Storms. A storm can be defined as a *disturbed* state of the atmosphere, the opposite of what we would call *calm*. Storms are a natural part of the environment, arising as a consequence of solar heating and the Earth's topography and rotation. Humans tend to categorize storms according to we see as the weather's most damaging or impressive aspect; hence, we refer to snowstorms, thunderstorms, ice storms, hailstorms, windstorms, and so on. Other types of storms have special or local names, such as tornadoes, hurricanes, or blizzards. The latter often involve several different aspects of weather. For example, the definition of a blizzard involves a set of threshold values for snowfall rate, wind speed, and perhaps temperature. A tornado is a special kind of windstorm associated with thunderstorms.

However, from the point of view of a meteorologist, the notion of a storm takes on a different meaning. The meteorologist wants to understand the *causes* of the snow, wind, hail, and other events. Disturbed weather of all sorts tends to be associated with regions of relatively low atmospheric pressure, whereas the weather associated with relatively high pressure is typically calm and undisturbed. Because of the way wind and pressure are related, regions of low pressure are almost always characterized by winds rotating cyclonically (anticlockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere) around the center of the low pressure. Thus, disturbed weather of all sorts (i.e., the variety of different storms) occurs primarily in association with *cyclones*. Cyclones come in all sizes, the largest span thousands of kilometers and last for days or even weeks, and the smallest are only a few kilometers across and last for a few hours at most. There are three classes of cyclones considered to be most important in connection with storms. {*see* Cyclones}

Extratropical Cyclones. Outside of the tropics, the most important storm makers are those with characteristic sizes of several thousand kilometers, called *extratropical cyclones*. These cyclones, which persist for several days or occasionally longer, are the traveling centers of low pressure seen on television and newspaper weather maps. Extratropical cyclones in middle latitudes are the atmosphere's primary large-scale response to the unequal distribution of solar heating between the equatorial regions and the poles. The tropics are much warmer than the polar regions, and when the temperature difference becomes too large, these large cyclones develop to export the excess heat from the tropics to the poles.

In this heat transfer process, many of the important weather events we call *storms* are created: rain, snow, ice, wind, and hail. In a sense, all the stormy weather events that affect us are simply side-effects of the large-scale heat transfer from the equator to the poles. The extratropical cyclone is itself a storm, of course, but its actions create conditions that make many other types of storms possible. For example, thunderstorms arise when conditional instability in the presence of water vapor in the air is "triggered" by a process of strong lifting. An extratropical cyclone can create such conditions by its poleward transport of warm, moist air at low levels, while the frontal boundaries associated with the moving air masses in the cyclone can provide lifting to initiate thunderstorms. Water falling as snow in a blizzard probably evaporated from the tropical oceans and was brought poleward in the flow ahead of a cyclone.

As the extratropical cyclone develops, it can produce very strong winds over a large, deep region. To obtain a feeling for the energies involved in an extratropical cyclonic storm, assume that such a storm covers an area of about 1 million square kilometers, and the average windspeed within the cyclone is about 10 meters per second (roughly 20 miles per hour). Just to maintain those winds within the volume of a single extratropical cyclone, it takes the energy of around 100 1-megaton thermonuclear bombs every second. There are several such cyclones occurring worldwide at any moment. The winds themselves can be damaging to structures and vegetation, and they also are important in creating the potential for other types of damaging storms. Severe thunderstorms, including tornadic storms, usually arise in the high-energy environment associated with an extratropical cyclone. In the winter, moisture can fall as rain in one part of the extratropical cyclone, ice in another part, sleet in another, and snow in yet another. As an extratropical storm moves by, a single observer may see several different types of storms in succession: a severe thunderstorm with hail and a tornado, a rainstorm, an ice storm, and a snowstorm, all within 24 hours.

The damage and loss of life associated with extratropical cyclones can be quite extensive. A notable recent example was the major winter storm of 13-14 March 1993 over the eastern United States. This event produced severe thunderstorms in the southeastern United States and heavy snowfalls over a swath covering the middle Atlantic and New England, as well as wind gusts exceeding hurricane force. Another well-known storm surprised the United Kingdom on October 15-16, 1987, with devastating winds. Such storms are almost always characterized by a phase of very rapid development, with accelerating winds and rapidly falling pressure.

Tropical Cyclones. The second major type of storm-producing cyclone is the tropical variety. Tropical cyclones have different names in different parts of the world, including *typhoon*, *hurricane*, *cyclone*. All such storms originate in the tropics from an initial disturbance characterized by a cluster of thunderstorms. These thunderstorms become organized into a cyclonic disturbance with a warm core. Tropical cyclones characteristically span hundreds of kilometers and last from several to 10 days or more. Whereas extratropical cyclones gain energy from *vertical wind shear* (that is, winds changing speed and direction with height) ultimately related to the equatorial-polar temperature contrast, tropical cyclones are dissipated by vertical wind shear and develop only in the relatively weak shear of the tropics. Tropical cyclones develop almost exclusively over warm ocean waters and dissipate rapidly after making landfall, or when they travel over cold water. A major energy source for tropical cyclones lies in the warm surface waters of the ocean.

Tropical cyclones come in a variety of sizes and intensities. At their strongest, they are potentially the most damaging storms produced by the atmosphere because they produce violent winds, sometimes approaching the speeds seen in tornadoes, over an area of hundreds of square kilometers, often combined with torrential rainfall and sometimes with a *storm surge*. The storm surge is an increase in the height of the sea caused by the reduced atmospheric pressure of the disturbance and the force of the wind, combined with ocean-floor topography. This increase in sea height is enhanced by storm winds, so that low-lying areas where tropical cyclones make landfall can be inundated with rising sea water at the same time as they are experiencing destructive winds and torrential rainfall. Storm surges occasionally coincide with the high tide phase of the normal tidal cycle; when this happens, destruction and casualties can be especially high. Tropical cyclones have been responsible for tremendous property damage, as recently seen with hurricanes Hugo (South Carolina, 22 September 1989) and Andrew (24 August 1992 in Florida and 26 August in Louisiana) in the United States. Devastation in tropical cyclones can be intense, as with Cyclone Tracy (Darwin, Australia on 25 December 1974), with many casualties; reports of tens of thousands of deaths have been associated with tropical cyclones in the Bay of Bengal.

Tropical cyclones also can produce local conditions favoring the development of tornadoes within them, typically after a storm makes landfall. Tornadoes within tropical cyclones usually are not as violent as those produced in other circumstances, but they can produce local swaths of particularly intense damage within the area affected by the parent cyclone.

Dissipating hurricanes may contribute to further damage from torrential rainfall long after their winds have diminished below hurricane force. In some arid parts of the world, such as the American Southwest, the occasional hurricane's rainfall may be a significant portion of the total precipitation in the region over a decade. Not all of the effects of such storms are damaging, however; the rainfall from a tropical storm in the fall can provide relief after a summer's drought.

Other important types of cyclones. Over the polar seas, another type of intense cyclone called a *polar low* can occur. These small systems form in airstreams flowing off the poles over relatively warm sea surfaces. Such a polar airstream occurs in the wake of an extratropical cyclone, after cold frontal passage. As with all other cyclones, the sizes and intensities of polar lows vary, but they characteristically are less than about 100 kilometers in diameter. These polar lows can produce heavy snowfalls with near-hurricane force winds and sometimes have embedded thunderstorms. They appear to have some features in common with tropical cyclones, including an energy source from the relatively warm ocean surface temperatures. The name *arctic hurricanes* has been applied to them. Aside from the danger they represent to shipping and aircraft, their impact when making landfall can be both surprising and devastating. Scandinavia and the countries bordering the Baltic Sea are often affected, because polar lows are especially common in air flowing off Greenland. {*see* Polar Lows}

Another type of cyclone, called a *mesocyclone*, arises in association with thunderstorms. In some special situations, a large portion of a single thunderstorm can be in cyclonic rotation. A thunderstorm that has this characteristic is called a *supercell thunderstorm*, and is almost always accompanied by some sort of severe local storm activity, such as tornadoes, damaging winds, large hailstones. Supercells also can produce heavy rain and abundant lightning. Not all severe local storm events are associated with mesocyclones, but most mesocyclones include at least one form of hazardous weather. Mesocyclones are characteristically less than about 10 kilometers across, and can last for several hours. {*see* Thunderstorms}

When thunderstorms develop in groups, they can form a system called a *mesoscale convective system* . It is not uncommon for such a system to develop a cyclonic disturbance in association with it. Such disturbances usually exist above the Earth's surface, so their presence can be rather difficult to observe. On some occasions, however, the disturbance can persist after the thunderstorm activity dissipates and the cyclonic rotation can be seen in satellite images of the cloud debris left by the thunderstorms. Such remnant cyclonic disturbances may be associated with subsequent redevelopment of new thunderstorms and the organization of those new thunderstorms into another mesoscale convective system. This formation and dissipation of deep, moist convection in association with a traveling cyclone can continue for several days. Much remains to be learned about cyclones that develop in conjunction with thunderstorms.

Observations, Technology, and Forecasting. Our ability to observe the weather is a key factor in recognizing and forecasting storms. Meteorological satellites and special radars have increased knowledge about storms significantly. Weather satellites have been especially important in the detection and prediction of storms coming onshore from the ocean. A few decades ago, tropical and extratropical storms could make landfall with little or no warning, resulting in many casualties. Current and planned observing systems will continue to improve our capability to detect and forecast such evens.

As we learn more about storms and their causes, we should be able to use that knowledge to make better forecasts, including forecasts by computer models of the atmosphere. With the rapid development of computer technology, computer-based models of atmospheric behavior are becoming increasingly capable of predicting many of the processes that lead to storms. However, most storm phenomena are nonlinear, which means that the phenomena are not the simple sum of their components. This imposes an inherent limit to the predictability of storms. Thus the future of storm forecasting will not depend entirely on computer models.

Bibliography

Anthes, R. A. *Tropical Cyclones: Their Evolution, Structure and Effects*. Boston, 1982.

Cotton, W. R. *Storms*. Fort Collins, Colo., 1990.

Frazier, K. *The Violent Face of Nature*. New York, 1979.

Houze, R. A., Jr., and P. V. Hobbs. "Organization and Structure of Precipitating Cloud Systems." *Advances in Geophysics*, **24** (1982): 225-315.

Ludlam, F. H. *Clouds and Storms* University Park, Pa., 1980.

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Figure

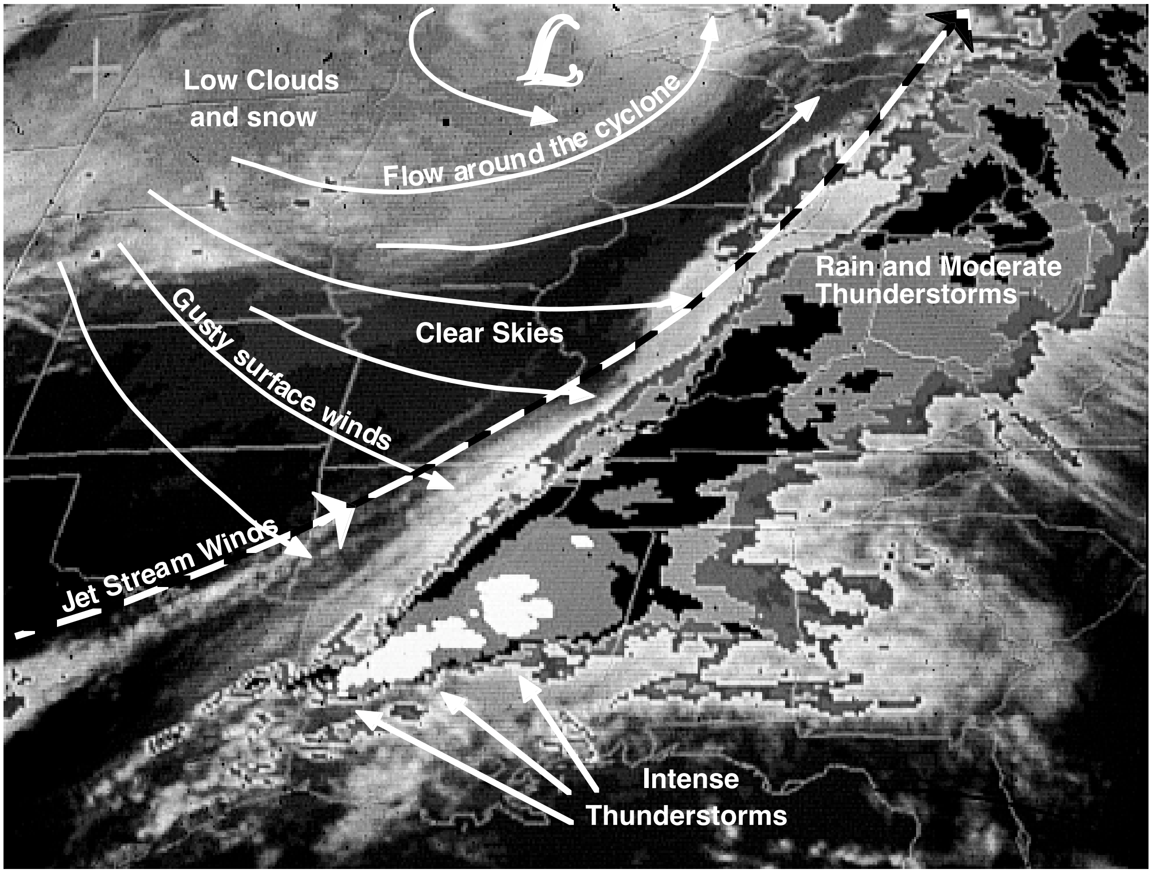

Figure 1. An example of the distribution of various types of stormy weather within an extratropical cyclone. The center of the large-scale cyclone is denoted with a script "L" and various types of storms, including thunderstorms, rainstorms, and snowstorms are indicated on an infrared satellite image. Streamlines of wind flow at selected places at the surface and along the jet stream aloft are also indicated On the satellite image, cloud top temperatures are shown with various shades of gray; the image has been artificially enhanced by changing the shading abruptly at certain specified temperatures. The very coldest, and therefore the highest, clouds are indicated by the lightest gray shades.