Flooding

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Introduction

Flooding is arguably the weather-related hazard that is most widespread around the globe. It can occur virtually anywhere. A flood is defined as water overflowing onto land that usually is dry. Flooding is often thought of as a result of heavy rainfall, but floods can arise in a number of ways that are not directly related to ongoing weather events. Thus, a complete description of flooding must include processes that may have little or nothing to do with meteorological events. Nevertheless, it is clear that in some ultimate sense, the water that is involved in flooding has fallen as precipitation at *some* time, perhaps long ago. The origins of flooding, therefore, ultimately lie in atmospheric processes creating precipitation, no matter what specific event causes the flooding.

Floods produce damage through the immense power of moving water and through the deposition of dirt and debris when floodwaters finally recede. People who have not experienced a flood may have little or no appreciation for the dangers of moving water. The energy of that moving water goes up as the square of its speed; when the speed doubles, the energy associated with it increases by a factor of four. Flooding is typically coupled to water moving faster than normal, in part because of the weight of an increased amount of water upstream, leading to an increase in the pressure gradient that drives the flow. In most cases, the damage potential of the flood is magnified by the debris that the waters carry: trees, vehicles, boulders, buildings, etc. When the waters move fast enough, they can sweep away all before them, leaving behind scenes of terrible destruction (Fig. 1).

The effect of the water itself can be devastating on structures and on the objects within them: books, furniture, photographs, electronic equipment, and so on can be damaged simply by being immersed in water, even if they are not directly damaged by the water movement. Moreover, floodwaters typically contain suspended silt and potentially toxic microorganisms and dissolved chemicals. This means that floods usually compromise drinking water supplies, resulting in short-term shortages of potable water, with the additional long-term costs in restoring drinking water service to the residents of a flooded area. The mud and debris left behind when floodwaters recede can be costly to clean up and represent a health hazard, as well, especially when there are decomposing bodies of drowned wild and domestic animals in the debris. In some situations, floods drive wild animals (including invertebrates of all sorts) from their normal habitats and into human habitations near and within the flooded areas, which can create various problems, especially when the animals are venomous or aggressive.

Although flooding has some large negative impacts on humans, it also is part of the natural processes shaping the Earth. Floodplains along rivers and streams are among the most fertile regions known. Most of the so-called "cradles of civilization" are within floodplains for this very reason (e.g., the Nile River, the Tigris-Euphrates River, among others). Hence, humans have been affected by flooding both positively and negatively since before historical times, whenever they find themselves in the path of these natural events.

Floods as a direct result of precipitation

When the waters of a flood arise directly from precipitation, atmospheric processes can be identified as directly responsible for the event. That is, rainfalls occur that are well beyond the average values for the affected area. It is only when those rainfalls exceed the average that land which is usually dry can be affected; that is, a flood occurs. Thus, the rainfall amounts needed for floods can not be defined in absolute terms. A precipitation event that causes a flood in one location might be well within the bounds of what is typical for another location. Generally speaking, the threshold for flood-producing rainfalls increases as the annual average rainfall for a region increases.

Flash floods

Flash floods are defined as those flood events where the rise in water is either during or within a few hours of the rainfall that produces the rise. Therefore, flash floods occur within small catchments, where the response time of the drainage basin is short. Many hydrological factors have relevance to the occurrence of a flash flood: terrain gradients, soil type, vegetative cover, human habitation, antecedent rainfall, and so on. In steep, rocky terrain or within heavily urbanized regions, even a relatively small amount of rainfall can trigger flash flooding. These hydrological factors determine the response of the catchment to the precipitation event. Thus, a flash flood is clearly the result of the concatenation of both meteorological and hydrological circumstances.

Most flash floods associated with rainfall are produced by thunderstorms; that is, deep, moist convection. A single thunderstorm cell is unlikely to produce enough rainfall to cause a flash flood, so the typical flash flood is the result of several thunderstorms moving successively over the same area, known as "training" thunderstorms (Fig. 2), because it resembles the passage of cars in a freight train. A succession of thunderstorms results when new thunderstorms pass repeatedly over the same place while the overall system of thunderstorms is very nearly stationary. The infamous Johnstown, Pennsylvania flash flood of 19-20 July 1977 was produced by such a system. Thunderstorms forming in northwestern Pennsylvania moved southeastward, only to be replaced by newly formed thunderstorms, a process that went on for several hours. The result was torrential rainfall concentrated near Johnstown, with amounts exceeding 400 mm. The ensuing flood was responsible for 77 fatalities and $550 million (in 1999 dollars).

Occasionally, flash floods are created in conditions that aren't favorable for thunderstorms but which still produce heavy rainfalls. This can occur when moist air is forced upward over mountains by the wind flow, called *orographic* precipitation. When the air forced upward is very moist, the rainfall can be quite heavy. The steep, rocky terrain also promotes rapid runoff of the rainfall. Flooding along the West Coast of the United States or in the European Alps is often of this type; that is, not involving thunderstorms.

A characteristic of flash floods is the localized nature of the heaviest rainfall. As shown in Fig. 3, the most intense rainfall is typically confined to a relatively small area. When large amounts of this localized precipitation falls within a small drainage basin, flash floods can occur. Sometimes, the location where flash flood damage occurs may actually receive little or no rainfall. That is, the rainfall that causes the problem can occur upstream of threatened areas. This separation between the rainfall and the flood can cause confusion because it may not even be raining in an area for which flash flood warnings are issued. Another factor in the impact of flash floods is that the precipitation causing the event often falls during the night, when it can be difficult to get warnings to sleeping residents. The central part of the United States is well known for its heavy thunderstorm-produced rains during nighttime hours. Worldwide, thunderstorms are most common during the day, but on the central plains of the United States (and in a few other places around the world), the unique geography of the region favors nocturnal thunderstorms. This setting promotes a strong flow of moisture northward from the Gulf of Mexico, called a *low-level jet stream*, during the warm months of the year. Moisture carried by the low-level jet stream helps to maintain thunderstorm systems that often begin during daytime hours on the higher terrain to the east of the Rocky Mountains. Because of the low-level jet stream, such storms can persist well into the nighttime hours, often forming clusters of thunderstorms known as *mesoscale convective systems*(Fig. 4).

It is the rapidity of the event that makes flash floods so damaging and dangerous. Flash floods involve rapidly rising, fast-moving waters that can do immense damage; the suddenness of the onset of the flood can result in people being caught unawares. Most fatalities result from drowning, with perhaps some traumatic injuries from being carried along in the debris-laden waters and being swept into standing objects. The potential for loss of human life with flash floods is high. Debris carried in flash floods can form temporary "debris dams" that typically fail as waters back up behind them. Failure of these debris dams then results in a "wall of water" surging downstream. Debris dam failure events can happen repeatedly during the course of the flash flood. Not all flash floods are characterized by a "wall of water" but all of them (by definition) involve rapidly rising floodwaters.

Because urbanized areas promote runoff of rainfall, rather than permitting most of the rain to be absorbed into the ground, flash flooding is more likely in cities than in rural areas surrounding a city. It takes much less rainfall in a city to create a flash flood situation than in a rural area of comparable size.

Flash floods continue to be a major contributor to loss of life, in spite of improved precipitation forecasting. Some noteworthy examples include events in the Big Thompson Canyon in Colorado (1976 - 144 fatalities) and near the town of Biescas in the Spanish Pyrenees (1996 - 86 fatalities).

Tropical cyclones often create devastating flash floods as a result of torrential rainfalls. In late October of1998, Hurricane Mitch caused more than 9,000 fatalities (the exact number is not known), mostly in Nicaragua and Honduras, in Central America, from flash floods and landslides associated with its rainfall. It was the worst weather disaster in terms of casualties in the Western Hemisphere during the 20th century.

River floods

River floods, in contrast to flash floods, typically unfold over days, or even months. This is because they occur in large basins involving "main stem" rivers like the Missouri, or the Nile and are usually the result of many individual rainfall episodes spread out over many days. In fact, within a river flood event, several flash flood events can occur. Again, hydrological factors often contribute to a river flood, but river floods are not so sensitive to them as are flash floods. Whereas individual thunderstorm systems can cause flash floods, river floods are usually the result of a stagnant synoptic-scale weather pattern. Localized heavy rainfall events occur many times during a period of days or even months, each contributing its share of rainfall to the tributaries, which then discharge into the main stem of a river. The river rises gradually in response to all the input rainfall. The river flood potential of a situation can be increased by concurrent snowmelt and other factors besides rainfall.

The major flooding event during June and July of 1993 was the result of a weather pattern (Fig. 5a) that produced a storm track across the upper Midwestern United States. Abnormally low heights of the pressure surfaces (associated with cool temperatures) over the northern Plains produced a pattern in which traveling weather disturbances intensified in the Midwest after crossing the Rocky Mountains, This pattern aloft also produced an anomalously strong poleward flow of low-level moisture from the Gulf of Mexico into the Midwest. Mesoscale convective systems developed almost every evening during the early summer, typically persisting through the night. These passed repeatedly over the nearly the same areas, resulting in widespread significant rainfalls (Fig. 5b) for the period over the lower Missouri and upper Mississippi basins. In addition to these factors, considerable rainfall over the region had fallen during the previous several months, providing a hydrological setting that favored runoff of the precipitation. This event produced disastrous flooding that persisted for many weeks.

Owing to the long time scale of the rising waters, river floods pose a lower risk of fatalities; people have more time to take proper actions. Of course, some casualties result from waiting until it has become too late to respond to the threat. Levee and dam failures, as well as intentional rapid release of impounded waters to prevent the catastrophic failure of the flood control structures, can produce rapidly-rising water situations embedded within a river flood, and these also can contribute to loss of life.

Because of the large scale of river floods, the damage figures may be enormous; easily into the billions of dollars. Crop losses are a major factor in the costs of river floods, whenever large tracts of prime agricultural land along floodplains are inundated. Levees are often used to protect populated areas, so the failure of those levees can generate major property losses. The damage and dislocations along the Upper Mississippi and Lower Missouri basins during the summer floods of 1993, during which several levees were breached, illustrate the huge impact such events can have.

Floods arising from non-precipitation events

Apart from floods resulting directly from rainfall, there are many ways that precipitation can cause floods, perhaps long after it has fallen. When flowing water is impounded by the construction of dams, there is some risk that the dams will fail. Johnstown, Pennsylvania was inundated by a dam failure during a rainfall event in 1889, for example. Such rapid releases of stored water can be cataclysmic, manifesting themselves as an enormous "wall of water" choked with debris.

Flood also can arise through the melting of snowfall. In situations where the preceding winter's snowpack is deep, a sudden change to warm temperatures in the spring can result in abnormally rapid melting and runoff of the snowmelt. The devastating flood created in Grand Forks, North Dakota in April of 1997 is an example. Occasionally, warm rain falls directly onto the melting snow, exacerbating such situations by speeding the melting process and adding more liquid water.

Deposits of snow and ice on volcanic peaks can melt rapidly during eruptions. The resulting runoff, often turned into a thick slurry by the inclusion of volcanic ash, roars down the mountainside and is called a *lahar*. A tragic example occurred with the Nevado del Ruiz volcano in Colombia on November 13,1985, which killed more than 23,000 people, mostly in the town of Armero. Another occurred in Iceland during 1996 on the Vatnajökull glacier, with no fatalities owing to its remote location. Lahars can continue occasionally for years after an eruption, when heavy rains fall onto ash deposited by the volcano,

During the winter and late spring, when ice can build up on rivers in cold climates, the breakup of the ice can create *ice dams* on the river. The ice dams cause the waters to back up, sometimes flooding the land upstream of the ice dam. Then, the breakup of the ice dam can result in a flash flood wave that surges downstream of the ice dam's position.

Other flood situations can develop along the shores of the world's oceans and even with large freshwater lakes. *Tsunamis*, typically caused by underwater earthquakes and landslides, can flood the shorelines with huge waves that break on the shallow waters near the shore. Storms of all sorts, including tropical cyclones, can drive the waters before the winds into *storm surges* that inundate shore areas when the storms are near the land. Large lakes can experience flooding on their shores due to *seiches*, which are surges of water (usually oscillatory) within enclosed bodies of water. Seiches can be caused by earthquakes or by atmospheric processes.

Societal impacts and their mitigation

The results of floods on society worldwide are substantial. Flooding is responsible for many drowning fatalities in tropical cyclones, either from storm surges or from freshwater rain-induced flash floods. Flash floods and river floods typically produce more fatalities every year than either tornadoes or hurricanes in the United States. In many parts of the world, flood fatalities are associated with the most significant weather-related disasters. Flood damage cost in the United States is now on the order of several billion dollars annually and the numbers continue to rise.

Many people now live and play in flood-prone areas: for example, within flood plains of rivers and their tributaries, as well as along coastlines that are vulnerable to storm-caused flooding from tsunamis, tropical cyclones, and non-tropical storms. Development of flood-prone areas for habitation and recreation has been increasing, with a corresponding increase in the risks to life and property. The 1993 Upper Mississippi and Lower Missouri River floods provided a grim reminder of the risks of building permanent structures within flood plains, even when flood-control measures have been taken.

In the case of flash floods, it is difficult to take measures to protect property, owing to the rapidity with which the event happens. However, prevention of flash flood casualties is possible, provided warnings can be issued and acted upon properly in a timely fashion. Considerable attention has been paid to increasing public awareness of the dangers of driving into rapidly-rising flood waters, for instance, as a result of recent experiences with flash floods.. Unfortunately, situations can still arise where warnings are not issued in time. People living and engaging in recreational activities in places prone to flash floods need to be alert during heavy rainfalls and be prepared to seek safety even when they do not receive timely warnings.

For river floods and other relatively slow-developing situations (such as rising snow melt or ice action events), it may be possible to reduce the property damage as well by removing the contents of structures. Obviously, any structures (and their contents) built in flood-prone areas are permanently at risk; the only way to guarantee their not being involved in floods is to move them out of those areas. Prevention of fatalities in river flood events is a matter of heeding the warnings of danger and getting residents out of the danger areas before the number of options is reduced by the rising waters and by the failure of levees or other flood-prevention structures..

Forecasting the details of flooding events is an important part of mitigation. Knowing precisely when and where a flood will occur would no doubt be helpful, but it is also important to be able to anticipate the magnitude of the flood. An example of this is the tragedy of the 1997 Grand Forks, North Dakota case, where the river level was a only a few feet higher than that forecast. Those few feet, however, had a large impact, because the flood-control operations were based on the lower forecast value. When the river rose above that level, the flood-control measures failed catastrophically. In reality, such a forecast can never be a precise statement; uncertainty is implicitly a part of every forecast, a point that perhaps needs greater emphasis in the future.

Flooding, by its very nature, is usually a result of both meteorological and hydrologic processes; the character of a flood is determined both by the detailed behavior of the precipitation and by the nature of situation in which the event is likely to occur (soil conditions, amount of antecedent rainfall, and so on). It is not likely that precisely detailed forecasts of flooding events will ever be possible, although it certainly is well within our capability to anticipate the *possibility* of most flood events. The challenge for reducing the social impacts of floods is how best to make use of the *uncertain* meteorological and hydrological forecasts that are within practical means. The challenge is to make effective use of whatever forecasting capability we have, even as we seek to improve that capability.

Effects of human activities on flooding

In addition to the risks to lives and property that people take by moving into flood-prone areas, development for human use often involves clearing land of its native vegetation and altering the characteristics of the ground cover. Vegetation works together with the soil to store rainfall, so when that vegetation is cleared, rainfall runoff can increase substantially. Rather than being absorbed by the soil and its natural vegetation, in areas where that vegetation has been cleared (either for construction or for agriculture), heavy rainfall is more likely to run off and pour into streams and rivers, increasing the potential threat from flash floods and river floods. Construction of roads and buildings also acts to increase runoff, and leads to an increasing likelihood of localized urban flooding. Such construction increases dramatically the fraction of the rainfall that runs off, regardless of antecedent rainfall. Human-caused fires also can produce at least temporary increases in the runoff potential in the headwater regions of streams and rivers. It is evident that human activities are increasing the potential for floods around the world.

Again recalling the Mississippi River floods of 1993 as an example, the issue of flood control through levees and other structures was dramatically recalled to public attention. The value of structural methods for flood control (levees, flood control dams, breakwaters, etc.) remains controversial, but the 1993 floods made it apparent that structures such as levees *can* be breached during *major* flooding episodes, even though they may be able to contain lesser events. Structural failures create rapidly rising waters (flash floods) artificially within a river flood event, increasing the hazards to human life as well as destroying property. The decision about when and where to take structural approaches will continue to be a challenge.

Finally, the use of flood-prone areas for human activities puts lives and property at risk, although the major flood events may be separated by many years. The long time between events can lead to complacency and subsequent disasters. The choices associated with land use are a continuing challenge, now and in the future. When humans live and play in ways that put them in the path of potential floodwaters, major societal impacts are inevitable.

See also: **Air-Sea Interaction (Momentum, Heat and vapour fluxes), Convective Storms, Hurricanes, Hydrology (Hydrologic Cycle), Hydrology (Precipitation and Evaporation), Hydrology (Soil Moisture), Mesoscale Meteorology (Cloud and Rain Bands), Mesoscale Meteorology (Mesoscale Convective Systems), Nowcasting, Palmer Drought Index, Predictability and Chaos, Radar (Precipitation Radar), Satellite Remote Sensing (Precipitation), Severe Storms, Weather Prediction (Severe Weather Forecasting)**

Further Reading

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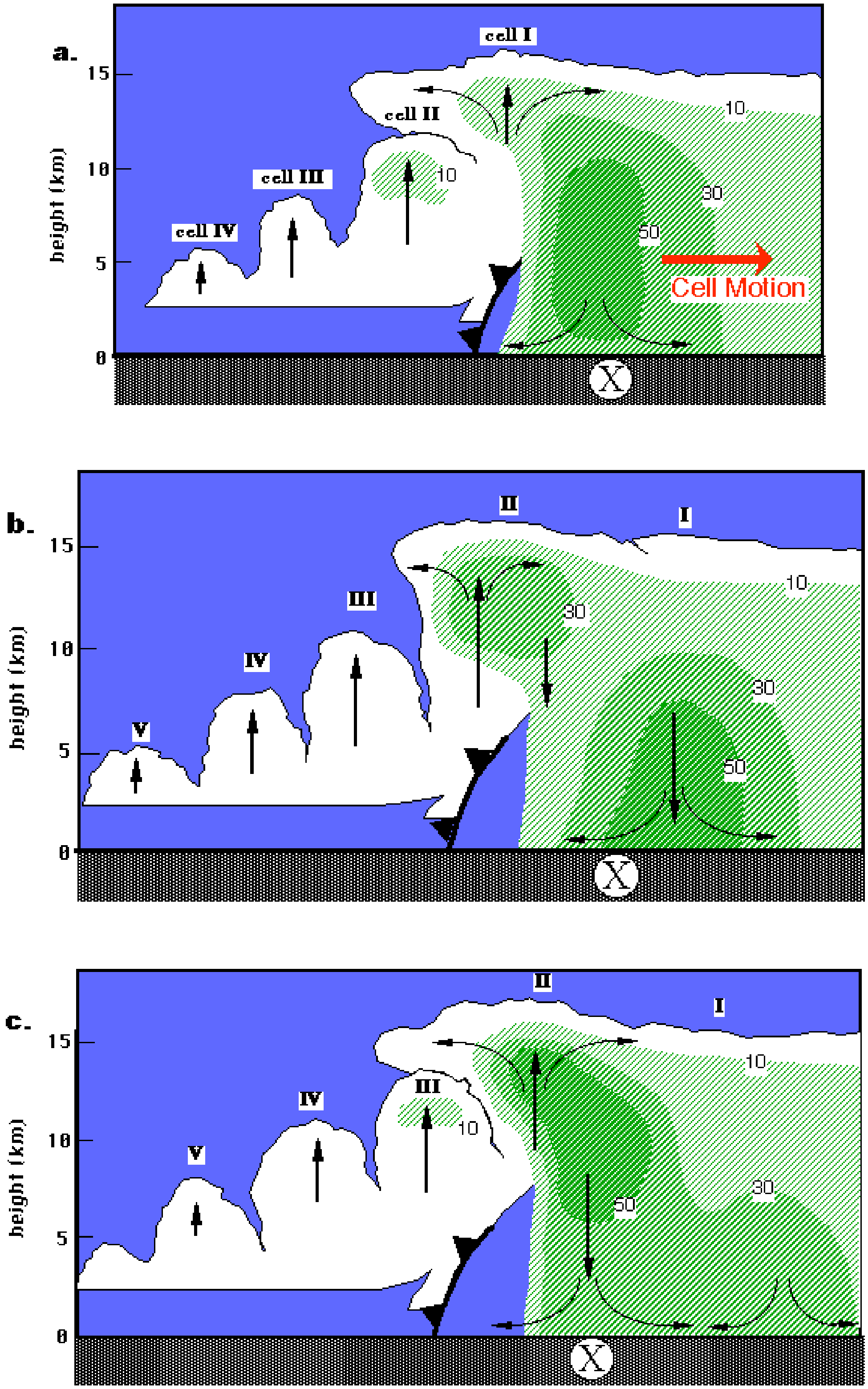
Figure 1. Damage resulting from the 1977 Johnstown, Pennsylvania flash flood event.



a.
cell I
cell II
cell III
cell IV
height (km)
15
10
5
0
10
10
30
50
Cell Motion
X
b.
II
I
III
IV
V
height (km)
15
10
5
0
10
30
30
50
X
c.
II
I
III
IV
V
height (km)
15
10
5
0
10
10
30
50
X

Figure 2. Schematic of the "training" effect. (a) At this time, there are four numbered thunderstorm cells in various stages of development. Cell I is mature, with both updrafts and downdrafts, and heavy rain is about to commence at point "X". Cells II, III, and IV are still developing, and have only updrafts. Cell II has precipitation forming aloft. The hatched contours are radar reflectivity, in units of dBz, which is related to the rainfall rate. (b) About 15 minutes later, Cell I's updraft is dissipated, and it is now dominated by downdraft. Heavy rain continues at "X" while Cell II is maturing and developing a downdraft. Cells III, IV, and now V are still immature. (c) About 15 more minutes have elapsed. Cell I's rainfall is continuing but it is now nearly dissipated, while Cell II is entering late maturity. It is still raining at "X" but now the rainfall is from Cell II, and heavy rain from Cell II is descending from aloft. Now Cell III is developing its first precipitation aloft. Cells IV and V are still immature. [Adapted from Fig. 7 in Doswell, C.A. III, H.E. Brooks, and R.A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560-581.]

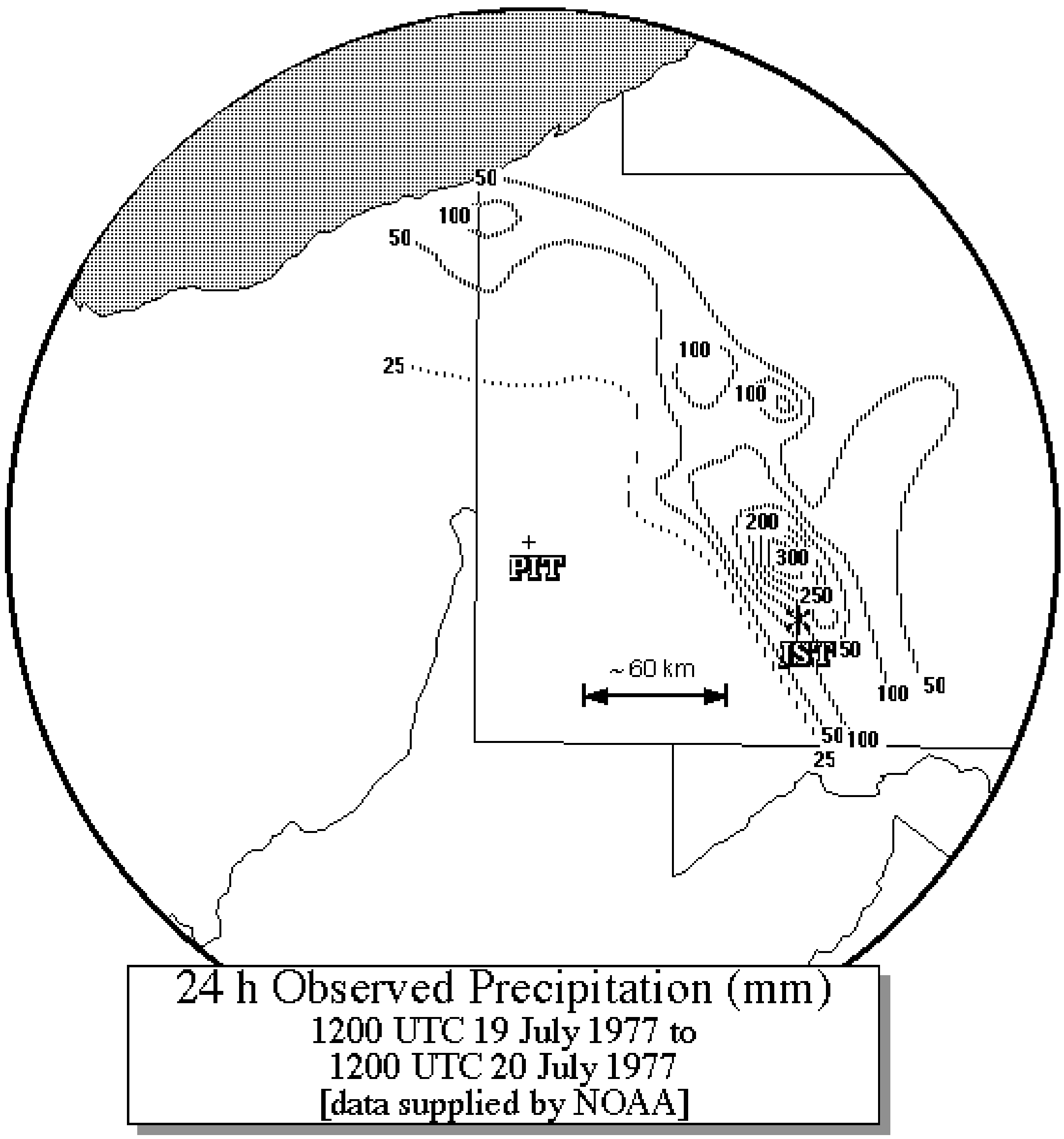


Figure 3. Observed total precipitation (mm) during the Johnstown, Pennsylvania (JST, located by an asterisk) flash flood event. For reference, Pittsburgh, Pennsylvania (PIT, located by the plus sign) is also shown. [Adapted from Fig. 14a in Hoxit, L.R., R.A. Maddox, C.F. Chappell, F.L. Zuckerberg, H.M. Mogil, I. Jones, D.R. Greene, R.E. Saffle and R.A. Scofield, 1987: *Meteorological Analysis of the Johnstown, Pennsylvania, Flash Flood, 19-20 July 1977*. NOAA Tech. Rept. ERL 401-APCL 43, NTIS Accession No. PB297412.]

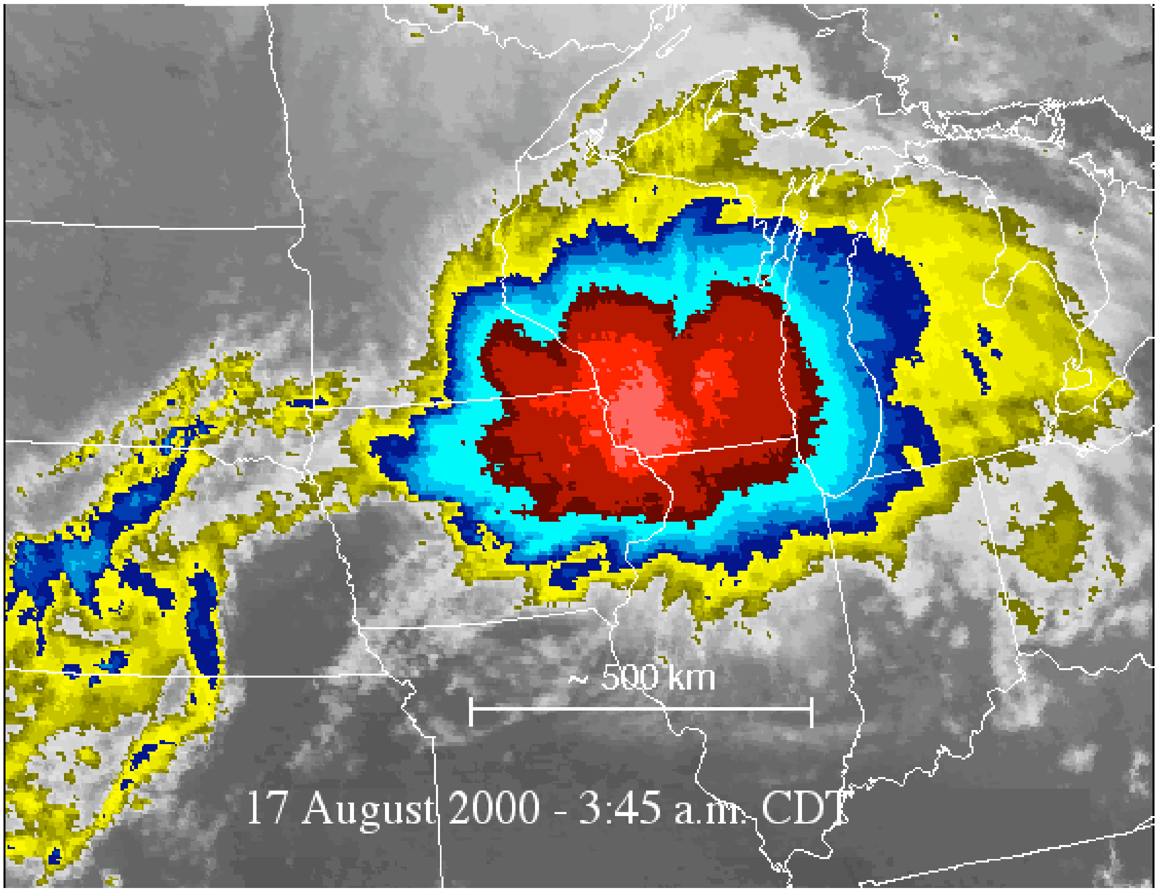


Figure 4.. False-color enhanced infrared satellite image of a mesoscale convective system, with the light red colors indicating the coldest (therefore the highest) clouds. Note that this image is at 0345, local time, which corresponds to 0845 UTC.

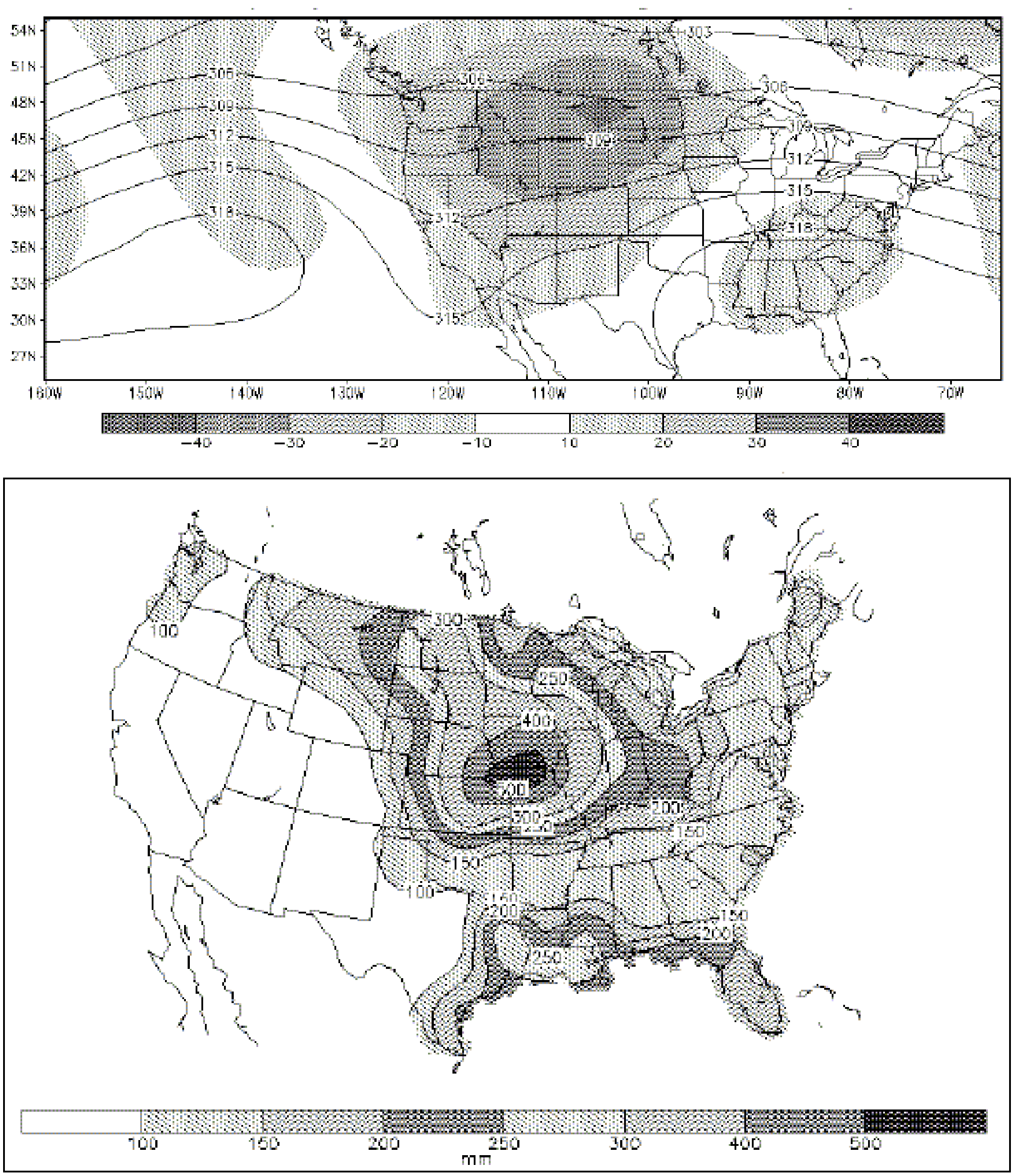


Figure 5. (a) Map of the 700 hPa heights (thin lines, in dam) and height anomalies (shading, in m) for June/July 1993, and (b) observed precipitation for the same period (shading, in mm). Based on data supplied by J. Janowiak of the NOAA Climate Prediction Center.