing the pressure to drop further and the storm to strengthen. When upper-level winds are weak, surface cyclonic storms tend to move more slowly than when the winds at this level are strong.

The jet stream also plays an important role in the development of the severe weather and extended life span of supercells. Recall that thunderstorms have areas of updrafts that feed moisture into the storm and that they are situated side by side with downdrafts, which cause entrainment of cool, dry air into the storm. Typically, thunderstorms are relatively short-lived events that dissipate because downdrafts grow in size and eventually dominate the entire cloud (see Figure 10–4 p. 288). Supercells tend to develop near the jet stream where winds near the top of the thunderstorm may be two to three times as fast as winds near the base. This tilts the thunderstorm as it grows vertically, separating the area of updrafts from the area of downdrafts. When the updrafts are displaced from the downdrafts, the rising cells are not canceled by the downdrafts and the storm grows in intensity.

The Connection Between Upper-Level Flow and Surface Weather

Up to this point, we have considered the relationship between upper-level flow and short-lived weather phenomena—for example, how winds aloft steer and support the growth of thunderstorms. Next we will examine long-period changes that occur in the wavy flow of the westerlies and see how that behavior impacts our weather. Recall that

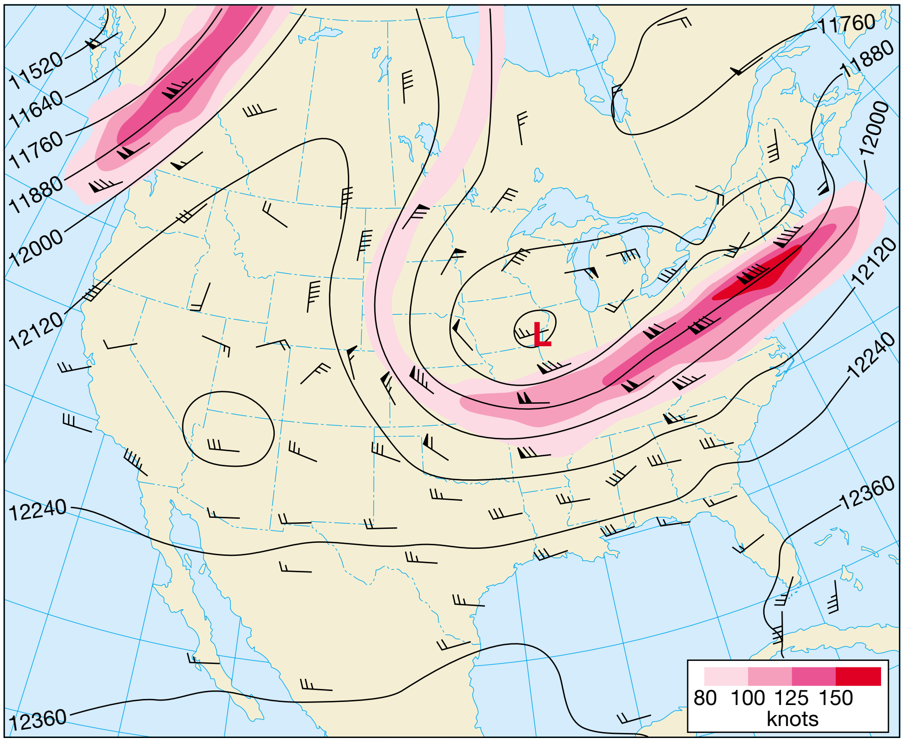


FIGURE 12-11 A 200-mb map showing the locatin of the jet stream (pink) and a jet streak (red). Height contours are spaced at 120-meter intervals.

mid-latitude winds are generated by temperature contrasts that are most extreme where warm tropical air clashes with cold, polar air. The boundary between these two contrasting air masses is the site of the polar jet stream, which is embedded in the meandering westerly flow near the top of the troposphere.

Occasionally, the flow within the westerlies is directed along a relatively straight path from west to east, a pattern referred to as *zonal*. Storms embedded in this zonal flow are quickly carried across the country, particularly in winter. This situation results in rapidly changing weather conditions in which periods of light to moderate precipitation are followed by brief periods of fair weather.

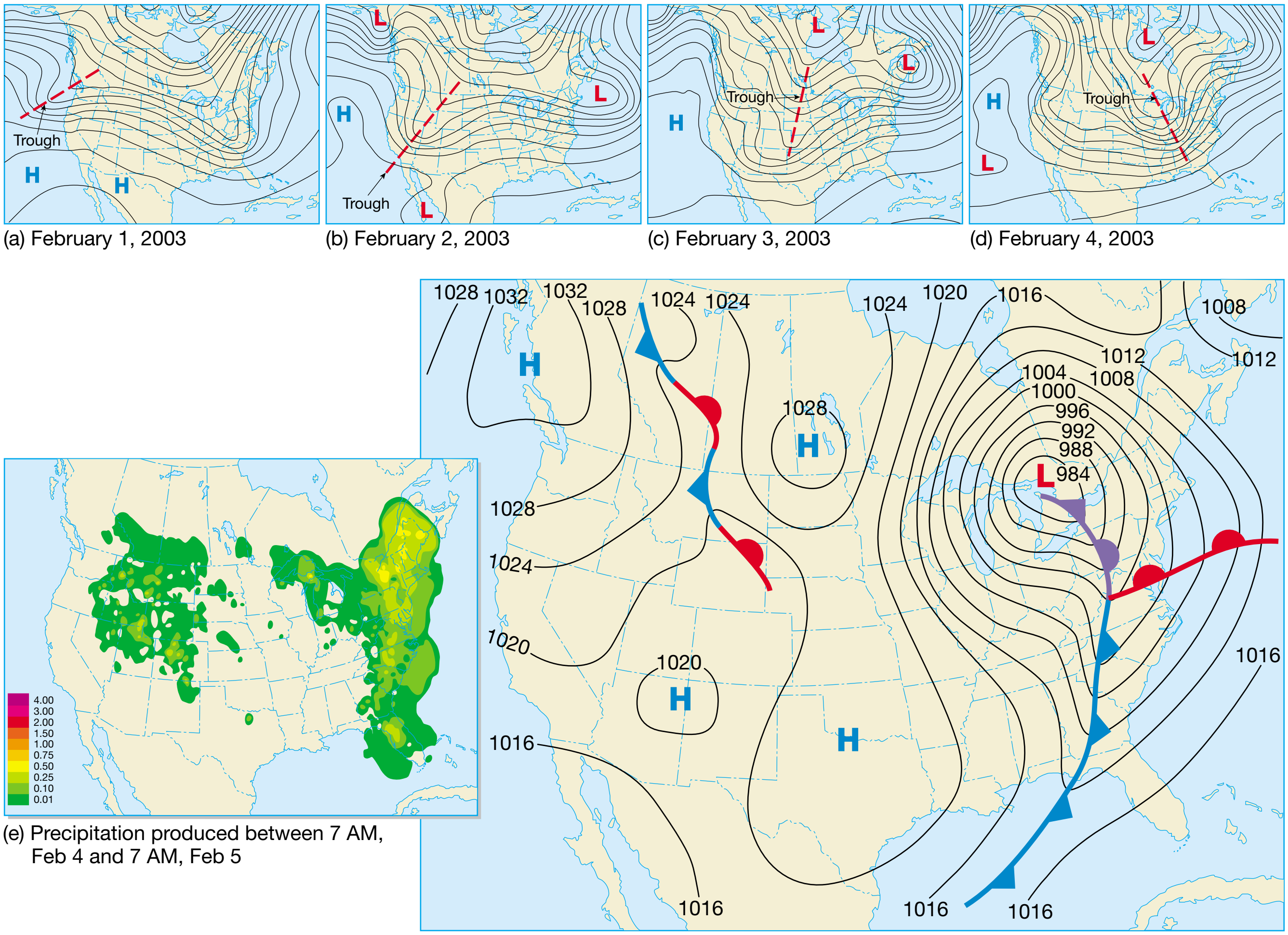
More often, however, the flow aloft consists of long-wave troughs and ridges that have large components of north–south flow, a pattern that meteorologists refer to as *meridional*. Typically, these airflow patterns slowly drift from west to east, but occasionally they stall and sometimes may even reverse direction. As this wavy pattern gradually migrates eastward, cyclonic storms embedded in the flow are carried across the country.

Figure 12–12 shows a trough that on February 1, 2003, was centered off the Pacific Coast. Over the next four days the trough grew in strength as it moved eastward into the Ohio Valley. This change in intensity is shown by the height contours, which are more closely packed around the trough on February 4 as compared to February 1. Embedded in this upper-level trough was a cyclonic system, which grew into the major storm that is shown on the surface map in Figure 12–12f. By February 5, this disturbance generated considerable precipitation over much of the eastern U.S. (Notice that the center of the surface low is located somewhat to the east of the 500-mb trough—something typical of these weather patterns.)

In general, high-amplitude patterns have the potential for generating extreme conditions. During winter, strong troughs tend to spawn large snowstorms, whereas in summer they are associated with severe thunderstorms and tornado outbreaks. By contrast, high-amplitude ridges are associated with record heat in summer and tend to bring mild conditions in winter.

Sometimes these "looped" patterns stall over an area, causing surface patterns to change very little from one day to another or, in extreme cases, from one week to another. Locations in and just east of a stationary or slow-moving trough experience extended periods of rainy or stormy conditions. By contrast, areas in and just east of a stagnant ridge experience prolonged periods of unseasonably warm, dry weather.

The strength and position of the polar jet stream fluctuate seasonally. The jet is strongest (faster wind speeds) in winter and early spring when the contrast between the warm tropics and the cold polar realm is greatest. As summer approaches and the temperature gradient diminishes, the westerlies weaken. The position of the jet stream also changes with the migration of the Sun's vertical rays. With the approach of winter, the mean position of the jet moves toward the equator. By midwinter, it may penetrate as far south as central Florida. Because the paths of mid-latitude cyclones shift with the flow aloft, we can expect the southern tier of states to encounter most of their severe weather in the winter and spring. (We are not considering the impact of hurricanes, which are tropical cyclones associated with high surface temperatures over the ocean.) During the



(a) February 1, 2003
(b) February 2, 2003
(c) February 3, 2003
(d) February 4, 2003
(e) Precipitation produced between 7 AM, Feb 4 and 7 AM, Feb 5
(f) Surface map February 4, 2003

FIGURE 12-12 The movement and intensification of an upper-level trough over a four-day period from February 1 to February 4, 2003. The surface map shows a strong cyclonic storm that formed and moved in conjunction with this trough.

summer, because of a poleward shift of the jet, the northern states and Canada experience an increase in the number of severe storms and tornadoes. This more northerly storm track also carries most Pacific storms toward Alaska during the warm months, producing a rather long, dry summer season for much of the Pacific Coast to the south.

The position of the jet stream relative to where you live is important for other reasons. In winter, should the jet stream move considerably south of your location, you will experience a "cold snap" as frigid air from Canada moves in. During the summer, by contrast, the core of the jet tends to be positioned over Canada, and warm, moist tropical air dominates much of the United States east of the Rockies. If, during the winter or early spring, strong cyclonic storms carried by the flow aloft pass immediately south of your location, expect cyclonic disturbances to bring heavy snowfall and cooler conditions. In summer, if the jet is overhead, periods of heavy rain, and perhaps hail and tornadic winds, may occur.

An Extreme Winter. Let us consider an example of the influence of the flow aloft for an extended period during a atypical winter. During a normal January an upper-air ridge tends to be situated over the Rocky Mountains, while a trough extends across the eastern two-thirds of the United States. In January 1977, however, the normal flow pattern was greatly accentuated, as illustrated in Figure 12–13. The greater amplitude of the upper-level flow caused an almost continuous influx of cold air into the Deep South, producing record-low temperatures throughout much of the eastern and central United States (Figure 12–14). Because of dwindling natural-gas supplies, many industries experienced layoffs. Much of Ohio was hit so hard that four-day workweeks and massive shutdowns were ordered.

While most of the East and South were in the deep freeze, the westernmost states were being influenced by a strong ridge of high pressure. Generally mild temperatures and clear skies dominated their weather. This was no

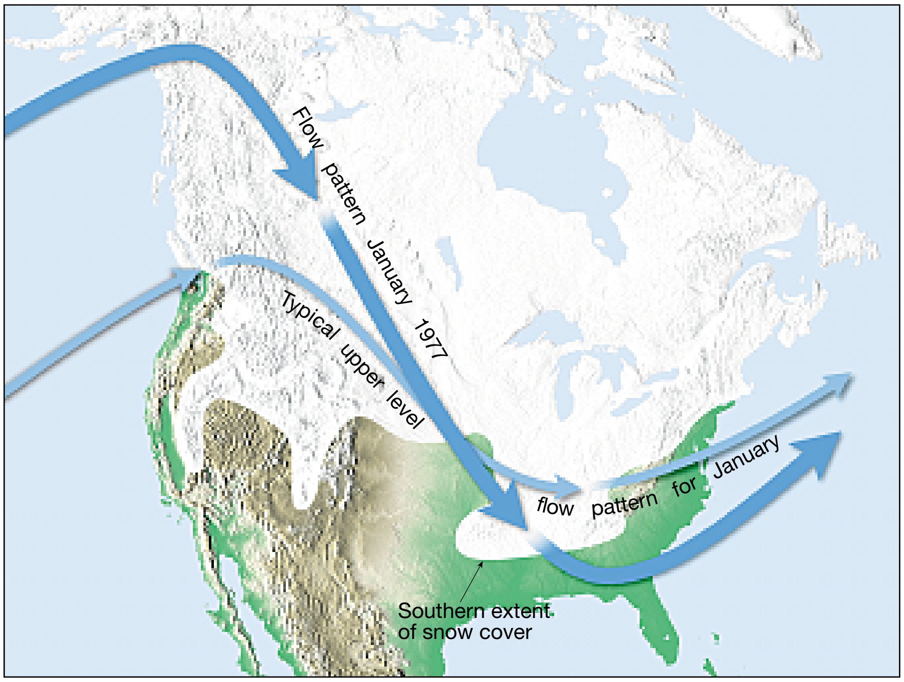


FIGURE 12-13 The unusually high amplitude experienced in the flow pattern of the prevailing westerlies during the winter of 1977 brought warmth to Alaska, drought to the west, and frigid temperatures to the central and eastern United States.

blessing, because the ridge of high pressure blocked the movement of Pacific storms that usually provide much needed winter precipitation. The shortage of moisture was especially serious in California, where January is the middle of its three-month rainy season.

Throughout most of the western states, the winter rain and snow that supply water for summer irrigation were far below normal. This dilemma was compounded by the fact that the previous year's precipitation had also been far below normal and many reservoirs were almost empty. Although much of the country was concerned about economic disaster caused either by a lack of moisture or frigid temperatures, the highly accentuated flow pattern channeled unseasonably warm air into Alaska. Even Fairbanks, which generally experiences temperatures as low as –40°C (–40°F), had a mild January, with numerous days above freezing.*

In summary, the wavy flow aloft governs, to a large extent, the overall magnitude and distribution of weather disturbances observed in the mid-latitudes. Thus, accurate forecasts depend on our ability to predict long- and short-term

*For an excellent review of the winter weather of 1976–1977, see Thomas Y. Canby, "The Year the Weather Went Wild," *National Geographic,* 152, no. 6 (1977), 798–892.

FIGURE 12-14 Arctic air invades the eastern United States. *(Photo by Seth Resnick, Stock Boston).*

changes in the upper-level flow. Although the task of forecasting long-term variations remains beyond the capabilities of meteorologists, it is hoped that future research will allow forecasters to answer questions such as: Will next winter be colder or warmer than recent winters? Will the Southwest experience a drought next year?

Long-Range Forecasts

The National Weather Service issues a number of computer-generated forecasts for time spans ranging from a few hours to more than two weeks. Beyond seven days, however, the accuracy of these forecasts diminishes considerably. In addition, the Climate Prediction Center, a branch of the NWS, produces *30- and 90-day outlooks*. These are not weather forecasts in the usual sense. Instead, they offer insights into whether it will be drier or wetter, and colder or warmer than normal in a particular region of the country.

A series of thirteen 90-day outlooks are produced in one-month increments. The series begins with the outlook for the next three months—for example, November, December, and January. Next, a separate 90-day outlook for the period beginning one month later (December, January, and February) is constructed. Figure 12–15 shows the temperature and precipitation 90-day outlooks issued for November, December, and January (2005–06). The temperature outlook for this period calls for warmer-than-usual conditions across much of the western United States. The remainder of the country is labeled "equal chance," which indicates there are not climatic signals for either above or below normal conditions during the forecast period (Figure 12–15a). As shown in Figure 12–15b, the precipitation outlook calls for wetter-than-normal conditions across most of Arkansas, Louisiana, and eastern Texas, whereas drier-than-normal conditions are expected in much of the Southwest from New Mexico to southern California.

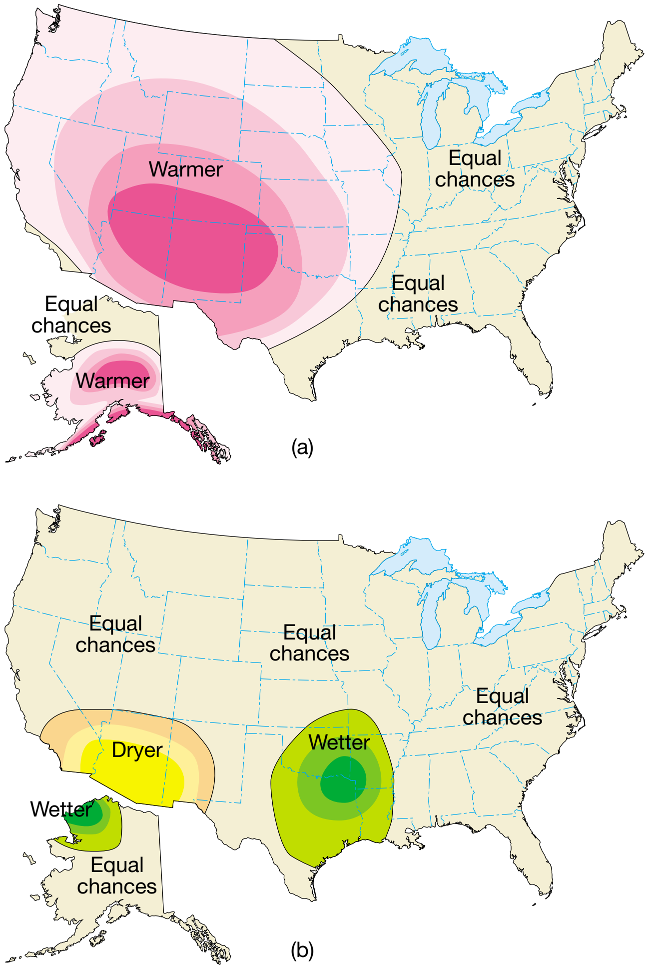


FIGURE 12-15 Extended forecast (90-day outlook) for (a) temperature and (b) precipitation for November, December, and January 2005–06. "Equal chances" means that there are not climatic signals for either above- or below-normal conditions.

Monthly and seasonal outlooks of this type are generated using a variety of criteria. Meteorologists consider the climatology of each region—the 30-year average of variables such as temperature. Factors such as snow and ice cover in the winter and persistently dry or wet soils in the summer are all taken into account. Forecasters also consider current patterns of temperature and precipitation. For example, over the past few years the southwestern United States has experienced below-normal levels of precipitation. Based on climatological data, the weather patterns that produce these conditions tend to gradually move toward the norm rather than making an abrupt change. Thus, forecasters predicted that this below-normal trend would continue for at least the next few months. Naturally, other climatological factors also have to be considered before a seasonal outlook is issued.

Recently, the relationship between sea-surface temperatures and patterns in the flow aloft have been shown to be particularly significant in making skillful seasonal forecasts for many parts of the world. For this reason, a great deal of emphasis is placed on monitoring and assessing oceanic conditions in the tropical Pacific, where El Niño / La Niña episodes have their roots. Although warm episodes (El Niño) have their greatest impact on Indonesia, Australia, and South America, they also influence conditions in regions outside the tropical Pacific, such as southern Africa and North America. During El Niño episodes, the westerlies increase in strength (especially during the winter) and produce above-normal precipitation over southern California and along the Gulf Coast states. In addition, warmer-than-average temperatures are the rule in the northern half of the United States. By contrast, cold (La Niña) episodes tend to result in weaker and more variable flow in the westerlies of both hemispheres.

Despite improved seasonal outlooks, the reliability of extended forecasts has been disappointing. Although some forecast skill is observed during the late winter and late summer, outlooks prepared for the "transition months," when the weather can fluctuate wildly, have shown little reliability.

Forecast Accuracy

> Never, no matter what the progress of science, will honest scientific men who have a regard for their professional reputations venture to predict the weather.
>
> *Dominique François Arago*
>
> *French physicist (1786–1853)*

Some might argue that Arago's statement is still true! Nevertheless, a great deal of scientific and technological progress has been made in the two centuries since this observation. Today accurate weather forecasts and warnings of extreme weather conditions are provided by the U.S. National Weather Service (Figure 12–16). Their forecasts are used by government agencies to protect life and property, by electric utilities and farmers, by the construction industry, travelers, airlines—in other words, nearly everyone.

How does the NWS measure the **skill** of its forecasts? In determining the occurrence of precipitation, for example, NWS forecasts are correct more than 80 percent of the time. Does this mean the NWS is doing a great job? Not necessarily. When establishing the skill of a forecaster, we need to examine more than the percentage of accurate forecasts. For example, measurable precipitation in Los Angeles is recorded only 11 days each year, on average. Therefore, the chance of rain in Los Angeles is 11 out of 365, or about 3 percent. Knowing this, a forecaster could predict no rain for every day of the year and be correct 97 percent of the time! Although the accuracy would be high, it would not indicate skill.

Any measure of forecasting skill must consider climatic data. Thus, if a forecaster is to exhibit forecasting skill, he or she must do better than forecasts that are based simply on climatic averages. In the Los Angeles example, the forecaster must be able to predict rain on at least a few of the rainy days to demonstrate forecasting skill.

The only aspect of the weather that is predicated as a percentage probability is rainfall (see Box 12–4). Here statistical data are studied to determine how often precipitation occurred under similar conditions. Although the fact that precipitation will take place can be predicted with better than 80 percent accuracy, predictions of the amount and time of occurrence are not as reliable.

Just how skillful are the weather forecasts provided by the National Weather Service? In general, very short-range forecasts (0 to 12 hours) have demonstrated considerable skill, especially for predicting the formation and movement of large weather systems like mid-latitude cyclones. The so-called short-range forecasts (12 to 72 hours) are much better at predicting precipitation amounts than forecasts made only two decades ago. However, the exact distribution of precipitation is tied to mesoscale structures, such as individual thunderstorms, that cannot be predicted by the current numerical models.

Thus, a forecast could predict 2 inches of rain for an area, but one town might receive only a trace while a neighboring community is deluged with 4 inches. Predictions of maximum and minimum temperatures and wind, in contrast, are quite accurate. Medium-range forecasts (3 to 7 days) have also shown significant improvement in the last few decades. Large cyclonic storms, such as the 1993 East Coast blizzard described at the beginning of Chapter 9, are often predicted a few days in advance. Yet, beyond day seven, the predictability of day-to-day weather using these modern methods proves no more accurate than projections made from climatic data.

The reasons for the limited range of modern forecasting techniques are many. As noted, the network of observing stations is incomplete. Not only are large areas of Earth's land–sea surface monitored inadequately, but on a global scale data from the middle and upper troposphere is meager. Moreover, the physical laws governing the atmosphere

FIGURE 12-16 Meterologist at the National Hurricane Center, in Miami Florida examining satellite imagery of Hurricane Ivan as the eye crosses the Alabama coastline on September 16, 2004. *(Photo by Andy Newman/ Associated Press)*

BOX 12-4 Precipitation Probability Forecasts*

Many of us are satisfied with a precipitation forecast that simply tells us whether rain is likely or not (Figure 12–F). In traditional precipitation forecasts like these, the inherent uncertainty is expressed using qualifiers such as "chance" and "likely." However, such vague terminology is subject to a wide range of misinterpretations by everyone. Moreover, compared to the use of probabilities to express level of uncertainty, traditional forecast terminology is imprecise and often ambiguous. To overcome these shortcomings, the National Weather Service instituted *precipitation probability forecasts* in 1965.

FIGURE 12-F Umbrellas serve as safe haven in rainy weather. *(Photo by Roy Morsch/The Stock Market)*

Probability refers to the chance that an event will occur and is represented as a number between 0 (the probability of an impossible one) and 1 (the probability of an inevitable one). Probability can also be expressed as a percentage, so that a 0.3 chance of an event occurring is expressed as 30 percent. This expresses the idea of probability in terms that people quickly understand.

In forecasting, probability is the percentage chance that at least 0.01 inch (0.025 cm) of precipitation will fall at *any point* in the area during the time period covered by the forecast. Thus, a 70 percent probability indicates a 7 in 10 chance of precipitation, and a 3 in 10 chance of no measurable precipitation at any location in the forecast area. In general, these forecasts cover 12-hour periods and moderate-sized metropolitan areas.

Unfortunately, most people interpret this forecast to mean that there is a 70 percent chance of precipitation somewhere in the forecast area, and a 30 percent chance that it will not occur anywhere in that area. This is not the case.

In actuality, this forecast states that at any point in the forecast area (for example, your home), there is a 70 percent chance of measurable precipitation.

Further, the chance of a shower occurring at a specific site is the product of two quantities: the probability that a precipitation-producing storm will develop or move into the area and the percent of the area that the storm is expected to cover.

For example, a forecaster can have a high degree of confidence that a storm will move into an area (say, 80 percent), but determine that only 40 percent of the area will be affected. Under these conditions, the forecaster will call for a 30 percent chance of precipitation ($0.80 \times 0.40 = 0.32$, or about 30 percent). Although precipitation is nearly certain, the chance that it will affect you, wherever you are in the forecast area, is only 3 in 10. Consequently, in the summer, when storms are frequently isolated or scattered, the probability that your immediate area will have rain tends to be smaller than during the winter months when storms are more widespread.

*The information presented here is based on a National Weather Service publication "Precipitation Probability Forecasts" and an article by Allan H. Murphy et al., "Misinterpretations of Precipitation Probability Forecasts," *Bulletin of the American Meteorological Society,* 61, no. 6 (June), 695–700.

are not fully understood and the current models of the atmosphere remain incomplete.

Nevertheless, numerical weather prediction has greatly improved the forecaster's ability to project changes in the upper-level flow. When the flow aloft can be tied more closely to surface conditions, weather forecasts should show even greater skill.

The following abridged version of a policy statement by the American Meteorological Society summarizes the predictive skill of weather forecasts.

1. ***Very short-range forecasts (0-12 hours).*** These forecasts have shown considerable skill and utility, especially for predictions of the evolution and movement of large- and medium-sized weather systems. However, the accuracy of the forecasts decreases rapidly as the scale of the weather features decreases and the time range of the forecasts increases. Forecasting the evolution and movement of smaller-scale, short-lived, often intense weather phenomena such as tornadoes, hail storms, and flash floods is less mature than for predictions of larger-scale weather systems.

   Despite the difficulties in predicting these small-scale phenomena, the lead time of watches and warnings has increased. For example, the lead time for tornado warnings has more than doubled in the last decade due to the improved observing systems provided by the NWS operational Doppler radar network and satellite imagery. These warnings and watches rely heavily on observing and detecting when conditions are favorable for the development of severe convection and then monitoring each storm's evolution.

2. ***Short-range forecasts (12–72 hours).*** The accuracy of short-range forecasts (12–72 hours) has continued to increase during the past decade. Improvements in observing systems and in how the data are assimilated into the computer models have resulted in steady improvement in the ability to predict the evolution of major, larger-scale weather systems. Accurate predictions of the development and movement of large-scale weather systems and the associated day-to-day variations in temperature, precipitation, cloudiness, and air quality are made regularly throughout this time range.

   Forecasts of how much precipitation will fall in the 36–60-hour time frame are now more accurate than 12–36-hour predictions were during the late 1970s. However, the details of precipitation patterns are often tied to smaller-scale structures such as fronts, thunderstorm outflow boundaries, and mesoscale convective systems that are still difficult for the current generation of numerical models to simulate.

3. ***Medium-range forecasts (3–7 days into the future).*** Medium-range forecasts have shown significant improvement in the last two decades. Large-scale events like the East Coast blizzards of 1993 and 1996 are now often forecast days in advance of the first flake of snow, allowing emergency managers the opportunity to make plans to mitigate potential life-threatening situations that might develop. Three-day forecasts of major low-pressure systems that determine the general evolution of the weather are more skillful today than 36-hour forecasts were 15 years ago. In the late 1970s, day 5 forecasts of precipitation were no more accurate than climatology. Since then, skill of day 5 forecasts has more than doubled, with predictions of major cyclones now being as skillful as day 3 forecasts were a decade ago.

4. ***Extended-range forecasts (week 2).*** The predictability of the day-to-day weather for periods beyond day 7 is usually small. Operationally, forecasts at these time ranges have taken the form of 6–10 day mean temperature and occurrence of precipitation departures from normal. (see Box 12–5) The accuracy of these five-day mean temperature and precipitation forecasts has more than doubled since the 1970s. The accuracy of precipitation forecasts is less than that for temperature, even though the skill of both has increased at about the same rate.

5. ***Monthly and seasonal forecasts.*** As a result of research over the last decade, monthly and seasonal forecasts of mean temperature and precipitation are now useful for specialized applications in major economic sectors, such as agricultural and energy interests, if utilized over a long period. There is reason for optimism that the utility of these long-range forecasts can be improved as computer models and statistical methods become more sophisticated. These new techniques are expected to improve monthly and seasonal outlooks, especially when the relatively strong signals associated with El Niño and La Niña events are present. Notwithstanding these advances, no verifiable skill exists or is likely to exist for forecasting day-to-day weather changes beyond two weeks. Claims to the contrary should be viewed with skepticism.*

Students Sometimes Ask . . .

Why are weather forecasts so often inaccurate?

The atmosphere is a dynamic system composed of countless interacting parts. As a result, weather forecasting is an extraordinarily complex process. Nevertheless, with the advent of high-speed computers and enhanced numerical models, meteorologists are able to produce 24-hour weather forecasts that are accurate more than 80 percent of the time. Perhaps the main reason people feel forecasts are often wrong is that they are much more likely to remember the few inaccurate forecasts that have inconvenienced them.

*From the *Bulletin of the American Meteorological Society*, 79, no. 10 (October 1998), 2161–63.

BOX 12-5 What Is "Normal"?

When we watch a weather report on TV, the person making the presentation usually lists statistics for the day. Frequently, after stating the high, low, and average temperatures, the reporter indicates whether the daily mean is above or below normal. Similarly, following a report that includes the monthly or annual precipitation total, we will be told how much of a *departure from normal* the figure represents. Sometimes the weathercaster even follows up such information with a remark informing us that the daily mean temperature or the monthly rainfall total is "much" above or below normal.

Does this mean that we are experiencing abnormal conditions? Certainly, many people would assume that the statistics are unusual or even extraordinary, because most of us perceive "normal" as implying ordinary or frequent. Such a perception arises from the common usage of the word *normal:* "Conforming, adhering to, or constituting a typical or usual standard, pattern, level or type."*

If normal does not imply ordinary or frequent, just what does it mean when applied to meteorological observations? *Normal is simply an average of a climate element over a 30-year period.* It is a standard that is used in making comparisons. A departure from normal is the difference between currently observed values and the 30-year average. The normal is usually not the most frequent value (called the *mode*) nor the value above which half the cases fall (called the median). It is safe to say that no matter what meteorological statistic is considered, experiencing a value that equals the normal is actually the exception and not the rule (Figure 12–G).

The World Meteorological Organization has established a standard definition for the 30-year span used to compute normals:

> Normals are recalculated each decade in an attempt to keep up with any climatic changes that might take place. For example, on January 1, 2001, the period for computing normals changes. Prior to that date, normals represent the period January 1, 1961, through December 31, 1990. Beginning January 1, 2001, data for the 1990s replaces the observations from the 1960s.

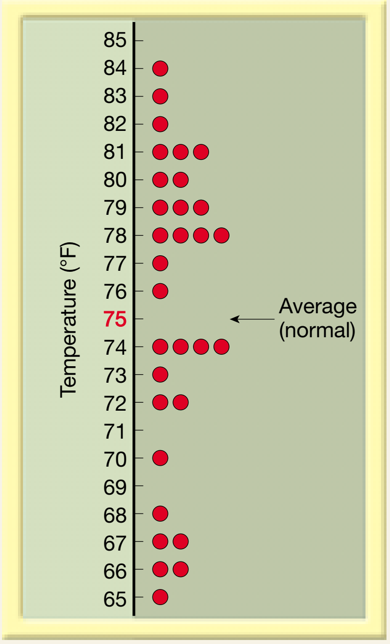


FIGURE 12-G Plot of daily mean temperatures for Peoria, Illinois, August 1993.

*From *Webster's II New Riverside University Dictionary* (Boston: Houghton Mifflin Company, 1984), p. 803.

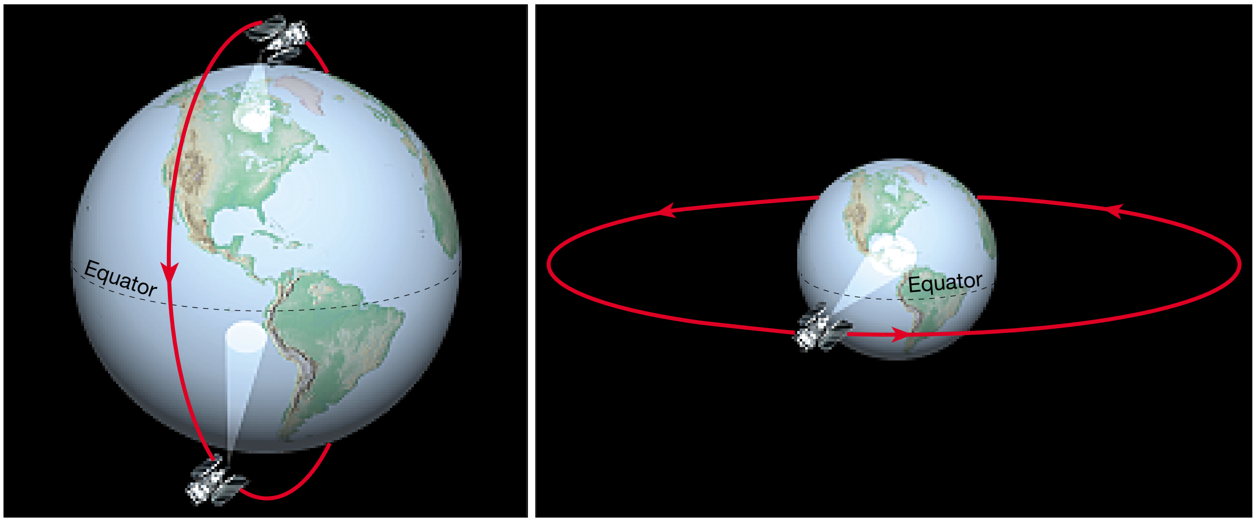
In summary, the accuracy of weather forecasts covering short- and medium-range periods has improved steadily over the past few decades, particularly in forecasting the evolution and movement of middle-latitude cyclones. Technological developments and improved computer models, as well as an increased understanding of how the atmosphere behaves, have greatly contributed to this success. The ability to accurately predict the weather beyond day seven, however, remains poor.

Satellites in Weather Forecasting

Meteorology entered the space age on April 1, 1960, when the first weather satellite, *TIROS* 1, was launched. (*TIROS* stands for Television and Infra-Red Observation Satellite.) In its short life span of only 79 days, *TIROS* 1 transmitted thousands of images to Earth. Nine additional *TIROS* satellites were launched by 1965. In 1964, the second-generation *Nimbus* (Latin for *cloud*) satellites had infrared sensors capable of "seeing" cloud coverage at night.

Another series of satellites was placed into polar orbits so that they circled Earth in a north-to-south direction (Figure 12–17a). These **polar satellites** orbit Earth at low altitudes (a few hundred kilometers) and require only 100 minutes per orbit. By properly orienting the orbits, these satellites drift about 15° westward over Earth's surface during each orbit. Thus, they are able to obtain images of the entire Earth twice each day and coverage of a large region in only a few hours.

By 1966 **geostationary satellites** were placed in orbit over the equator (Figure 12–17b). These satellites, as their name implies, remain fixed over a point on Earth because their rate of travel keeps pace with Earth's rate of rotation. To keep a satellite positioned over a given site, however, the



(a) Polar-orbiting satellites (b) Geostationary satellite

FIGURE 12-17 Weather satellites. (a) Polar-orbiting satellites about 850 kilometers (530 miles) above Earth travel over the North and South poles. (b) A geostationary satellite moves west to east above the equator at a distance of 36,000 kilometers (22,300 miles) and at the same rate that Earth rotates.

satellite must orbit at a greater distance from Earth's surface (about 35,000 kilometers, or 22,000 miles). At this altitude, the speed required to keep a satellite in orbit will also keep it moving in time with the rotating Earth. However, at this distance, some detail is lost on the images.

What Weather Satellites Provide

Weather satellites greatly add to our knowledge of weather patterns and help fill gaps in observational data, especially over the oceans. For example, examine the clarity with which the clouds outline the fronts of the wave cyclone shown in Figure 9–25. These wishbone-shaped swirls are easily traced by satellites as they migrate across even the most remote portions of our planet. Moreover, as you learned in Chapter 11, satellites allow us to identify and track developing hurricanes long before they are detected by the land-based surface observational network.

Weather satellites are equipped to generate several types of images simultaneously, including visible, infrared, and water vapor images. *Visible images*, like the one shown in Figure 12–18, are views of Earth the way an astronaut would see our planet from space. The primary difference is that the satellite images are often black and white. Visible images are produced by measuring the intensity of light reflected from cloud tops and other surfaces. By contrast, *infrared images* are obtained from radiation emitted (rather than reflected) from the same objects.

Infrared images are very useful in determining regions of possible precipitation within a middle-latitude cyclone. Compare the visible image in Figure 12–18 with the infrared image in Figure 12–19. Note that in the visible image all the clouds exhibit the same intensity of white and appear very similar (Figure 12–18).

By contrast, the infrared image provides a way to determine which clouds are the most probable precipitation producers (Figure 12–19). Here, warm objects appear darker and cold objects appear lighter. Because high cloud tops are colder than low cloud tops, towering cumulonimbus clouds that may generate heavy precipitation appear very white. By contrast, the lower, thinner nimbostratus clouds that produce only medium-to-light precipitation appear darker. Thus, infrared satellite images are valuable forecasting tools. For more on this idea, see Box 2–5 "Infrared Imaging, p. 55."

Water-vapor images provide yet another way to view our planet. Most of Earth's radiation with a wavelength of 6.7 micrometers is emitted by water vapor. Therefore, satellites equipped with detectors for this narrow band of radiation are, in effect, mapping the concentration of water vapor in the atmosphere. Bright regions in Figure 12–20 translate into regions of high water-vapor concentration whereas dark areas are covered by drier air. In addition, because most fronts occur between air masses having contrasting moisture contents, water-vapor images are valuable tools for locating frontal boundaries.

The third generation of weather satellites, known as Geostationary Operational Environmental Satellites (GOES), provides visible, infrared, and water-vapor images for North America every half hour (Figure 12–21). (These are the same satellite images that often appear on The Weather Channel.) Such frequent observations allow meteorologists to track the movement of large weather systems that cannot be adequately followed by weather radar or polar-orbiting satellites. GOES has also been very important in monitoring the development and movement of tropical storms and hurricanes (Figure 12–22).

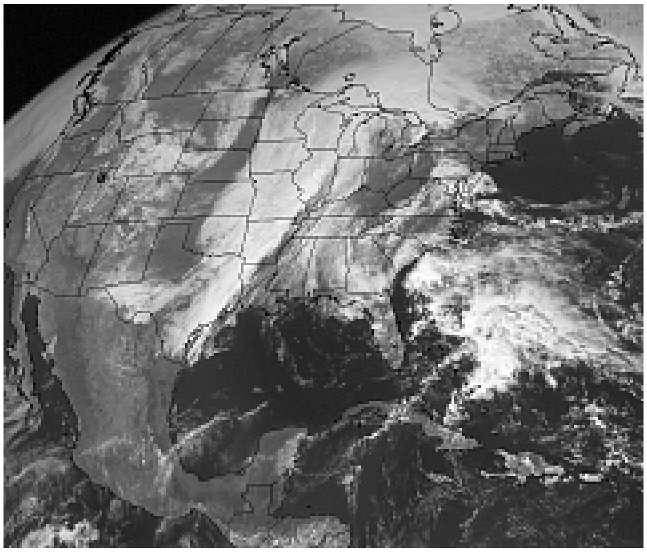


FIGURE 12-18 *GOES 8* satellite view of cloud distribution about midday on March 28, 2003. This image records visible light, much as your eyes would see it. Compare this with the infrared image in Figure 12–19. *(Courtesy of NOAA)*

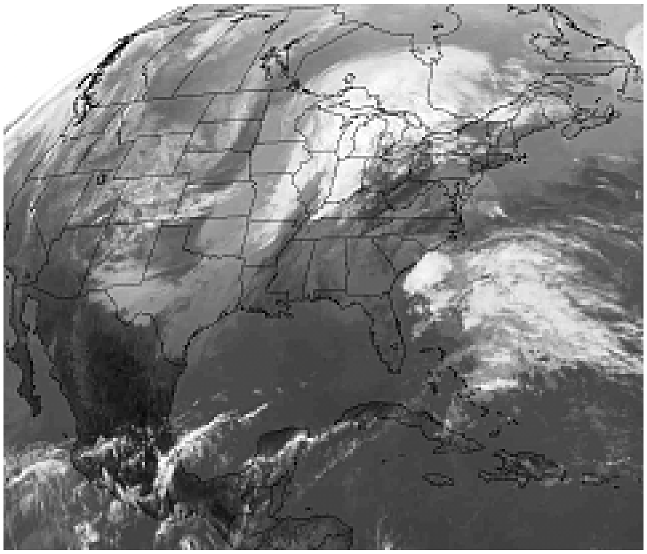


FIGURE 12-19 *GOES 8* infrared image of the same cloud pattern shown in Figure 12–18. On this image, some of the clouds appear much whiter than others. These are the thicker, vertically developed clouds that have cold tops. A band of rain clouds can be seen over the north-central United States and extending into Canada. *(Courtesy of NOAA).*

Satellite Measurements

Although weather satellites are still more weather observers than weather forecasters, ingenious developments have made them more than simply TV cameras pointed at Earth from space. For example, some satellites are equipped with instruments designed to measure temperatures at various altitudes. How is this accomplished? The technique relies on the fact that different wavelengths of energy are absorbed and radiated by different layers of the atmosphere. On a clear night, for example, the atmosphere does not absorb radiation from Earth's surface that has a wavelength of 10 micrometers (recall that this is the *atmospheric window*). Thus, by measuring the radiation at 10 micrometers, we have a method of determining Earth's surface temperature. Because other wavelengths indicate the altitudes within the atmosphere from which they originate, they too can be used to measure temperatures. This method of obtaining temperature readings aloft is simpler in principle than in

FIGURE 12-20 Water-vapor image from the *GOES 10* satellite for March 19, 2003. The greater the intensity of white, the greater the atmosphere's water-vapor content. Black areas are driest. *(Courtesy of NOAA).*

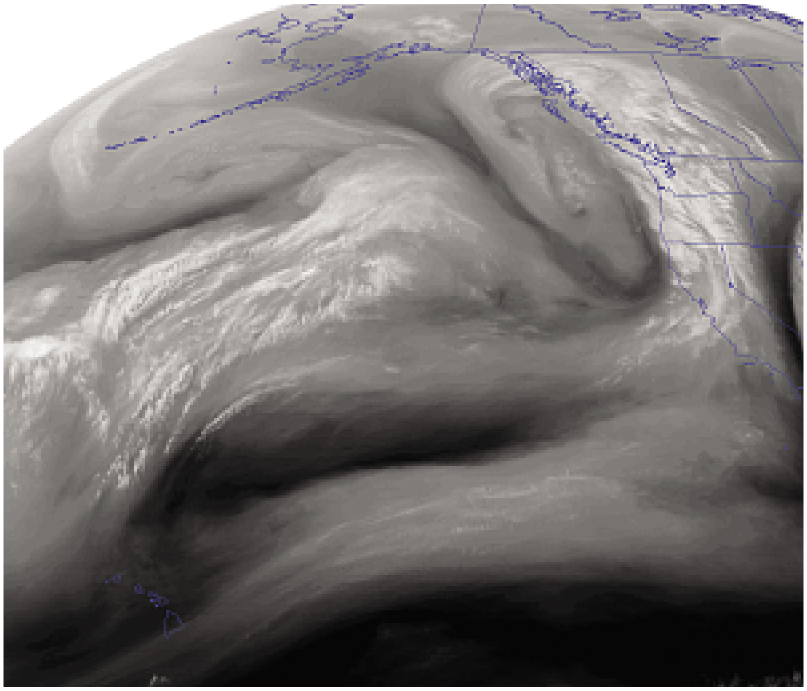
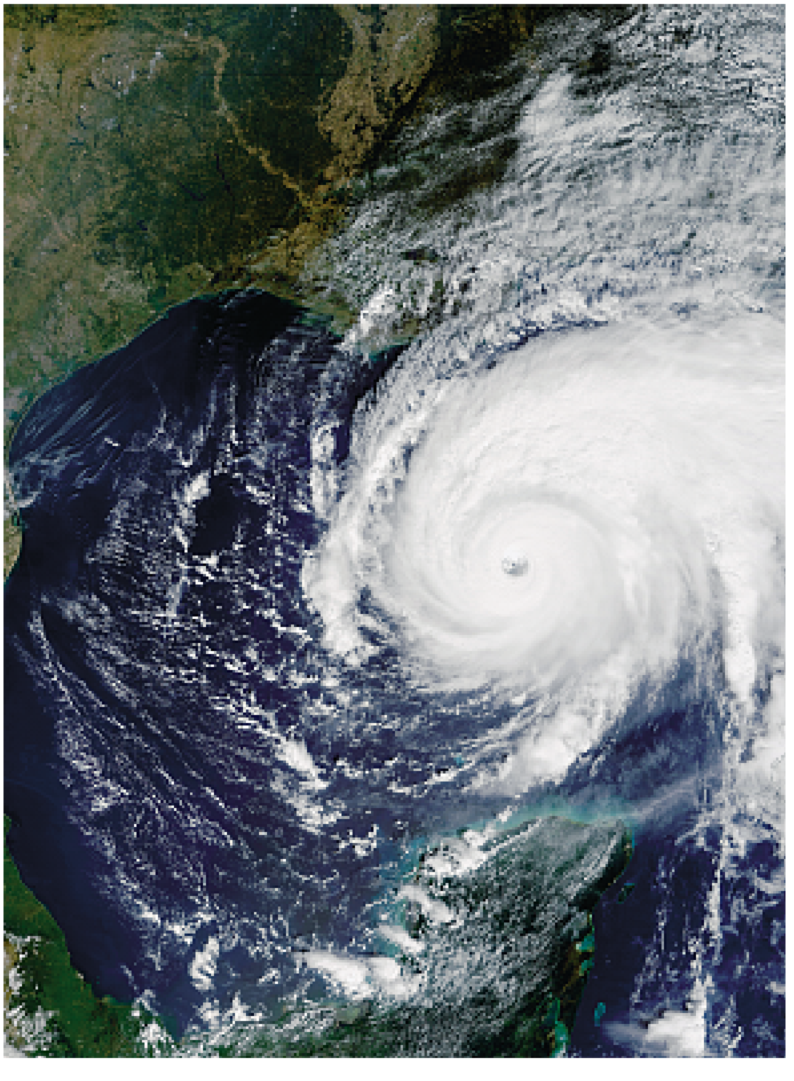


FIGURE 12-21 *GOES-N* being prepared for launch. *GOES-N* is one of three satellites that will monitor atmospheric conditions that trigger severe weather events such as tornadoes, flash floods, hailstorms, and hurricanes. *(Courtesy of NASA)*

practice, but with refinement it can supplement the limited supply of conventional radiosonde data.

Other satellites allow us to measure rainfall intensity and amounts, both at the surface and above the surface, and to monitor winds in regions where few, if any, conventional instruments are available. Images from the *Tropical Rainfall Measuring Mission (TRMM)* illustrate satellite-based precipitation measurement. For examples refer to Box 1–1, "Monitoring Earth from Space" (p. 11), and to Box 11–4, "A 3-D Look Inside a Hurricane" (p. 340). A satellite that provides data on winds is NASA's *QuickSCAT* spacecraft, which is discussed in Box 7–3, "Monitoring Winds from Space" (p. 222). It provides data that allows us to continuously map winds under most atmospheric conditions over 90 percent of Earth's ice-free oceans. Box 11–3, "Examining Hurricane Katrina from Space" (p. 334), provides excellent images from both the *TRMM* and *QuickSCAT* spacecraft.



Students Sometimes Ask…

When were the first U.S. weather maps produced?

Meteorological observations were made by the U.S. Weather Bureau, the predecessor to the National Weather Service, for the first time on November 1, 1870. These observations and recordings led to the production of the first U.S. Daily Weather Map in 1871. The early maps included isobars and described the weather conditions at select locations but had little predictive value. It wasn't until the late 1930s that air-mass and frontal-analysis techniques were used by the U.S. Weather Bureau. On August 1, 1941, a new Daily Weather Map was introduced. In addition to including various types of fronts, this map made use of the station model—a group of symbols indicating weather conditions at nearly 100 locations (see Box 12–3). Although the look has changed, the basic structure of the Daily Weather Map remains largely the same today as it was over 65 year ago.

FIGURE 12-22 Weather satellites are invaluable tools for tracking storms and gathering atmospheric data. This enhanced infrared image shows Hurricane Rita approaching the Gulf Coast on September 22, 2005. *(Courtesy of NASA)*

Chapter Summary

- In the United States, the government agency responsible for gathering and disseminating weather-related information is the *National Weather Service (NWS).* Perhaps the most important services provided by the NWS are forecasts and warnings of hazardous weather including thunderstorms, flooding, hurricanes, tornadoes, winter weather, and extreme heat.
- The process of providing weather forecasts and warnings throughout the United States occurs in three stages. First, data are collected and analyzed on a global scale. Second, a variety of techniques are used to establish the future state of the atmosphere; a process called *weather forecasting.* Finally, forecasts are disseminated to the public, mainly through the private sector.
- Assessing current atmospheric conditions, called *weather analysis,* involves collecting, transmitting, and compiling millions of pieces of observational data. On a global scale the *World Meteorological Organization* is responsible for gathering, plotting, and distributing weather data.
- Initially, weather data are displayed on a synoptic weather map. A weather map shows the status of the atmosphere and includes data on temperature, humidity, pressure, and airflow. In addition to surface maps, twice-daily upper-air charts depicting the pressure field are drawn at 850-, 700-, 500-, 300-, and 200-millibar levels.
- The methods used in weather forecasting include *numerical weather prediction, persistence forecasting, climatological forecasting*, the *analog method*, and *trend forecasting. Numerical weather prediction (NWP)* is the backbone of modern forecasting. The underlying premise of NWP is that the behavior of atmospheric gases is governed by a set of physical principals that can be expressed mathematically. Meteorologists apply current conditions to computer models that predict the future state of the atmosphere. Perhaps the simplest forecasting method, *persistence forecasting*, is based on the tendency of the weather to remain unchanged for several hours. *Climatological forecasting* uses 30-year statistical averages of weather elements, such as temperature, to make predictions. This type of forecasting is particularly useful when making agricultural decisions. Using the *analog method*, forecasters look for well-established weather patterns from the past that match a current weather event. From such comparisons meteorologists predict how the current event might evolve. *Trend forecasting* determines the speed and direction of a weather disturbance and, from this information, extrapolates its future position. A related technique, called *nowcasting*, uses radar and geostationary satellites to detect and track severe weather events, such as thunderstorms and tornadoes.
- For many years meteorologists have been aware of a strong correlation between cyclonic disturbances at the surface and the daily and seasonal fluctuations in the wavy flow of the westerlies aloft. Upper-air maps are generated twice daily and provide forecasters with a picture of conditions at various levels in the troposphere. These maps provide information that can be used to predict daily maximum temperature, locate areas where precipitation is likely to occur, and determine whether a thunderstorm will develop into a supercell. When the upper airflow exhibits large-amplitude waves, extreme weather is the rule. In winter strong troughs tend to spawn heavy snowstorms, whereas in summer they are associated with severe thunderstorms and tornado outbreaks. Because the position of the jet stream migrates with the Sun's vertical rays, the southern tier of states encounters most of their severe weather in winter and spring. During the summer, the northern states and Canada experience an increase in the number of strong storms and tornadoes.
- *Long-range weather forecasting* is an area that relies heavily on statistical averages obtained from past weather events, also referred to as *climatic data.* Weekly, monthly, and seasonal weather outlooks prepared by the National Weather Service are not weather forecasts in the usual sense. Rather, they indicate only whether the region will experience near-normal precipitation and temperatures or not.
- Weather forecasting relies on the validity of prognostic maps produced by computer-generated models and the skill of the forecaster. Very short-range (0–12 hours) forecasts have demonstrated considerable skill, especially for predicting the formation and movement of large weather systems. Short-range forecasts (12–72 hours) of maximum and minimum temperatures and wind speeds are quite accurate. Furthermore, predicting precipitation amounts is much better than forecasts made only two decades ago. Medium-range forecasts (3–7 days into the future) have shown significant improvement in the last 20 years. However, the accuracy of day-to-day weather forecasts for periods beyond seven days is relatively unreliable.

Vocabulary Review

National Weather Service (NWS), (p. 346)
nowcasting (p. 358)
numerical weather prediction (p. 353)
persistence forecasts (p. 356)
polar satellite (p. 368)
prognostic charts (progs) (p. 354)
skill (p. 365)
synoptic weather maps (p. 350)
trend forecasting (p. 358)
weather analysis (p. 348)
weather forecast (p. 346)
Weather Forecast Offices (p. 373)
wind profilers (p. 349)
World Meteorological Organization (p. 348)

Review Questions

1. What is the mission of the National Weather Service?
2. List the three steps involved in providing weather forecasts.
3. What is meant by *weather analysis?*
4. What information is provided by a surface weather map? (See Box 12–2.)
5. Why is the name "numerical weather forecasting" somewhat misleading?
6. Briefly describe the basis of numerical weather predictions.
7. How are prognostic charts different from synoptic weather maps?
8. What do computer-generated numerical models try to predict?
9. What is *ensemble forecasting?*
10. What additional information does an ensemble forecast provide over a traditional numerical weather prediction?
11. What method of forecasting is based on pattern recognition?
12. What term is applied to the very short-range forecasting technique that relies heavily on weather radar and satellites.
13. When forecasters predict the weather based on average weather statistics accumulated over many years, it is called _____.
14. Describe the statistical approach called the "analog method." What are its drawbacks?
15. If it is snowing today, what could be predicted for tomorrow if persistence forecasting were employed?
16. What type of weather is typically forecast using nowcasting techniques?
17. Which upper-level map is most effective for observing the polar jet stream in winter?
18. During winter, if the jet stream is considerably south of your location, will the temperatures likely be warmer or colder than normal?
19. What is a *jet streak*?
20. What are two pieces of information that forecasters can glean from 850-mb maps?
21. What elements are predicted in a long-range (monthly) weather chart?
22. Give an example of why the percent of correct forecasts is not always a good measure of forecasting skill.
23. How do satellites help identify clouds that are most likely to produce precipitation?
24. What information is provided by water-vapor images?
25. What advantage do geostationary satellites have over polar satellites? Name one disadvantage.

Problems

1. The map in Figure 12–23 has several weather stations plotted on it. Using the weather data for a typical day in March, which are given in Table 12–1, complete the following:
   a. On a copy of Figure 12–23, plot the temperature, wind direction, pressure, and sky coverage by using the international symbols given in Appendix B.
   b. Using Figure 12–D as a guide, complete this weather map by adding isobars at 4-millibar intervals, the cold front and the warm front, and the symbol for low pressure.
   c. Apply your knowledge of the weather associated with a middle-latitude cyclone in the spring of the year, and describe the weather conditions at each of the following locations:
      1. Philadelphia, Pennsylvania
      2. Quebec, Canada
      3. Toronto, Canada
      4. Sioux City, Iowa
2. Many TV weather reports include a seven-day outlook. Tune in such a report and jot down the forecast for the last (seventh) day. Then, each day thereafter, write

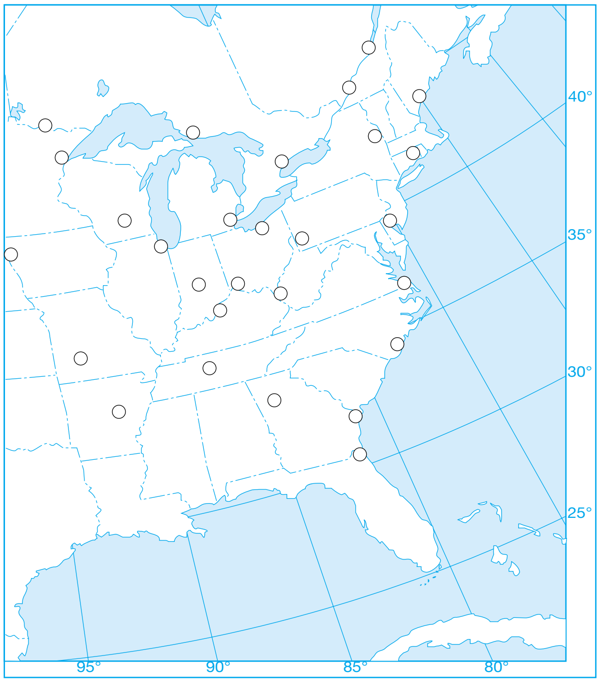


FIGURE 12-23 Map to accompany problem number 1.

down the forecast for the day in question. Finally, record what actually occurred on that day. Contrast the forecast seven days ahead with what actually took place. How accurate (or inaccurate) was the seven-day forecast for the day you selected? How accurate was the five-day forecast for this day? The two-day forecast?

3. Using Box 12–4 as a guide, calculate the precipitation probability for the following situations:

a. There is a 50 percent chance that a storm will move into the forecast area and that it will affect 20 percent of the area.

b. There is a 90 percent chance that a storm will move into the forecast area and that it will affect 100 percent of the area.

c. There is a 50 percent chance that a storm will move into the forecast area and that it will affect 50 percent of the area.

TABLE 12-1 Weather data for a typical March day

Location	Temperature (°F)	Pressure (MB)	Wind direction	Sky cover (tenths)
Wilmington, N.C.	57	1009	SW	7
Philadelphia, Pa.	59	1001	S	10
Hartford, Conn.	47	1001	SE	Sky obscured
International Falls, Minn.	−12	1008	NE	0
Pittsburgh, Pa.	52	995	WSW	10
Duluth, Minn.	−1	1006	N	0
Sioux City, Iowa	11	1010	NW	0
Springfield, Mo.	35	1011	WNW	2
Chicago, Ill.	34	985	NW	10
Madison, Wis.	23	995	NW	10
Nashville, Tenn.	40	1008	SW	10
Louisville, Ky.	40	1002	SW	5
Indianapolis, Ind.	35	994	W	10
Atlanta, Ga.	49	1010	SW	7
Huntington, W.Va.	52	998	SW	6
Toronto, Canada	44	985	E	9
Albany, N.Y.	50	998	SE	7
Savanna, Ga.	63	1012	SW	10
Jacksonville, Fla.	66	1013	WSW	10
Norfolk, Va.	67	1005	S	10
Cleveland, Ohio	49	988	SW	4
Little Rock, Ark.	37	1014	WSW	0
Cincinnati, Ohio	41	997	WSW	10
Detroit, Mich.	44	984	SW	10
Montreal, Canada	42	993	E	10
Quebec, Canada	34	999	NE	Sky obscured

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
- **Internet-wide key term searches**

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