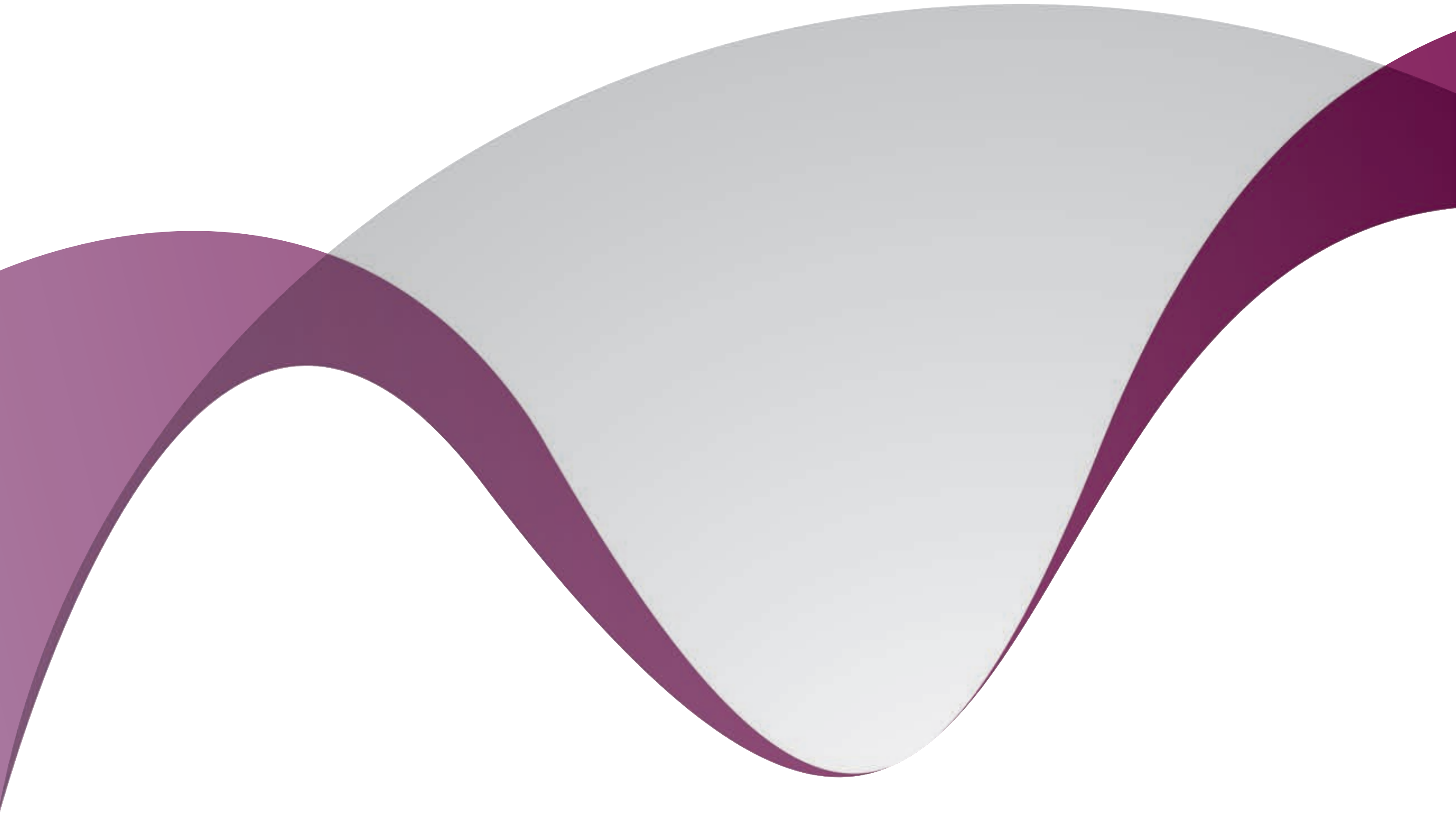
Handbook of
Natural Hazards and Disasters



Robinson Bird

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Robinson Bird
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Preface

A natural phenomenon which can have a negative impact on the environment or humans is known as a natural hazard. Such events are categorized into two types, namely, geophysical and biological. Geological and meteorological phenomenon such as wildfires, earthquakes and droughts fall under the category of geophysical hazards. A wide variety of diseases, infections and infestations come under the umbrella of biological hazards. Natural disaster refers to a natural hazard which has already occurred. It refers to a particular event, which occurs over a relatively shorter period of time. Identification of different types of hazards is known as hazard analysis. It plays a vital role in reducing the risk posed by a disaster or a hazard. The topics included in this book on natural hazards and disasters are of utmost significance and bound to provide incredible insights to readers. It is appropriate for students seeking detailed information in this area as well as for experts. Those in search of information to further their knowledge will be greatly assisted by this book.

A short introduction to every chapter is written below to provide an overview of the content of the book:

Chapter 1 - The natural phenomena which can have a harmful effect on the environment or humans is termed as a natural hazard. Natural disasters are significant adverse events which occur as a result of Earth's processes. This chapter has been carefully written to provide an easy understanding of the varied facets of natural hazards and disasters as well as the various types of natural hazards.; **Chapter 2** - A disaster resulting from the shaking of the surface of the Earth, which in turn creates seismic waves, is called an earthquake. There are various prediction methods for earthquakes such as observing animals for abnormal behavior, measuring water level and temperature change, and monitoring the emission of radon gas. The topics elaborated in this chapter will help in gaining a better perspective about the causes of earthquakes along with the methods of predicting them.; **Chapter 3** - The probability of eruption of a volcano or the occurrence of a related geophysical event within a particular time frame is called volcano hazard. This chapter closely examines the different types of volcanic eruptions as well as the types of lava flows to provide an extensive understanding of the subject.; **Chapter 4** - There are numerous hazards which are related to weather such as droughts, dust storms, heat waves, wildfires, tropical cyclones, blizzards, hailstorms and hurricanes. A thunderstorm is another weather hazard which features lightning and thunder. The topics elaborated in this chapter will help in gaining a better perspective about these weather hazards.; **Chapter 5** - The disasters which are caused due to a severe amendment either in quality of earth's water, or in distribution or movement of water, are called hydrological disasters. The different types of hydrological disasters are coastal floods, urban floods, flash floods and tsunamis. This chapter discusses in detail the diverse aspects of these hydrological disasters.; **Chapter 6** - The actions which are taken for the reduction or elimination of long-term harm that can be caused by hazards and disasters is termed as hazard mitigation. Prevention of hazards refers to the preventive and protective actions that aid in lessening the scale of impact from a hazard. This chapter closely examines the key aspects of mitigation and prevention of hazards such as establishing temporary shelters and keeping food and water safe after a disaster.

I extend my sincere thanks to the publisher for considering me worthy of this task. Finally, I thank my family for being a source of support and help.

Robinson Bird

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Natural Hazards and Disasters: An Introduction

The natural phenomena which can have a harmful effect on the environment or humans is termed as a natural hazard. Natural disasters are significant adverse events which occur as a result of Earth's processes. This chapter has been carefully written to provide an easy understanding of the varied facets of natural hazards and disasters as well as the various types of natural hazards.

Natural Hazards

A widely accepted definition characterizes natural hazards as "those elements of the physical environment, harmful to man and caused by forces extraneous to him." More specifically, in this document, the term "natural hazard" refers to all atmospheric, hydrologic, geologic (especially seismic and volcanic), and wildfire phenomena that, because of their location, severity, and frequency, have the potential to affect humans, their structures, or their activities adversely. The qualifier "natural" eliminates such exclusively manmade phenomena as war, pollution, and chemical contamination. Hazards to human beings not necessarily related to the physical environment, such as infectious disease, are also excluded from consideration here.

How Natural are Natural Hazards?

Notwithstanding the term "natural," a natural hazard has an element of human involvement. A physical event, such as a volcanic eruption, that does not affect human beings is a natural phenomenon but not a natural hazard. A natural phenomenon that occurs in a populated area is a hazardous event. A hazardous event that causes unacceptably large numbers of fatalities and/or overwhelming property damage is a natural disaster. In areas where there are no human interests, natural phenomena do not constitute hazards nor do they result in disasters. This definition is thus at odds with the perception of natural hazards as unavoidable havoc wreaked by the unrestrained forces of nature. It shifts the burden of cause from purely natural processes to the concurrent presence of human activities and natural events.

Although humans can do little or nothing to change the incidence or intensity of most natural phenomena, they have an important role to play in ensuring that natural events are not converted into disasters by their own actions. It is important to understand that human intervention can increase the frequency and severity of natural hazards. For example, when the toe of a landslide is removed to make room for a settlement, the earth can move again and bury the settlement. Human intervention may also cause natural hazards where none existed before. Volcanoes erupt periodically, but it is not until the rich soils formed on their eject are occupied by farms and human settlements that they are considered hazardous. Finally, human intervention reduces the mitigating effect of natural ecosystems. Destruction of coral reefs, which removes the shore's first line of defense against ocean currents and storm surges, is a clear example of an intervention that diminishes the ability of an ecosystem to protect itself. An extreme case of destructive human intervention into an ecosystem is desertification, which, by its very definition, is a human-induced "natural" hazard.

Earthquakes

Earthquakes are caused by the sudden release of slowly accumulated strain energy along a fault in the earth's crust. Earthquakes and volcanoes occur most commonly at the collision zone between tectonic plates. Earthquakes represent a particularly severe threat due to the irregular time intervals between events, lack of adequate forecasting, and the hazards associated with these:

- Ground shaking is a direct hazard to any structure located near the earthquake's center. Structural failure takes many human lives in densely populated areas.
- Faulting, or breaches of the surface material, occurs as the separation of bedrock along lines of weakness.
- Landslides occur because of ground shaking in areas having relatively steep topography and poor slope stability.
- Liquefaction of gently sloping unconsolidated material can be triggered by ground shaking. Flows and lateral spreads (liquefaction phenomena) are among the most destructive geologic hazards.
- Subsidence or surface depressions result from the settling of loose or unconsolidated sediment. Subsidence occurs in waterlogged soils, fill, alluvium, and other materials that are prone to settle.
- Tsunamis or seismic sea waves usually generated by seismic activity under the ocean floor, cause flooding in coastal areas and can affect areas thousands of kilometers from the earthquake center.

Volcanoes

Volcanoes are perforations in the earth's crust through which molten rock and gases escape to the surface. Volcanic hazards stem from two classes of eruptions:

- Explosive eruptions which originate in the rapid dissolution and expansion of gas from the molten rock as it nears the earth's surface. Explosions pose a risk by scattering rock blocks, fragments, and lava at varying distances from the source.

- Effusive eruptions where material flow rather than explosions is the major hazard. Flows vary in nature (mud, ash, lava) and quantity and may originate from multiple sources. Flows are governed by gravity, surrounding topography, and material viscosity.

Hazards associated with volcanic eruptions include lava flows, falling ash and projectiles, mudflows, and toxic gases. Volcanic activity may also trigger other natural hazardous events including local tsunamis, deformation of the landscape, floods when lakes are breached or when streams and rivers are dammed and tremor-provoked landslides.

Landslides

The term landslide includes slides, falls, and flows of unconsolidated materials. Landslides can be triggered by earthquakes, volcanic eruptions, soil saturated by heavy rains or groundwater rise, and river undercutting. Earthquake shaking of saturated soils creates particularly dangerous conditions.

Although landslides are highly localized, they can be particularly hazardous due to their frequency of occurrence. Classes of landslide include:

- Rockfalls, which are characterized by free-falling rocks from overlying cliffs. These often collect at the cliff base in the form of talus slopes which may pose an additional risk.
- Slides and avalanches, a displacement of overburden due to shear failure along a structural feature. If the displacement occurs in surface material without total deformation it is called a slump.
- Flows and lateral spreads, which occur in recent unconsolidated material associated with a shallow water table. Although associated with gentle topography, these liquefaction phenomena can travel significant distances from their origin.

The impact of these events depends on the specific nature of the landslide. Rockfalls are obvious dangers to life and property but, in general, they pose only a localized threat due to their limited areal influence. In contrast, slides, avalanches, flows, and lateral spreads, often having great areal extent, can result in massive loss of lives and property. Mudflows, associated with volcanic eruptions, can travel at great speed from their point of origin and are one of the most destructive volcanic hazards.

Flooding

Two types of flooding can be distinguished: (1) land-borne floods, or river flooding, caused by excessive run-off brought on by heavy rains, and (2) sea-borne floods, or coastal flooding, caused by storm surges, often exacerbated by storm run-off from the upper watershed. Tsunamis are a special type of sea-borne flood.

1. Coastal flooding: Storm surges are an abnormal rise in sea water level associated with hurricanes and other storms at sea. Surges result from strong on-shore winds and/or intense low pressure cells and ocean storms.

Water level is controlled by wind, atmospheric pressure, existing astronomical tide, waves and swell, local coastal topography and bathymetry, and the storm's proximity to the coast.

Most often, destruction by storm surge is attributable to:

- Wave impact and the physical shock on objects associated with the passing of the wave front.
- Hydrostatic/dynamic forces and the effects of water lifting and carrying objects. The most significant damage often results from the direct impact of waves on fixed structures. Indirect impacts include flooding and undermining of major infrastructure such as highways and railroads.

Flooding of deltas and other low-lying coastal areas is exacerbated by the influence of tidal action, storm waves, and frequent channel shifts.

2. River flooding: Land-borne floods occur when the capacity of stream channels to conduct water is exceeded and water overflows banks. Floods are natural phenomena, and may be expected to occur at irregular intervals on all stream and rivers. Settlement of floodplain areas is a major cause of flood damage.

Tsunamis

Tsunamis are long-period waves generated by disturbances such as earthquakes, volcanic activity, and undersea landslides. The crests of these waves can exceed heights of 25 meters on reaching shallow water. The unique characteristics of tsunamis (wave lengths commonly exceeding 100 km, deep-ocean velocities of up to 700 km/hour, and small crest heights in deep water) make their detection and monitoring difficult. Characteristics of coastal flooding caused by tsunamis are the same as those of storm surges.

Hurricanes

Hurricanes are tropical depressions which develop into severe storms characterized by winds directed inward in a spiralling pattern toward the center. They are generated over warm ocean water at low latitudes and are particularly dangerous due to their destructive potential, large zone of influence, spontaneous generation, and erratic movement. Phenomena which are associated with hurricanes are:

- Winds exceeding 64 knots (74 mi/hr or 119 km/hr), the definition of hurricane force. Damage results from the winds direct impact on fixed structures and from wind-borne objects.

- Heavy rainfall which commonly precedes and follows hurricanes for up to several days. The quantity of rainfall is dependent on the amount of moisture in the air, the speed of the hurricane's movement, and its size. On land, heavy rainfall can saturate soils and cause flooding because of excess runoff (landborne flooding); it can cause landslides because of added weight and lubrication of surface material; and/or it can damage crops by weakening support for the roots.

- Storm surge (explained above), which, especially when combined with high tides, can easily flood low-lying areas that are not protected.

All this is the key to developing effective vulnerability reduction measures: if human activities can cause or aggravate the destructive effects of natural phenomena, they can also eliminate or reduce them.

The Environment, Natural Hazards and Sustainable Development

The work of the OAS/DRDE is focused upon helping countries plan spatial development and prepare compatible investment projects at a prefeasibility level. In a general sense, these tasks may be called "environmental planning"; they consist of diagnosing the needs of an area and identifying the resources available to it, then using this information to formulate an integrated development strategy composed of sectorial investment projects. This process uses methods of systems analysis and conflict management to arrive at an equitable distribution of costs and benefits, and in doing so it links the quality of human life to environmental quality. In the planning work, then, the environment-the structure and function of the ecosystems that surround and support human life-represents the conceptual framework. In the context of economic development, the environment is that composite of goods, services, and constraints offered by surrounding ecosystems. An ecosystem is a coherent set of interlocking relationships between and among living things and their environments. For example, a forest is an ecosystem that offers goods, including trees that provide lumber, fuel, and fruit. The forest may also provide services in the form of water storage and flood control, wildlife habitat, nutrient storage, and recreation. The forest, however, like any physical resource, also has its constraints. It requires a fixed period of time in which to reproduce itself, and it is vulnerable to wildfires and blights. These vulnerabilities, or natural hazards, constrain the development potential of the forest ecosystem.

Hazards in Arid and Semi-arid Areas

Desertification

Desertification, or resource degradation in arid lands that creates desert conditions, results from interrelated and interdependent sets of actions, usually brought on by drought combined with human and animal population pressure. Droughts are prolonged dry periods in natural climatic cycles. The cycles of dry and wet periods pose serious problems for pastoralists and farmers who gamble on these cycles. During wet periods, the sizes of herds are increased and cultivation is extended into drier areas. Later, drought destroys human activities which have been extended beyond the limits of a region's carrying capacity.

Overgrazing is a frequent practice in dry lands and is the single activity that most contributes to desertification. Dry-land farming refers to rain-fed agriculture in semiarid regions where water is the principal factor limiting crop production. Grains and cereals are the most frequently grown crops. The nature of dry-land farming makes it a hazardous practice which can only succeed if special conservation measures such as stubble mulching; summer fallow, strip cropping, and clean tillage are followed. Decertified dry lands in Latin America can usually be attributed to some combination of exploitative land management and natural climate fluctuations.

Erosion and Sedimentation

Soil erosion and the resulting sedimentation constitute major natural hazards that produce social and economic losses of great consequence. Erosion occurs in all climatic conditions, but is discussed as an arid zone hazard because together with salinization, it is a major proximate cause of desertification. Erosion by water or wind occurs on any sloping land regardless of its use. Land uses which increase the risk of soil erosion include overgrazing, burning and/or exploitation of forests, certain agricultural practices, roads and trails, and urban development. Soil erosion has three major effects: loss of support and nutrients necessary for plant growth; downstream damage from sediments generated by erosion; and depletion of water storage capacity, because of soil loss and sedimentation of streams and reservoirs, which results in reduced natural stream flow regulation.

Stream and reservoir sedimentation is often the root of many water management problems. Sediment movement and subsequent deposition in reservoirs and river beds reduces the useful lives of water storage reservoirs, aggravates flood water damage, impedes navigation, degrades water quality, damages crops and infrastructure, and results in excessive wear of turbines and pumps.

Salinization

Saline water is common in dry regions, and soils derived from chemically weathered marine deposits (such as shale) are often saline. Usually, however, saline soils have received salts transported by water from other locations. Salinization most often occurs on irrigated land as the result of poor water control, and the primary source of salts impacting soils is surface and/or ground water. Salts accumulate because of flooding of low-tying lands, evaporation from depressions having no outlets, and the rise of ground water close to soil surfaces. Salinization results in a decline in soil fertility or even a total loss of land for agricultural purposes. In certain instances, farm land abandoned because of salinity problems may be subjected to water and wind erosion and become desertified.

Inexpensive water usually results in over-watering. In dry regions, salt-bearing ground water is frequently the major water resource. The failure to properly price water from irrigation projects can create a great demand for such projects and result in misuse of available water, causing waterlogging and salinization.

A survey of environmental constraints, whether focused on urban, rural, or wildland ecosystems, includes (1) the nature and severity of resource degradation; (2) the underlying causes of the degradation, which include the impact of both natural phenomena and human use; and (3) the range of feasible economic, social, institutional, policy, and financial interventions designed to retard or alleviate degradation. In this sense, too, natural hazards must be considered an integral aspect of the development planning process.

Recent development literature sometimes makes a distinction between "environmental projects" and "development projects." "Environmental projects" include objectives such as sanitation, reforestation, and flood control, while "development projects" may focus on potable water supplies, forestry, and irrigation. But the project-by-project approach is clearly an ineffective means of promoting socioeconomic well-being. Development projects, if they are to be sustainable, must incorporate sound environmental management. By definition, this means that they must be designed to improve the quality of life and to protect or restore environmental quality at the same time and must also ensure that resources will not be degraded and that the threat of natural hazards will not be exacerbated. In short, good natural hazard management is good development project management.

Indeed, in high-risk areas, sustainable development is only possible to the degree that development planning decisions, in both the public and private sectors, address the destructive potential of natural hazards. This approach is particularly relevant in post-disaster situations, when tremendous pressures are brought to bear on local, national, and international agencies to replace, frequently on the same site, destroyed facilities. It is at such times that the pressing need for natural hazard and risk assessment information and its incorporation into the development planning process become most evident.

To address hazard management, specific action must be incorporated into the various stages of the integrated development planning study: first, an assessment of the presence and effect of natural events on the goods and services provided by natural resources in the plan area; second, estimates of the potential impact of natural events on development activities, and third, the inclusion of measures to reduce vulnerability in the proposed development activities. Within this framework, "lifeline" networks should be identified: components or critical segments of production facilities, infrastructure, and support systems for human settlements, which should be as nearly invulnerable as possible and be recognized as priority elements for rehabilitation following a disaster.

Natural Disasters

Natural disasters are any catastrophic event that is caused by nature or the natural processes of the earth. The severity of a disaster is measured in lives lost, economic loss, and the ability of the population to rebuild. Events that occur in unpopulated areas are not considered disasters. So a flood on an uninhabited island would not count as a disaster, but a flood in a populated area is called a natural disaster.

All natural disasters cause loss in some way. Depending on the severity, lives can be lost in any number of disasters. Falling buildings or trees, freezing to death, being washed away, or heat stroke are just some of the deadly effects. Some disasters cause more loss of life than others, and population density affects the death count as well.

Then there is loss of property, which affects people’s living quarters, transportation, livelihood, and means to live. Fields saturated in salt water after tsunamis take years to grow crops again. Homes destroyed by floods, hurricanes, cyclones, landslides and avalanches, a volcanic eruption, or an earthquake are often beyond repair or take a lot of time to become livable again. Personal effects, memorabilia, vehicles, and documents also take a hit after many natural disasters.

The natural disasters that really affect people worldwide tend to become more intense as the years go on. Frequency of earthquakes, mega storms, and heat waves has gone up considerably in the last few decades. Heavy population in areas that get hit by floods, cyclones, and hurricanes has meant that more lives are lost. In some areas, the population has gotten somewhat prepared for the eventuality of disasters and shelters are built for hurricanes and tornadoes. However, loss of property is still a problem, and predicting many natural disasters isn’t easy.

Scientists, geologists, and storm watchers work hard to predict major disasters and avert as much damage as possible. With all the technology available, it’s become easier to predict major storms, blizzards, cyclones, and other weather related natural disasters. But there are still natural disasters that come up rather unexpectedly, such as earthquakes, wildfires, landslides, or even volcanic eruptions. Sometimes, a time of warning is there, but it’s often very short with catastrophic results. Areas that are not used to disasters affected by flash floods or sudden hail storms can be affected in an extreme way.

Flood-Natural disaster

However, despite the many natural disasters the world over, mankind has shown amazing resilience. When an area or country is badly affected by a natural disaster, the reaction is always one of solidarity and aid is quick to come. There are organizations set up with the primary goal of being prepared for natural disasters. These groups work on global and local scale rescue work. Aside from those who have chosen to make disaster relief their life-work, when disasters hit, it's the individuals who step in who help to make a difference.

Many people talk about when a disaster has hit and their neighbours and countrymen have come to aid, often to their own loss. People will step in and donate items, time, and skills in order to help those affected by a natural disaster. Celebrities will often do what they can to raise money through concerts, phone marathons, and visiting affected areas with aid. People have also shown that they can rebuild, lives can be remade or start over. Trauma is a big after effect of natural disasters and getting counseling has been the focus of aid—to heal emotionally as well as physically.

It's clear that natural disasters are a part of life as we know it. However, science is making it more possible to predict, aid is faster at coming, and people are learning how to rebuild in safer areas.

Geological Hazards

The word geo means the earth. The earth consists of all things that can be seen by the physical eye and also those that exist dip in the earth crust. Most of what comprises the earth is natural and very few of them are artificial. These things include mountains, rivers, lakes, trees, Ice Mountains and other phenomena. Human being is the soul living creature that is in charge of the earth's happens and the events that take place in the earth directly affect human beings.

A geological hazards or disasters entail all the happenings that put human life in danger and under threat of death.

The basic geological hazards include tsunamis, volcanoes, sinkholes, landslides, geomagnetic storms and earth quakes among the rest. These occurrences have resulted into the deaths of very many people. The incidences are selective in the areas of their occurrences depending on the type of the hazard. Earth quakes for example are most prevalent in the sections of Japan and Korea.

Various preparations are always put in place to help avert the destructions caused by the happenings. The United States geological survey (USGS) is one such body that provides immediate information on the happenings above.

Earth quakes come as a result if vibrations of the earth surface of movements that occur along the fault lines of the earth. They are caused by occurrences like manmade explosions and volcanic eruptions. The quakes can in turn trigger more harmful events like tsunamis and the land slides. Earth quakes always cause damage over large sections of the land depending on the magnitude and its strength. Statistics reveal that most earthquakes occur without any warning and result in loss of many lives and damage to property.

People who live in the prevalent areas have great fear because they never know when the deadly day may arrive. Sudden release of energy from the earth's surface results into tremors and shakings on the earth's surface and as a result, there is creation of the seismic waves. The seismic waves sweep across the earth hence causing a lot of trouble and destruction in the earth and the people. The intensity of the earth quake is measured using a seismometer which is also known as a seismograph. The intensity of 7 is very dangerous and causes great damage.

Mercalli scale is the unit of measurement of the shaking strengths. The zone of origin of the earthquakes is called epicenter. Tsunamis always come as a result of the epicenter location in the sea beds. Research reveals that this environmental hazard comes as a result of many factors. These include geological faults, volcanic activities and even landslides. Other human activities that can cause earthquakes include nuclear reactions especially during the testing of nuclear weapons. Many parts of the world are considered as dander zones as far as earthquakes are concerned.

Middle East coasts like Japan and Korea are among the most dangerous places. The quakes begin from one place which is called the epicenter and then spread to longer distance depending on the magnitude of the shakes. The earthquakes are considered is counted to be one of the most dangerous geological hazards in history. The event damages buildings and other infrastructures in the regions of occurrence. Other far places may also face danger because the sent signals can seriously affect the foundations of distant buildings especially the tall towers.

Landslides and avalanches are other events that come as a result of the earthquakes. This is because the earth's stability is put to stress whenever there is a shakeup. Some fires have also been started by the quakes. Fires occur whenever the electric poles fall down and opposite poles come into contact. Many people have always died from these fires. The San Francisco earth quake of 1906 is one such example were more people died from fire than the shakeups. Human beings are the main sufferers in the event of an earth quake. Many lives are always lost because of the buildings falling on people.

Meteorological Hazards

Disasters caused by extreme weather conditions are referred to as meteorological disasters. Such disasters are usually related to sudden and adverse changes in the weather or weather-forming processes. Extreme heat, excessive rainfall, and strong winds affecting the Earth's atmosphere in a negative manner and causing death or destruction are labeled as meteorological disasters.

Types of Meteorological Disasters

Blizzards

A severe snowstorm with a strong and sustained wind speed of more than 35 mph is considered a blizzard. Such storms last for several hours and cause great harm to life and property in the area of occurrence. Blizzards are not only caused by falling snow but might also result from strong winds blowing away loose snow on the ground. The Great Blizzard of 1888 was one of the worst blizzards in recent history. Significant wheat crops were destroyed in the United States during the event.

Hailstorms

A hailstorm is a phenomenon in which ice pellets fall to the ground as a form of solid precipitation. The irregular lumps of ice that fall during such storms are called hailstones. Modern technology makes it possible to detect hail forming thunderstorms using sophisticated meteorological instruments. Hail is highly damaging to property, as well as vegetation and crops. In the absence of proper cover, hailstones of large size can also cause physical harm to people and animals. One of the most damaging hail events occurred in Munich, Germany on July 12, 1984, causing damages worth at least $2 billion in insurance claims.

Droughts

Significantly lower than normal levels of rainfall in an area over a sustained period of time can lead to unusual dryness of soil. Such soil is unable to support plant life including agricultural crops, resulting in a drought. Various other factors like high temperatures, water shortage, and hot winds can also contribute to the severity of drought. Famines triggered by crop failure are often caused as the after-effects of a drought. Humanitarian crises and mass migrations often result from prolonged droughts.

Heat Waves

A heat wave occurs when the temperature of an area becomes excessively hot and exceeds normal seasonal limits. Hot weather during a heat wave might also be accompanied by high levels of humidity. Severe heat waves can result in massive crop failure, power outages across large areas, and even deaths. One of the worst heat waves in recent history was the European Heat Wave of 2003.

Tornadoes

Tornadoes are extremely dangerous and violent rotating air columns that move at high speeds across a large area and damage everything in their path. The base of a tornado is always in touch with the Earth's surface, while the top is in contact with a cumulonimbus cloud. A tornado generally appears like a condensation funnel, with the narrow edge touching the Earth. The wind speed of a tornado can vary from less than 117 km/h to greater than 480 km/h.

Cyclonic Storms

A cyclonic storm is a destructive meteorological phenomenon that forms when a large air mass rotates around a central low atmospheric zone. Such storms originate over oceans and usually move towards land where they cause great destruction to life and property. A cyclone can also be referred to as a hurricane or typhoon, depending on its origin. For example, the term "hurricane" is used to refer to cyclonic storms that arise in the Northeast Pacific and Atlantic Oceans. Storms of a similar nature arising in the Indian and South Pacific Oceans are called "cyclones," while the term typhoon is used to refer to storms originating in the Northwest Pacific Ocean. The 1970 Bhola Cyclone is considered to be the deadliest cyclone ever recorded, striking Bangladesh and causing 500,000 deaths.

Thunderstorms

A thunderstorm is a meteorological phenomenon associated with intense lightning and its acoustic effect, thunder. Such storms can also be called electrical storms or thundershowers. These weather events are usually accompanied by heavy rainfall and strong winds. Occasionally, snow, hail or sleet might also fall during thunderstorms. Lightning can kill people, animals, and plants that come in direct contact with the electrical flashes, as well as triggering fires or damaging buildings. The strong winds and heavy precipitation associated with powerful thunderstorms also add to the damaging effects of such weather events. The crash of the LANSA Flight 508 is an example of a thunderstorm-related disaster. The flight crashed in a thunderstorm while en route to Pucallpa from Lima, Peru, resulting in 91 deaths.

Biological Hazards

Biological hazards are organic substances that pose a threat to the health of humans and other living organisms. Biological hazards include pathogenic micro-organisms, viruses, toxins (from biological sources), spores, fungi and bio-active substances. Biological hazards can also be considered to include biological vectors or transmitters of disease. Worldwide, it is estimated that around 320 000 workers die each year from communicable diseases caused by work-related exposures to biological hazards.

Biological hazards pose risks for many workers in a wide variety of ways. For example, workers in health care professions are exposed to biological hazards via contact with human bodily matter, such as blood, tissues, saliva, mucous, urine and faeces, because these substances have a high risk of containing viral or bacterial diseases. Likewise, people who work with live animals or animal products (blood, tissue, milk, eggs) are exposed to animal diseases and infections, some of which (zoonoses) have the potential to infect humans (for example, Q-fever, avian flu or Hendra virus) or cause serious allergy via sensitisation.

Exposure to biological hazards in the work environment can also occur when people are in contact with laboratory cell cultures, soil, clay and plant materials, organic dusts, food, as well as rubbish, wastewater and sewerage. Exposure to moulds and yeasts is common in some industrial processes, in workplaces with air conditioning systems and high humidity, and in the construction industry.

Exposure to biological hazards is therefore widespread and the risk of exposure is not always obvious.

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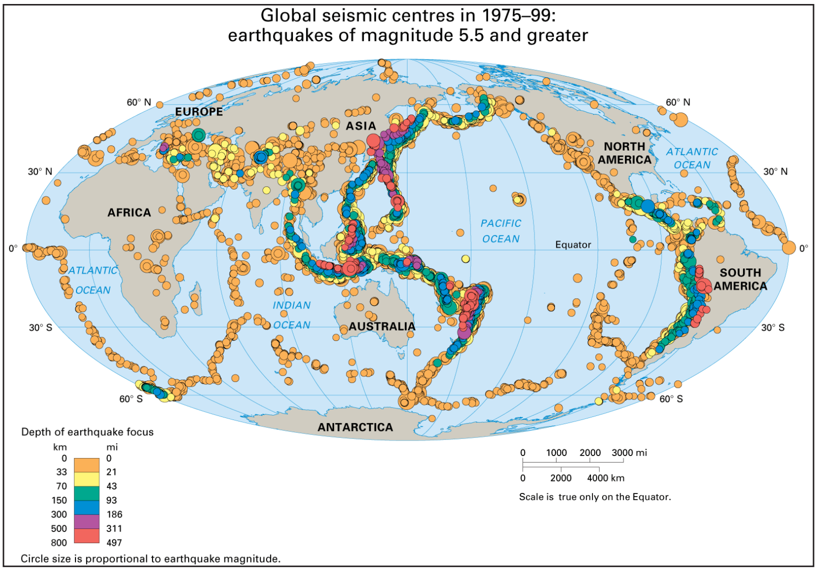
Understanding Earthquakes

A disaster resulting from the shaking of the surface of the Earth, which in turn creates seismic waves, is called an earthquake. There are various prediction methods for earthquakes such as observing animals for abnormal behavior, measuring water level and temperature change, and monitoring the emission of radon gas. The topics elaborated in this chapter will help in gaining a better perspective about the causes of earthquakes along with the methods of predicting them.

Earthquake is any sudden shaking of the ground caused by the passage of seismic waves through Earth's rocks. Seismic waves are produced when some form of energy stored in Earth's crust is suddenly released, usually when masses of rock straining against one another suddenly fracture and "slip." Earthquakes occur most often along geologic faults, narrow zones where rock masses move in relation to one another. The major fault lines of the world are located at the fringes of the huge tectonic plates that make up Earth's crust.

Residents of an earthquake-damaged neighbourhood of Port-au-Prince, Haiti, seeking safety in a sports field. The magnitude-7.0 earthquake struck the region the day before.

Little was understood about earthquakes until the emergence of seismology at the beginning of the 20th century. Seismology, which involves the scientific study of all aspects of earthquakes, has yielded answers to such long-standing questions as why and how earthquakes occur.



About 50,000 earthquakes large enough to be noticed without the aid of instruments occur annually over the entire Earth. Of these, approximately 100 are of sufficient size to produce substantial damage if their centres are near areas of habitation. Very great earthquakes occur on average about once per year. Over the centuries they have been responsible for millions of deaths and an incalculable amount of damage to property.

Crowds watching the fires set off by the earthquake in San Francisco.

The Nature of Earthquakes

Causes of Earthquakes

Earth’s major earthquakes occur mainly in belts coinciding with the margins of tectonic plates. This has long been apparent from early catalogs of felt earthquakes and is even more readily discernible in modern seismicity maps, which show instrumentally determined epicentres. The most important earthquake belt is the Circum-Pacific Belt, which affects many populated coastal regions around the Pacific Ocean—for example, those of New Zealand, New Guinea, Japan, the Aleutian Islands, Alaska, and the western coasts of North and South America. It is estimated that 80 percent of the energy presently released in earthquakes comes from those whose epicentres are in this belt. The seismic activity is by no means uniform throughout the belt, and there are a number of branches at various points. Because at many places the Circum-Pacific Belt is associated with volcanic activity, it has been popularly dubbed the "Pacific Ring of Fire."

A second belt, known as the Alpide Belt, passes through the Mediterranean region eastward through Asia and joins the Circum-Pacific Belt in the East Indies. The energy released in earthquakes from this belt is about 15 percent of the world total. There also are striking connected belts of seismic activity, mainly along oceanic ridges—including those in the Arctic Ocean, the Atlantic Ocean, and the western Indian Ocean—and along the rift valleys of East Africa. This global seismicity distribution is best understood in terms of its plate tectonic setting.

Natural Forces

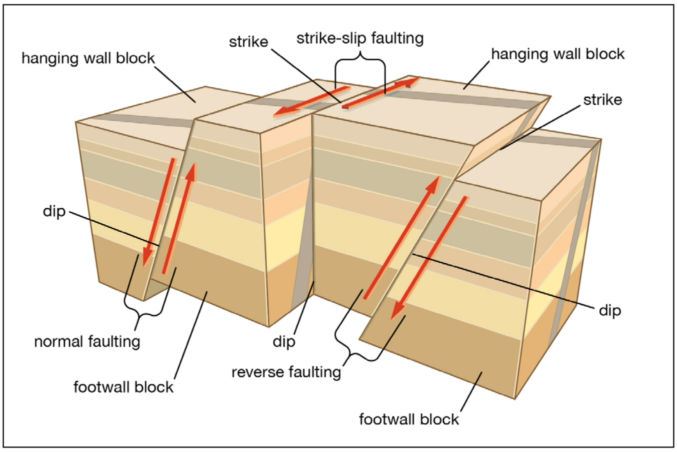
Earthquakes are caused by the sudden release of energy within some limited region of the rocks of the Earth. The energy can be released by elastic strain, gravity, chemical reactions, or even the motion of massive bodies. Of all these the release of elastic strain is the most important cause, because this form of energy is the only kind that can be stored in sufficient quantity in the Earth to produce major disturbances. Earthquakes associated with this type of energy release are called tectonic earthquakes.

Tectonics

Tectonic earthquakes are explained by the so-called elastic rebound theory, formulated by the American geologist Harry Fielding Reid after the San Andreas Fault ruptured in 1906, generating the great San Francisco earthquake. According to the theory, a tectonic earthquake occurs when strains in rock masses have accumulated to a point where the resulting stresses exceed the strength of the rocks, and sudden fracturing results. The fractures propagate rapidly through the rock, usually tending in the same direction and sometimes extending many kilometres along a local zone of weakness. In 1906, for instance, the San Andreas Fault slipped along a plane 430 km (270 miles) long. Along this line the ground was displaced horizontally as much as 6 metres (20 feet).

As a fault rupture progresses along or up the fault, rock masses are flung in opposite directions and thus spring back to a position where there is less strain. At any one point this movement may take place not at once but rather in irregular steps; these sudden slowings and restartings give rise to the vibrations that propagate as seismic waves. Such irregular properties of fault rupture are now included in the modeling of earthquake sources, both physically and mathematically. Roughnesses along the fault are referred to as asperities, and places where the rupture slows or stops are said to be fault barriers. Fault rupture starts at the earthquake focus, a spot that in many cases is close to 5–15 km under the surface. The rupture propagates in one or both directions over the fault plane until stopped or slowed at a barrier. Sometimes, instead of being stopped at the barrier, the fault rupture recommences on the far side; at other times the stresses in the rocks break the barrier, and the rupture continues.

Earthquakes have different properties depending on the type of fault slip that causes them. The usual fault model has a “strike” (that is, the direction from north taken by a horizontal line in the fault plane) and a “dip” (the angle from the horizontal shown by the steepest slope in the fault). The lower wall of an inclined fault is called the footwall. Lying over the footwall is the hanging wall. When rock masses slip past each other parallel to the strike, the movement is known as strike-slip faulting. Movement parallel to the dip is called dip-slip faulting. Strike-slip faults are right lateral or left lateral, depending on whether the block on the opposite side of the fault from an observer has moved to the right or left. In dip-slip faults, if the hanging-wall block moves downward relative to the footwall block, it is called “normal” faulting; the opposite motion, with the hanging wall moving upward relative to the footwall, produces reverse or thrust faulting.



Types of faulting in tectonic earthquakesIn normal and reverse faulting, rock masses slip vertically past each other. In strike-slip faulting, the rocks slip past each other horizontally.

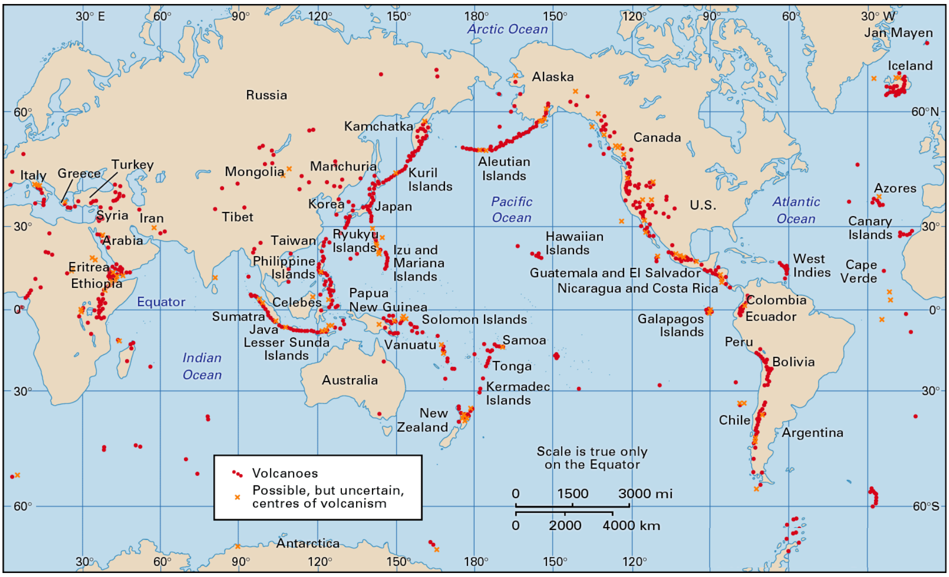
All known faults are assumed to have been the seat of one or more earthquakes in the past, though tectonic movements along faults are often slow, and most geologically ancient faults are now aseismic (that is, they no longer cause earthquakes). The actual faulting associated with an earthquake may be complex, and it is often not clear whether in a particular earthquake the total energy issues from a single fault plane.

Observed geologic faults sometimes show relative displacements on the order of hundreds of kilometres over geologic time, whereas the sudden slip offsets that produce seismic waves may range from only several centimetres to tens of metres. In the 1976 Tangshan earthquake, for example, a surface strike-slip of about one metre was observed along the causative fault east of Beijing, and in the 1999 Taiwan earthquake the Chelung-pu fault slipped up to eight metres vertically.

Volcanism

A separate type of earthquake is associated with volcanic activity and is called a volcanic earthquake. Yet it is likely that even in such cases the disturbance is the result of a sudden slip of rock masses adjacent to the volcano and the consequent release of elastic strain energy. The stored energy, however, may in part be of hydrodynamic origin due to heat provided by magma moving in reservoirs beneath the volcano or to the release of gas under pressure.

There is a clear correspondence between the geographic distribution of volcanoes and major earthquakes, particularly in the Circum-Pacific Belt and along oceanic ridges. Volcanic vents, however, are generally several hundred kilometres from the epicentres of most major shallow earthquakes, and many earthquake sources occur nowhere near active volcanoes. Even in cases where an earthquake's focus occurs directly below structures marked by volcanic vents, there is probably no immediate causal connection between the two activities; most likely both are the result of the same tectonic processes.



Volcanoes and thermal fields that have been active during the past 10,000 years.

Artificial Induction

Earthquakes are sometimes caused by human activities, including the injection of fluids into deep wells, the detonation of large underground nuclear explosions, the excavation of mines, and the filling of large reservoirs. In the case of deep mining, the removal of rock produces changes in the strain around the tunnels. Slip on adjacent, preexisting faults or outward shattering of rock into the new cavities may occur. In fluid injection, the slip is thought to be induced by premature release of elastic strain, as in the case of tectonic earthquakes, after fault surfaces are lubricated by the liquid. Large underground nuclear explosions have been known to produce slip on already strained faults in the vicinity of the test devices.

Reservoir Induction

Of the various earthquake-causing activities cited above, the filling of large reservoirs is among the most important. More than 20 significant cases have been documented in which local seismicity has increased following the impounding of water behind high dams. Often, causality cannot be substantiated, because no data exists to allow comparison of earthquake occurrence before and after the reservoir was filled. Reservoir-induction effects are most marked for reservoirs exceeding 100 metres (330 feet) in depth and 1 cubic km (0.24 cubic mile) in volume. Three sites where such connections have very probably occurred are the Hoover Dam in the United States, the Aswan High Dam in Egypt, and the Kariba Dam on the border between Zimbabwe and Zambia. The most generally accepted explanation for earthquake occurrence in such cases assumes that rocks near the reservoir are already strained from regional tectonic forces to a point where nearby faults are almost ready to slip. Water in the reservoir adds a pressure perturbation that triggers the fault rupture. The pressure effect is perhaps enhanced by the fact that the rocks along the fault have lower strength because of increased water-pore pressure. These factors notwithstanding, the filling of most large reservoirs has not produced earthquakes large enough to be a hazard.

The specific seismic source mechanisms associated with reservoir induction have been established in a few cases. For the main shock at the Koyna Dam and Reservoir , the evidence favours strike-slip faulting motion. At both the Kremasta Dam in Greece and the Kariba Dam in Zimbabwe-Zambia, the generating mechanism was dip-slip on normal faults. By contrast, thrust mechanisms have been determined for sources of earthquakes at the lake behind Nurek Dam in Tajikistan. More than 1,800 earthquakes occurred during the first nine years after water was impounded in this 317-metre-deep reservoir in 1972, a rate amounting to four times the average number of shocks in the region prior to filling.

Seismology and Nuclear Explosions

In 1958 representatives from several countries, including the United States and the Soviet Union, met to discuss the technical basis for a nuclear test-ban treaty. Among the matters considered was the feasibility of developing effective means with which to detect underground nuclear explosions and to distinguish them seismically from earthquakes. After that conference, much special research was directed to seismology, leading to major advances in seismic signal detection and analysis.

Recent seismological work on treaty verification has involved using high-resolution seismographs in a worldwide network, estimating the yield of explosions, studying wave attenuation in the Earth, determining wave amplitude and frequency spectra discriminants, and applying seismic arrays. The findings of such research have shown that underground nuclear explosions, compared with natural earthquakes, usually generate seismic waves through the body of the Earth that are of much larger amplitude than the surface waves. This telltale difference along with other types of seismic evidence suggest that an international monitoring network of 270 seismographic stations could detect and locate all seismic events over the globe of magnitude 4 and above (corresponding to an explosive yield of about 100 tons of TNT).

Causes of Earthquake

Tectonic earthquakes occur anywhere in the earth where there is sufficient stored elastic strain energy to drive fracture propagation along a fault plane. The sides of a fault move past each other smoothly and aseismically only if there are no irregularities or asperities along the fault surface that increase the frictional resistance. Most fault surfaces do have such asperities and this leads to a form of stick-slip behavior. Once the fault has locked, continued relative motion between the plates leads to increasing stress and therefore, stored strain energy in the volume around the fault surface. This continues until the stress has risen sufficiently to break through the asperity, suddenly allowing sliding over the locked portion of the fault, releasing the stored energy.

This energy is released as a combination of radiated elastic strain seismic waves, frictional heating of the fault surface, and cracking of the rock, thus causing an earthquake. This process of gradual build-up of strain and stress punctuated by occasional sudden earthquake failure is referred to as the elastic-rebound theory. It is estimated that only 10 percent or less of an earthquake's total energy is radiated as seismic energy. Most of the earthquake's energy is used to power the earthquake fracture growth or is converted into heat generated by friction. Therefore, earthquakes lower the Earth's available elastic potential energy and raise its temperature, though these changes are negligible compared to the conductive and convective flow of heat out from the Earth's deep interior.

Earthquake Fault Types

There are three main types of fault, all of which may cause an interplate earthquake: normal, reverse (thrust) and strike-slip. Normal and reverse faulting are examples of dip-slip, where the displacement along the fault is in the direction of dip and movement on them involves a vertical component. Normal faults occur mainly in areas where the crust is being extended such as a divergent boundary. Reverse faults occur in areas where the crust is being shortened such as at a convergent boundary. Strike-slip faults are steep structures where the two sides of the fault slip horizontally past each other; transform boundaries are a particular type of strike-slip fault. Many earthquakes are caused by movement on faults that have components of both dip-slip and strike-slip; this is known as oblique slip.

Reverse faults, particularly those along convergent plate boundaries are associated with the most powerful earthquakes, megathrust earthquakes, including almost all of those of magnitude 8 or more. Strike-slip faults, particularly continental transforms, can produce major earthquakes up to about magnitude 8. Earthquakes associated with normal faults are generally less than magnitude 7. For every unit increase in magnitude, there is a roughly thirtyfold increase in the energy released. For instance, an earthquake of magnitude 6.0 releases approximately 30 times more energy than a 5.0 magnitude earthquake and a 7.0 magnitude earthquake releases 900 times (30 × 30) more energy than a 5.0 magnitude of earthquake. An 8.6 magnitude earthquake releases the same amount of energy as 10,000 atomic bombs like those used in World War II.

Aerial photo of the San Andreas Fault in the Carrizo Plain, northwest of Los Angeles.

This is so because the energy released in an earthquake, and thus its magnitude, is proportional to the area of the fault that ruptures and the stress drop. Therefore, the longer the length and the wider the width of the faulted area, the larger the resulting magnitude. The topmost, brittle part of the Earth's crust, and the cool slabs of the tectonic plates that are descending down into the hot mantle, are the only parts of our planet which can store elastic energy and release it in fault ruptures. Rocks hotter than about 300 degrees Celsius flow in response to stress; they do not rupture in earthquakes. The maximum observed lengths of ruptures and mapped faults (which may break in a single rupture) are approximately 1000 km. Examples are the earthquakes in Chile, 1960; Alaska, 1957; Sumatra, 2004, all in subduction zones. The longest earthquake ruptures on strike-slip faults, like the San Andreas Fault, the North Anatolian Fault in Turkey and the Denali Fault in Alaska, are about half to one third as long as the lengths along subducting plate margins, and those along normal faults are even shorter.

The most important parameter controlling the maximum earthquake magnitude on a fault is however not the maximum available length, but the available width because the latter varies by a factor of 20. Along converging plate margins, the dip angle of the rupture plane is very shallow, typically about 10 degrees. Thus the width of the plane within the top brittle crust of the Earth can become 50 to 100 km, making the most powerful earthquakes possible.

Strike-slip faults tend to be oriented near vertically, resulting in an approximate width of 10 km within the brittle crust, thus earthquakes with magnitudes much larger than 8 are not possible. Maximum magnitudes along many normal faults are even more limited because many of them are located along spreading centers, as in Iceland, where the thickness of the brittle layer is only about 6 km.

In addition, there exists a hierarchy of stress level in the three fault types. Thrust faults are generated by the highest, strike slip by intermediate, and normal faults by the lowest stress levels. This can easily be understood by considering the direction of the greatest principal stress, the direction of the force that “pushes” the rock mass during the faulting. In the case of normal faults, the rock mass is pushed down in a vertical direction, thus the pushing force (greatest principal stress) equals the weight of the rock mass itself. In the case of thrusting, the rock mass “escapes” in the direction of the least principal stress, namely upward, lifting the rock mass up, thus the overburden equals the least principal stress. Strike-slip faulting is intermediate between the other two types. This difference in stress regime in the three faulting environments can contribute to differences in stress drop during faulting, which contributes to differences in the radiated energy, regardless of fault dimensions.

Earthquakes away from Plate Boundaries

Where plate boundaries occur within the continental lithosphere, deformation is spread out over a much larger area than the plate boundary itself. In the case of the San Andreas fault continental transform, many earthquakes occur away from the plate boundary and are related to strains developed within the broader zone of deformation caused by major irregularities in the fault trace (e.g., the “Big bend” region). The Northridge earthquake was associated with movement on a blind thrust within such a zone. Another example is the strongly oblique convergent plate boundary between the Arabian and Eurasian plates where it runs through the northwestern part of the Zagros Mountains. The deformation associated with this plate boundary is partitioned into nearly pure thrust sense movement’s perpendicular to the boundary over a wide zone to the southwest and nearly pure strike-slip motion along the Main Recent Fault close to the actual plate boundary itself. This is demonstrated by earthquake focal mechanisms.

All tectonic plates have internal stress fields caused by their interactions with neighboring plates and sedimentary loading or unloading (e.g. deglaciation). These stresses may be sufficient to cause failure along existing fault planes, giving rise to intraplate earthquakes.

Shallow-focus and Deep-focus Earthquakes

Collapsed Gran Hotel building in the San Salvador metropolis, after the shallow 1986 San Salvador earthquake.

The majority of tectonic earthquakes originate at the ring of fire in depths not exceeding tens of kilometers. Earthquakes occurring at a depth of less than 70 km are classified as shallow-focus earthquakes, while those with a focal-depth between 70 and 300 km are commonly termed mid-focus or intermediate-depth earthquakes. In subduction zones, where older and colder oceanic crust descends beneath another tectonic plate, deep-focus earthquakes may occur at much greater depths (ranging from 300 up to 700 kilometers).

These seismically active areas of subduction are known as Wadati–Benioff zones. Deep-focus earthquakes occur at a depth where the subducted lithosphere should no longer be brittle, due to the high temperature and pressure. A possible mechanism for the generation of deep-focus earthquakes is faulting caused by olivine undergoing a phase transition into a spinel structure.

Earthquakes and Volcanic Activity

Earthquakes often occur in volcanic regions and are caused there, both by tectonic faults and the movement of magma in volcanoes. Such earthquakes can serve as an early warning of volcanic eruptions, as during the 1980 eruption of Mount St. Helens. Earthquake swarms can serve as markers for the location of the flowing magma throughout the volcanoes. These swarms can be recorded by seismometers and tiltmeters (a device that measures ground slope) and used as sensors to predict imminent or upcoming eruptions.

Rupture Dynamics

A tectonic earthquake begins by an initial rupture at a point on the fault surface, a process known as nucleation. The scale of the nucleation zone is uncertain, with some evidence, such as the rupture dimensions of the smallest earthquakes, suggesting that it is smaller than 100 m while other evidence, such as a slow component revealed by low-frequency spectra of some earthquakes, suggests that it is larger. The possibility that the nucleation involves some sort of preparation process is supported by the observation that about 40% of earthquakes are preceded by foreshocks. Once the rupture has initiated, it begins to propagate along the fault surface. The mechanics of this process are poorly understood, partly because it is difficult to recreate the high sliding velocities in a laboratory. Also the effects of strong ground motion make it very difficult to record information close to a nucleation zone.

Rupture propagation is generally modeled using a fracture mechanics approach, likening the rupture to a propagating mixed mode shear crack. The rupture velocity is a function of the fracture energy in the volume around the crack tip, increasing with decreasing fracture energy. The velocity of rupture propagation is orders of magnitude faster than the displacement velocity across the fault.

Earthquake ruptures typically propagate at velocities that are in the range 70–90% of the S-wave velocity, and this is independent of earthquake size. A small subset of earthquake ruptures appear to have propagated at speeds greater than the S-wave velocity. These supershear earthquakes have all been observed during large strike-slip events. The unusually wide zone of coseismic damage caused by the 2001 Kunlun earthquake has been attributed to the effects of the sonic boom developed in such earthquakes. Some earthquake ruptures travel at unusually low velocities and are referred to as slow earthquakes. A particularly dangerous form of slow earthquake is the tsunami earthquake, observed where the relatively low felt intensities, caused by the slow propagation speed of some great earthquakes, fail to alert the population of the neighboring coast, as in the 1896 Sanriku earthquake.

Earthquake Clusters

Most earthquakes form part of a sequence, related to each other in terms of location and time. Most earthquake clusters consist of small tremors that cause little to no damage, but there is a theory that earthquakes can recur in a regular pattern.

Aftershocks

An aftershock is an earthquake that occurs after a previous earthquake, the mainshock. An aftershock is in the same region of the main shock but always of a smaller magnitude. If an aftershock is larger than the main shock, the aftershock is redesignated as the main shock and the original main shock is redesignated as a foreshock. Aftershocks are formed as the crust around the displaced fault plane adjusts to the effects of the main shock.

Earthquake Swarms

Earthquake swarms are sequences of earthquakes striking in a specific area within a short period of time. They are different from earthquakes followed by a series of aftershocks by the fact that no single earthquake in the sequence is obviously the main shock; therefore none have notable higher magnitudes than the other. An example of an earthquake swarm is the 2004 activity at Yellowstone National Park. In August 2012, a swarm of earthquakes shook Southern California's Imperial Valley, showing the most recorded activity in the area since the 1970s.

Sometimes a series of earthquakes occur in what has been called an earthquake storm, where the earthquakes strike a fault in clusters, each triggered by the shaking or stress redistribution of the previous earthquakes. Similar to aftershocks but on adjacent segments of fault, these storms occur over the course of years, and with some of the later earthquakes as damaging as the early ones. Such a pattern was observed in the sequence of about a dozen earthquakes that struck the North Anatolian Fault in Turkey in the 20th century and has been inferred for older anomalous clusters of large earthquakes in the Middle East.

Subduction Zones

Subduction zones are plate tectonic boundaries where two plates converge, and one plate is thrust beneath the other. This process results in geohazards, such as earthquakes and volcanoes. These hazards affect millions of people around the world, particularly around the edges of the Pacific Ocean, which mainly consist of subduction zones. The largest earthquakes on Earth occur at the interface between the two plates, called the megathrust. Recent examples include the magnitude 8.8 earthquake in Chile in February 2010 and the magnitude 9.1 earthquake offshore Sumatra in December 2004; the latter triggered a devastating tsunami.

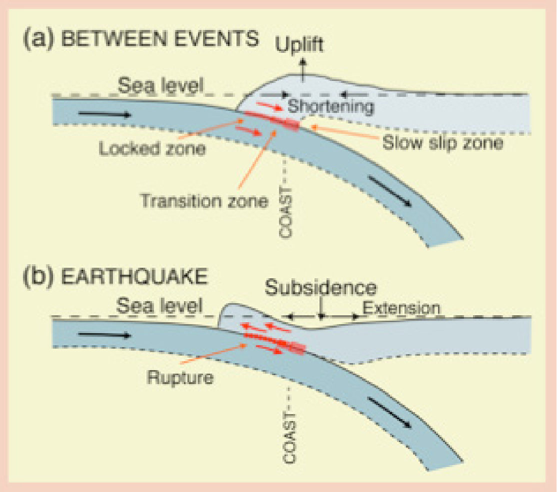


Figure showing cross section through subduction zone before an earthquake (above) and during an earthquake (below). Before the earthquake, stresses builds up on the part of the megathrust that is ‘locked’. This also causes the overriding plate to warp in response, such that the surface of the earth goes down near the trench, and the surface of the earth goes up farther inland. When an earthquake occurs, the locked zone ruptures, causing uplift near the trench and subsidence farther inshore.

Earthquakes are caused by movement over an area of the plate interface called the seismogenic zone. This zone ‘locks’ between earthquakes, such that stress builds up. It is then released catastrophically in one or more earthquakes. Above and below this area on the fault, stress cannot build up, and the movement between the plates occurs relatively smoothly through time, and thus does not produce large earthquakes. To improve our estimates of the likely damage that would be associated with an earthquake in a given location, we require better constraints on the size of the seismogenic zone, particularly the location of the lower limit.

The Alaska/Aleutian Subduction Zone

The ~2500-mile-long Alaska/Aleutian subduction zone stretches from Russia in the east to Alaska in the west. Here, the Pacific Plate and the North American plate are moving towards one another at a rate of ~6-7 centimeters (or 2-3 inches) per year. The Pacific Plate is thinner and denser, so it is being thrust underneath the North American plate. This subduction zone has generated many large, devastating earthquakes, including the second largest earthquake ever recorded: the magnitude 9.2 Good Friday earthquake in 1964. Not only did ground-shaking and landslides associated with this earthquake devastate Anchorage and other Alaskan towns, the resulting tsunami caused deaths as far away as California.

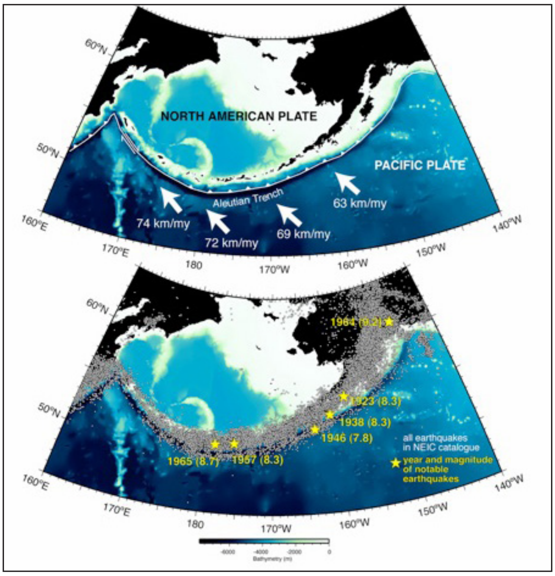


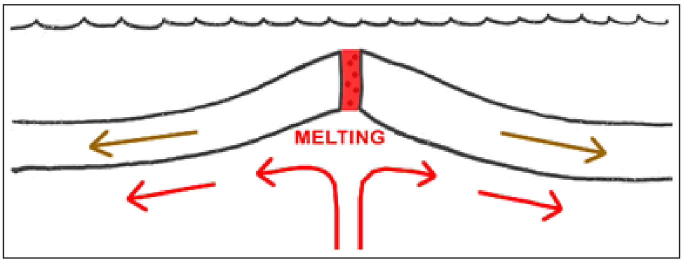
Figure showing the Alaska/Aleutian subduction zone in the northern Pacific Ocean. The Pacific plate is being thrust beneath the North American plate at a rate of ~6-7 cm (or 2-3 inch) per year. Rates above given in kilometers per million years. Below: Many earthquakes occur along this boundary, both on the contact between the plates and in the overriding North American plate. These include great earthquakes (yellow stars) such as the magnitude 9.2 Good Friday earthquake in Prince William Sound.

Divergent Boundaries

Divergent plate boundaries are locations where plates are moving away from one another. This occurs above rising convection currents. The rising current pushes up on the bottom of the lithosphere, lifting it and flowing laterally beneath it. This lateral flow causes the plate material above to be dragged along in the direction of flow. At the crest of the uplift, the overlying plate is stretched thin, breaks and pulls apart.

Divergent Plate Boundary - Oceanic

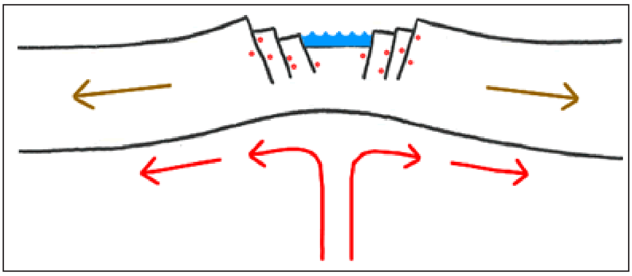
When a divergent boundary occurs beneath oceanic lithosphere, the rising convection current below lifts the lithosphere, producing a mid-ocean ridge. Extensional forces stretch the lithosphere and produce a deep fissure. When the fissure opens, pressure is reduced on the super-heated mantle material below. It responds by melting, and the new magma flows into the fissure. The magma then solidifies and the process repeats itself.



The Mid-Atlantic Ridge is a classic example of this type of plate boundary. The Ridge is a high area compared to the surrounding seafloor because of the lift from the convection current below. A frequent misconception is that the Ridge is a build-up of volcanic materials; however, the magma that fills the fissure does not flood extensively over the ocean floor and stack up to form a topographic high. Instead, it fills the fissure and solidifies. When the next eruption occurs, the fissure most likely develops down the center of the cooling magma plug with half of the newly solidified material being attached to the end of each plate.

Effects that are found at a divergent boundary between oceanic plates include: a submarine mountain range such as the Mid-Atlantic Ridge; volcanic activity in the form of fissure eruptions; shallow earthquake activity; creation of new seafloor and a widening ocean basin.

Divergent Plate Boundary - Continental



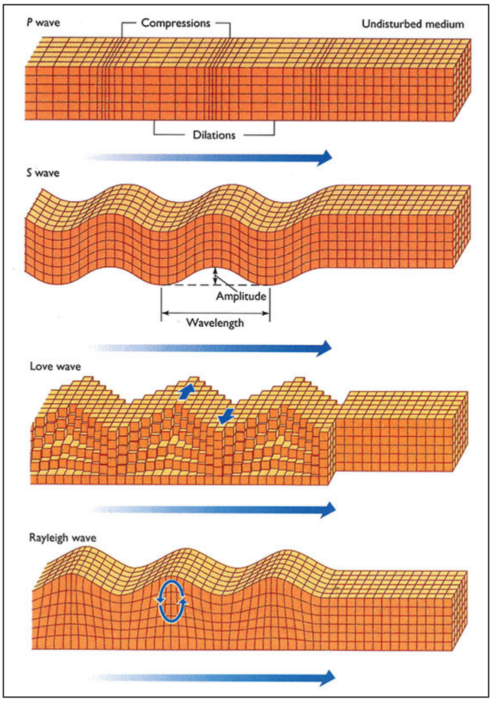
When a divergent boundary occurs beneath a thick continental plate, the pull-apart is not vigorous enough to create a clean, single break through the thick plate material. Here the thick continental plate is arched upwards from the convection current's lift, pulled thin by extensional forces, and fractured into a rift-shaped structure. As the two plates pull apart, normal faults develop on both sides of the rift, and the central blocks slide downwards. Earthquakes occur as a result of this fracturing and movement. Early in the rift-forming process, streams and rivers will flow into the sinking rift valley to form a long linear lake. As the rift grows deeper it might drop below sea level, allowing ocean waters to flow in. This will produce a narrow, shallow sea within the rift. This rift can then grow deeper and wider. If rifting continues, a new ocean basin could be produced.

The East Africa Rift Valley is a classic example of this type of plate boundary. The East Africa Rift is in a very early stage of development. The plate has not been completely rifted, and the rift valley is still above sea level but occupied by lakes at several locations. The Red Sea is an example of a more completely developed rift. There the plates have fully separated, and the central rift valley has dropped below sea level.

Effects that are found at this type of plate boundary include: a rift valley sometimes occupied by long linear lakes or a shallow arm of the ocean; numerous normal faults bounding a central rift valley; shallow earthquake activity along the normal faults. Volcanic activity sometimes occurs within the rift.

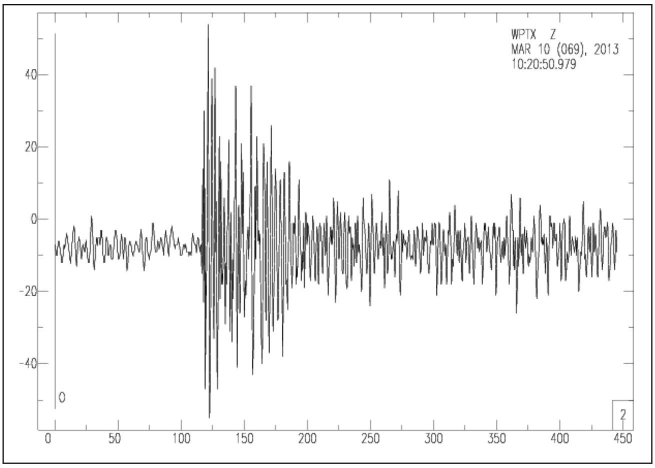
Earthquake Waves

Seismic waves are waves of energy that travel through the Earth's layers, and are a result of earthquakes, volcanic eruptions, magma movement, large landslides and large man-made explosions that give out low-frequency acoustic energy. Many other natural and anthropogenic sources create low-amplitude waves commonly referred to as ambient vibrations. Seismic waves are studied by geophysicists called seismologists. Seismic wave fields are recorded by a seismometer, hydrophone (in water), or accelerometer.



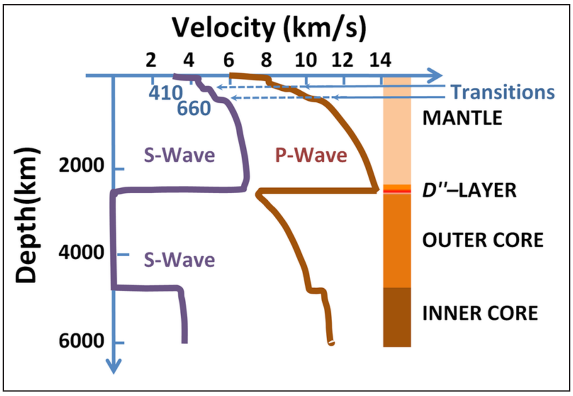
Body waves and surface waves.

The propagation velocity of seismic waves depends on density and elasticity of the medium as well as the type of wave. Velocity tends to increase with depth through Earth's crust and mantle, but drops sharply going from the mantle to the outer core.



p-wave and s-wave from seismograph.

Earthquakes create distinct types of waves with different velocities; when reaching seismic observatories, their different travel times help scientists to locate the source of the hypocenter. In geophysics the refraction or reflection of seismic waves is used for research into the structure of the Earth's interior, and man-made vibrations are often generated to investigate shallow, subsurface structures.



Velocity of seismic waves in the Earth versus depth. The negligible *S*-wave velocity in the outer core occurs because it is liquid, while in the solid inner core the *S*-wave velocity is non-zero.

Types

Among the many types of seismic waves, one can make a broad distinction between *body waves*, which travel through the Earth, and *surface waves*, which travel at the Earth's surface.

Other modes of wave propagation exist than those described in this article; though of comparatively minor importance for earth-borne waves, they are important in the case of asteroseismology:

- Body waves travel through the interior of the Earth.
- Surface waves travel across the surface. Surface waves decay more slowly with distance than body waves, which travel in three dimensions.
- Particle motion of surface waves is larger than that of body waves, so surface waves tend to cause more damage.

Body Waves

Body waves travel through the interior of the Earth along paths controlled by the material properties in terms of density and modulus (stiffness). The density and modulus, in turn, vary according to temperature, composition, and material phase. This effect resembles the refraction of light waves. Two types of particle motion result in two types of body waves: *Primary* and *Secondary* waves.

Primary Waves

Primary waves (P-waves) are compressional waves that are longitudinal in nature. P-waves are pressure waves that travel faster than other waves through the earth to arrive at seismograph stations first, hence the name "Primary". These waves can travel through any type of material, including fluids, and can travel nearly 1.7 times faster than the S-waves. In air, they take the form of sound waves, hence they travel at the speed of sound. Typical speeds are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite.

Secondary Waves

Secondary waves (S-waves) are shear waves that are transverse in nature. Following an earthquake event, S-waves arrive at seismograph stations after the faster-moving P-waves and displace the ground perpendicular to the direction of propagation. Depending on the propagational direction, the wave can take on different surface characteristics; for example, in the case of horizontally polarized S waves, the ground moves alternately to one side and then the other. S-waves can travel only through solids, as fluids (liquids and gases) do not support shear stresses. S-waves are slower than P-waves, and speeds are typically around 60% of that of P-waves in any given material. Shear waves can't travel through any liquid medium, so the absence of S-wave in earth's outer core suggests a liquid state.

Surface Waves

Seismic surface waves travel along the Earth's surface. They can be classified as a form of mechanical surface waves. They are called surface waves, as they diminish as they get further from the surface. They travel more slowly than seismic body waves (P and S). In large earthquakes, surface waves can have an amplitude of several centimeters.

Rayleigh Waves

Rayleigh waves, also called ground roll, are surface waves that travel as ripples with motions that are similar to those of waves on the surface of water (note, however, that the associated particle motion at shallow depths is retrograde, and that the restoring force in Rayleigh and in other seismic waves is elastic, not gravitational as for water waves). The existence of these waves was predicted by John William Strutt, Lord Rayleigh, in 1885. They are slower than body waves, roughly 90% of the velocity of S waves for typical homogeneous elastic media. In a layered medium (like the crust and upper mantle) the velocity of the Rayleigh waves depends on their frequency and wavelength.

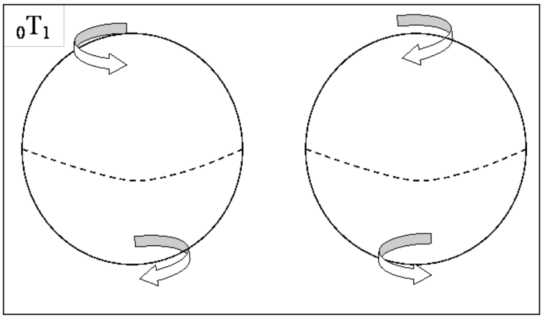
Love Waves

Love waves are horizontally polarized shear waves (SH waves), existing only in the presence of a semi-infinite medium overlain by an upper layer of finite thickness. They are named after A.E.H. Love, a British mathematician who created a mathematical model of the waves in 1911. They usually travel slightly faster than Rayleigh waves, about 90% of the S wave velocity, and have the largest amplitude.

Stoneley Waves

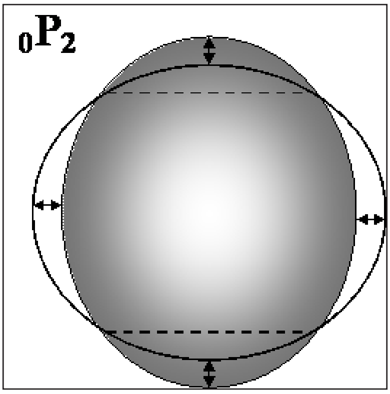
A Stoneley wave is a type of boundary wave (or interface wave) that propagates along a solid-fluid boundary or, under specific conditions, also along a solid-solid boundary. Amplitudes of Stoneley waves have their maximum values at the boundary between the two contacting media and decay exponentially towards the depth of each of them. These waves can be generated along the walls of a fluid-filled borehole, being an important source of coherent noise in VSPs and making up the low frequency component of the source in sonic logging. The equation for Stoneley waves was first given by Dr. Robert Stoneley, Emeritus Professor of Seismology, Cambridge.

Normal Modes



The sense of motion for toroidal $_0T_1$ oscillation for two moments of time.

Free oscillations of the Earth are standing waves, the result of interference between two surface waves traveling in opposite directions. Interference of Rayleigh waves results in *spheroidal oscillation S* while interference of Love waves gives *toroidal oscillation T*. The modes of oscillations are specified by three numbers, e.g., $_nS_l^m$, where l is the angular order number. The number m is the azimuthal order number. It may take on $2l+1$ values from $-l$ to $+l$. The number n is the *radial order number*. It means the wave with n zero crossings in radius. For spherically symmetric Earth the period for given n and l does not depend on m.



The scheme of motion for spheroidal $_0S_2$ oscillation.Dashed lines give nodal (zero) lines. Arrows give the sense of motion.

Some examples of spheroidal oscillations are the “breathing” mode ${}_{0}S_{0}$, which involves an expansion and contraction of the whole Earth, and has a period of about 20 minutes; and the “rugby” mode ${}_{0}S_{2}$, which involves expansions along two alternating directions, and has a period of about 54 minutes. The mode ${}_{0}S_{1}$ does not exist because it would require a change in the center of gravity, which would require an external force.

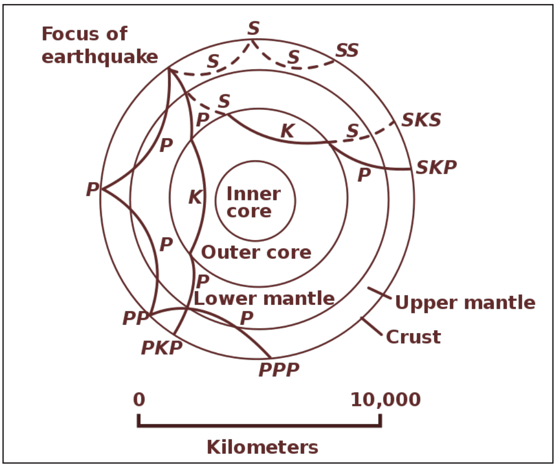
Of the fundamental toroidal modes, ${}_{0}T_{1}$ represents changes in Earth’s rotation rate; although this occurs, it is much too slow to be useful in seismology. The mode ${}_{0}T_{2}$ describes a twisting of the northern and southern hemispheres relative to each other; it has a period of about 44 minutes.

The first observations of free oscillations of the Earth were done during the great 1960 earthquake in Chile. Presently periods of thousands of modes are known. These data are used for determining some large scale structures of the Earth interior.

P and S Waves in Earth’s Mantle and Core

When an earthquake occurs, seismographs near the epicenter are able to record both P and S waves, but those at a greater distance no longer detect the high frequencies of the first S wave. Since shear waves cannot pass through liquids, this phenomenon was original evidence for the now well-established observation that the Earth has a liquid outer core, as demonstrated by Richard Dixon Oldham. This kind of observation has also been used to argue, by seismic testing, that the Moon has a solid core, although recent geodetic studies suggest the core is still molten.

Notation



Earthquake wave paths.

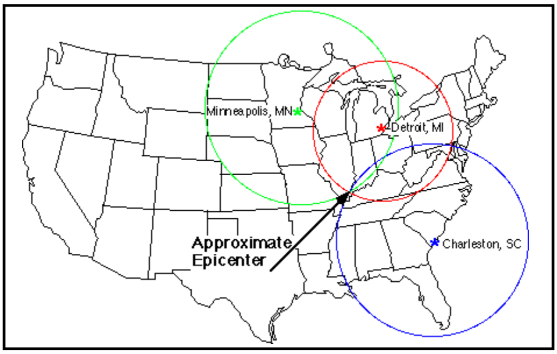
The path that a wave takes between the focus and the observation point is often drawn as a ray diagram. When reflections are taken into account there are an infinite number of paths that a wave can take. Each path is denoted by a set of letters that describe the trajectory and phase through the Earth. In general an upper case denotes a transmitted wave and a lower case denotes a reflected wave. The two exceptions to this seem to be “g” and “n”.

c	the wave reflects off the outer core
d	a wave that has been reflected off a discontinuity at depth d
g	a wave that only travels through the crust
i	a wave that reflects off the inner core
I	a P-wave in the inner core
h	a reflection off a discontinuity in the inner core
J	an S wave in the inner core
K	a P-wave in the outer core
L	a Love wave sometimes called LT-Wave (Both caps, while an Lt is different)
n	a wave that travels along the boundary between the crust and mantle
P	a P wave in the mantle
p	a P wave ascending to the surface from the focus
R	a Rayleigh wave
S	an S wave in the mantle
s	an S wave ascending to the surface from the focus
w	the wave reflects off the bottom of the ocean
	No letter is used when the wave reflects off of the surfaces

For example:

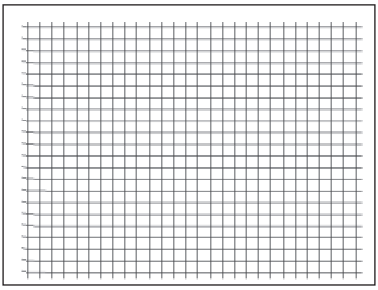
- ScP is a wave that begins traveling towards the center of the Earth as an S wave. Upon reaching the outer core the wave reflects as a P wave.
- sPKIKP is a wave path that begins traveling towards the surface as an S-wave. At the surface it reflects as a P-wave. The P-wave then travels through the outer core, the inner core, the outer core, and the mantle.

Usefulness of P and S Waves in Locating an Event



The Hypocenter/Epicenter of an earthquake is calculated by using the seismic data of that earthquake from at least three different locations.

In the case of local or nearby earthquakes, the difference in the arrival times of the P and S waves can be used to determine the distance to the event. In the case of earthquakes that have occurred at global distances, three or more geographically diverse observing stations (using a common clock) recording P-wave arrivals permits the computation of a unique time and location on the planet for the event. Typically, dozens or even hundreds of P-wave arrivals are used to calculate hypocenters. The misfit generated by a hypocenter calculation is known as “the residual”. Residuals of 0.5 second or less are typical for distant events, residuals of 0.1–0.2 s typical for local events, meaning most reported P arrivals fit the computed hypocenter that well. Typically a location program will start by assuming the event occurred at a depth of about 33 km; then it minimizes the residual by adjusting depth. Most events occur at depths shallower than about 40 km, but some occur as deep as 700 km.



P- and S-waves sharing with the propagation.

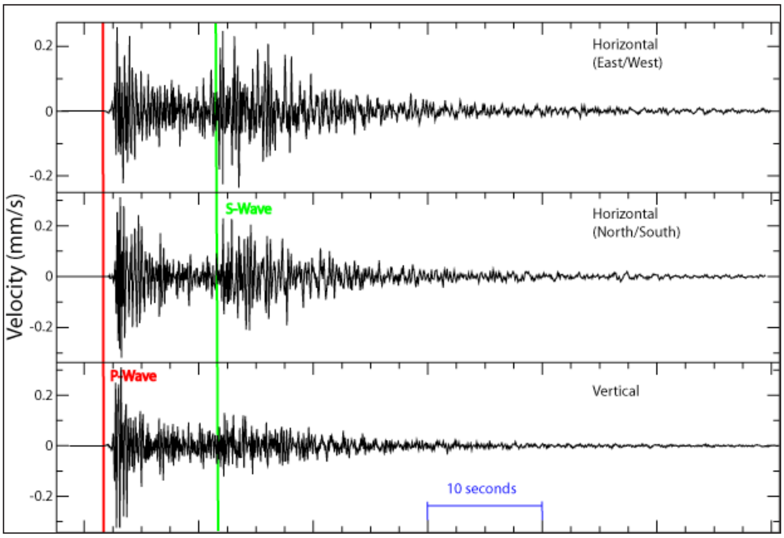
A quick way to determine the distance from a location to the origin of a seismic wave less than 200 km away is to take the difference in arrival time of the P wave and the S wave in seconds and multiply by 8 kilometers per second. Modern seismic arrays use more complicated earthquake location techniques.

At teleseismic distances, the first arriving P waves have necessarily travelled deep into the mantle, and perhaps have even refracted into the outer core of the planet, before travelling back up to the Earth’s surface where the seismographic stations are located. The waves travel more quickly than if they had traveled in a straight line from the earthquake. This is due to the appreciably increased velocities within the planet, and is termed Huygens’ Principle. Density in the planet increases with depth, which would slow the waves, but the modulus of the rock increases much more, so deeper means faster. Therefore, a longer route can take a shorter time.

The travel time must be calculated very accurately in order to compute a precise hypocenter. Since P waves move at many kilometers per second, being off on travel-time calculation by even a half second can mean an error of many kilometers in terms of distance. In practice, P arrivals from many stations are used and the errors cancel out, so the computed epicenter is likely to be quite accurate, on the order of 10–50 km or so around the world. Dense arrays of nearby sensors such as those that exist in California can provide accuracy of roughly a kilometer, and much greater accuracy is possible when timing is measured directly by cross-correlation of seismogram waveforms.

Measuring and Predicting Earthquakes

A seismograph produces a graph-like representation of the seismic waves it receives and records them onto a seismogram. Seismograms contain information that can be used to determine how strong an earthquake was, how long it lasted, and how far away it was. Modern seismometers record ground motions using electronic motion detectors. The data are then kept digitally on a computer.



These seismograms show the arrival of P-waves and S-waves. The surface waves arrive just after the S-waves and are difficult to distinguish. Time is indicated on the horizontal portion (or x-axis) of the graph.

If a seismogram records P-waves and surface waves but not S-waves, the seismograph was on the other side of the Earth from the earthquake. The amplitude of the waves can be used to determine the magnitude of the earthquake.

Finding the Epicenter

To locate an earthquake epicenter:

1. Scientists first determine the epicenter distance from three different seismographs. The longer the time between the arrival of the P-wave and S-wave, the farther away is the epicenter. So the difference in the P and S wave arrival times determines the distance between the epicenter and a seismometer.
2. The scientist then draws a circle with a radius equal to the distance from the epicenter for that seismograph. The epicenter is somewhere along that circle. This is done for three locations. Using data from two seismographs, the two circles will intercept at two points. A third circle will intercept the other two

circles at a single point. This point is the earthquake epicenter. Although useful for decades, this technique has been replaced by digital calculations.

Circles are drawn with radii representing the distance from each seismic station to the earthquake's epicenter. The intersection of these three circles is the earthquake's epicenter.

Earthquake Intensity

Measuring Earthquakes

People have always tried to quantify the size of and damage done by earthquakes. Since early in the 20th century, there have been three methods. What are the strengths and weaknesses of each?

- Mercalli Intensity Scale: Earthquakes are described in terms of what nearby residents felt and the damage that was done to nearby structures.
- Richter magnitude scale: Developed in 1935 by Charles Richter, this scale uses a seismometer to measure the magnitude of the largest jolt of energy released by an earthquake.
- Moment magnitude scale: Measures the total energy released by an earthquake. Moment magnitude is calculated from the area of the fault that is ruptured and the distance the ground moved along the fault.

The Richter scale and the moment magnitude scale are logarithmic.

- The amplitude of the largest wave increases ten times from one integer to the next.
- An increase in one integer means that thirty times more energy was released.
- These two scales often give very similar measurements.

How does the amplitude of the largest seismic wave of magnitude 5 earthquakes compare with the largest wave of a magnitude 4 earthquake? How does it compare with a magnitude 3 quake? The amplitude of the largest seismic wave of a magnitude 5 quake is 10 times that of a magnitude 4 quake and 100 times that of a magnitude 3 quake.

How does an increase in two integers on the moment magnitude scale compare in terms of the amount of energy released? Two integers equal a 900-fold increase in released energy.

With the Richter scale, a single sharp jolt measures higher than a very long intense earthquake that releases more energy. The moment magnitude scale more accurately reflects the energy released and the damage caused. Most seismologists now use the moment magnitude scale.

The way scientists measure earthquake intensity and the two most common scales, Richter and moment magnitude.

Annual Earthquakes

In a single year, on average, more than 900,000 earthquakes are recorded and 150,000 of them are strong enough to be felt. Each year about 18 earthquakes are major with a Richter magnitude of 7.0 to 7.9, and on average one earthquake has a magnitude of 8 to 8.9.

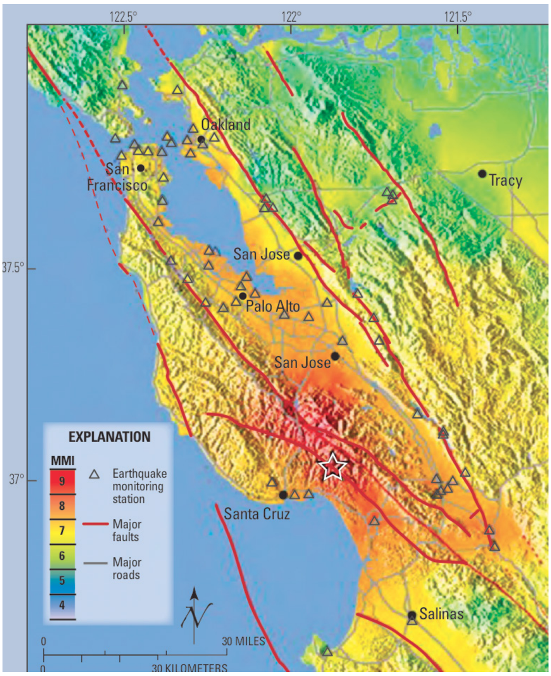
Magnitude 9 earthquakes are rare. The United States Geological Survey lists five since 1900. All but the Great Indian Ocean Earthquake of 2004 occurred somewhere around the Pacific Ocean basin.

The 1964 Good Friday Earthquake centered in Prince William Sound, Alaska released the second most amount of energy of any earthquake in recorded history.

Earthquakes of magnitude 9 or greater		
Location	Year	Magnitude
Valdivia, Chile	1960	9.5
Prince William Sound, Alaska	1964	9.2
Great Indian Ocean Earthquake	2004	9.1
Kamchatka, Alaska	1952	9.0
Tōhoku, Japan	2011	9.0

Earthquake Prediction

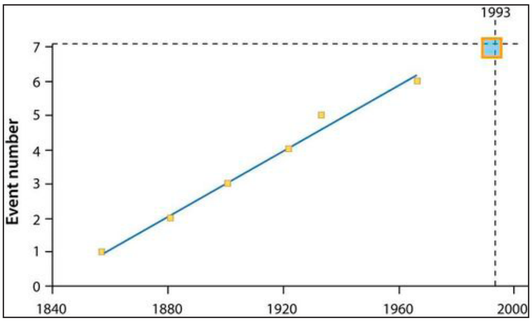
Scientists are a long way from being able to predict earthquakes. A good prediction must be accurate as to where an earthquake will occur, when it will occur, and at what magnitude it will be so that people can evacuate. An unnecessary evacuation is expensive and causes people not to believe authorities the next time an evacuation is ordered.



The probabilities of earthquakes striking along various faults in the San Francisco area between 2003 (when the work was done) and 2032.

Where an earthquake will occur is the easiest feature to predict. Scientists know that earthquakes take place at plate boundaries and tend to happen where they've occurred before. Earthquake-prone communities should always be prepared for an earthquake. These communities can implement building codes to make structures earthquake safe.

When an earthquake will occur is much more difficult to predict. Since stress on a fault builds up at the same rate over time, earthquakes should occur at regular intervals. But so far scientists cannot predict when quakes will occur even to within a few years.



Around Parkfield, California, an earthquake of magnitude 6.0 or higher occurs about every 22 years. So seismologists predicted that one would strike in 1993, but that quake came in 2004 – 11 years late.

Signs sometimes come before a large earthquake. Small quakes, called foreshocks, sometimes occur a few seconds to a few weeks before a major quake. However, many earthquakes do not have foreshocks and small earthquakes are not necessarily followed by a large earthquake. Often, the rocks around a fault will dilate as micro fractures form. Ground tilting, caused by the buildup of stress in the rocks, may precede a large earthquake, but not always. Water levels in wells fluctuate as water moves into or out of fractures before an earthquake. This is also an uncertain predictor of large earthquakes. The relative arrival times of P-waves and S-waves also decreases just before an earthquake occurs.

Folklore tells of animals behaving erratically just before an earthquake. Mostly these anecdotes are told after the earthquake. If indeed animals sense danger from earthquakes or tsunami, scientists do not know what it is they could be sensing, but they would like to find out.

Predictions Methods

Prediction is concerned with forecasting the occurrence of an earthquake of a particular intensity over a specific locality within a specific time limit. Normally prediction is of three types viz. long, medium and short range prediction.

While long range prediction is concerned with forecasting the occurrence of an earthquake a number of years in advance, medium term prediction is to be done a few months to a year or so and the short term prediction implies forecast ranging from a few hours to some days in advance.

Medium and short range predictions are very useful because they can help in saving the largest population from disaster in terms of life and property. Scientists believe that it is possible to predict major earthquakes by monitoring the seismicity caused by natural earthquakes, mining blasts, nuclear tests, etc.

However, no flawless technique has been developed to predict the earthquakes till date. Most of the methods and models are beyond the scope of the present work and only a few simple methods and models.

Unusual Animal Behaviour

It is a well-established fact that animals are endowed with certain sensory perceptions denied to human beings. Some of the animals have much better power of sniffing, hearing, seeing and sensing than the human beings. The unusual behaviour of animals prior to earthquakes received wide publicity after the Haichang earthquake in Liaoning province of China, in February 4, 1975 was successfully predicted.

Although fluctuations in water levels and radon content in water were given due consideration, behaviour of animals was not overlooked in the process of earthquake prediction. On the morning of February 4, 1975, a moderate forestock hit the city of Haichang and by 2 p.m. a general alert was proclaimed.

Within six hours, the area was rocked by a devastating earthquake of 7.3 magnitude but almost all the one lakh residents were saved. Chinese are considered to be pioneers in recognising the unusual behaviour of animals preceding a quake as an important indicator to predict an impending earthquake, particularly since the accurate prediction of Haichang quake of 1975.

In fact, national war against earthquakes was launched in 1966 with an effective slogan, “Rather a thousand days with no earthquake than one day with no precaution.” Chinese report was presented at the Intergovernmental meeting convened at UNESCO, Paris in February 1976. This stimulated considerable interest among scientists.

However, it should be mentioned that abnormal behaviour of animals prior to a devastating earthquake was noticed earlier also in different parts of the world. In Japan large number of rats were seen every day in a restaurant in Nagoya City, which suddenly disappeared on the evening prior to Nobi earthquake of 1891.

Similar observations about rats were reported at two earlier occasions i.e., Kanto earthquake of and Sankriku earthquake of. In China, unusual behaviour of rats was reported before Hsingtai earthquake in Hopei Province (300 km from Beijing).

In 1835 dogs escaped from the city of Talcahuano in Chile before the earthquake struck the city. Flocks of birds flew inland before the Chilean earthquakes of 1822 and 1835. Monkeys became restless a few hours before the Managua earthquake of 1972 in Nicaragua.

In summer of 1969, just before the Bahai quake (July, 1969), the custodians of Tientsin Zoo had observed that swans suddenly scrambled out of water and stayed away, a

Manchurian tiger stopped pacing, a Tibetan yak collapsed, pandas held their heads in paws and moaned; and turtles were restless.

Hens and cocks were reported restless about an hour's before in 1896 Ryakya earthquake in Japan. In Yugoslavia, birds in zoo started crying before 1963 earthquake. Deer gathered and cats disappeared from villages in northern Italy two or three hours before damaging earthquake of 1976.

Just before the earthquake which occurred in 1906 along the San Andreas Fault, horses whined and cows stampeded. In other cases cows about to be milked became restless before the shock. Bellowing of the cattle at the time of shock was very commonly reported. Howling by dogs was reported during the night preceding the earthquake.

Abnormal behaviour just before an earthquake has also been noticed among animals that live underground, like snakes, insects and worms, and those living in water (fishes). Abundant fishes were caught in just before the 1896 earthquake in north western coast of Japan and the Tango earthquake of 1927. However, in Kanto earthquake fishes were reported to have disappeared.

Just before the Edo earthquake (November 11, 1855), many grass snakes were reported to have come out of the ground near the epicentral areas even though it was severe cold winter. Very unusual behaviour of dogs was reported just before the Turkey earthquake (November 24, 1976). Barry Ralleigh of the U.S. Geological Survey noticed that the horses were fidget just before the earthquake of 28 November 1974 in Hollister, California.

In India, unusual behaviour of animals with respect to earthquake was noticed early in 1892. Animals were noticed to sniff the ground and exhibit nervousness such as a dog shows in the presence of an unaccustomed object, at the time of Govindpur (Manbhoom) a February 19, 1892. During the recent earthquakes of Uttarkashi Latur Jabalpur Chamoli and Bhuj there were isolated cases of unusual behaviour of pet dogs.

Extensive research is being carried on all over the world about the unusual behaviour of animals with respect to prediction of the earthquake. China and Japan are fore-runners in this regard. The USA has also shown keen interest in unusual behaviour of animals as a useful indicator of earthquake prediction.

The Stanford Research Institute, California, under the 'Project Earthquake Watch' has a network along the San Andreas Fault. This group keeps a watch on the behaviour of about 70 animal species. Dr. B.G. Deshpande has compiled a list of 87 animals which have been watched all over the world and whose behaviour might sense as an advance indicator of impending quake. Some of these which may be easily observed by the city dwellers are; cockroaches, crows, dogs, donkeys, ducks, fowls, frogs, geese, goats, horses, mice, monkeys, pigs, pigeons, rats, sheep, squirrels, swans and snakes.

The Group of Earthquake Research Institutes of Biophysics, China has arrived at the following conclusions after an extensive survey of animal behaviour before a strong earthquake:

- Most animals show increased restlessness before an earthquake.
- The precursor time varies from a few minutes to several days, with increased restlessness at 11 hours which becomes still more marked about 2 to 3 hours before the earthquake. In general precursor times of various animals are mostly within 24 hours before the earthquake.
- These observations have been noticed predominantly in high intensity or epicentral region close to active faults.
- Abnormal behaviour of the animals is observed during earthquakes of magnitude 5 or more.
- More intensive response can be noticed with the increase of intensity of earthquakes.

Hydrochemical Precursors

Chemical composition of underground water was observed on a regular basis in seismically active regions of Tadzhik and Uzbekistan. These observations yielded following results:

- Concentration levels of dissolved minerals and gaseous components remained almost constant during seismically inactive period.
- An appreciable increase in concentration of dissolved minerals was noticed 2 to 8 days before an earthquake. Variations in level of underground water, the pressure of artesian water, the discharge of water sources and temperature of underground water were also noticed during this period. These variations are large in the event of a strong earthquake.
- After the earthquake, anomalies in concentrations of the gaseous and mineral components disappear.

Meteorological Department report, significant pre-disaster and post disaster hydro geological changes rendering the ground water turbid were observed during the Jabalpur earthquake in Madhya Pradesh.

Temperature Change

There seems to be some relation between temperature and earthquakes. A considerable rise of temperature by 10 °C and 15 °C was reported before earthquakes in Lunglin in China and Przhevalsk in Russia. The epicentral distances of these earthquakes where observations were taken in hot spring/well were 10 and 30 km and precursory periods were 42 and 72 days respectively.

Water Level

There are drastic changes in water level in several wells just before a major earthquake. There was a fall in water level a few days before the Nankai earthquake in Japan. Rise of water level by 3 and 15 cm was reported before Lunglin (China) and Przhevalsk (Russia) earthquakes.

Similarly, water level rose by 3 cm a few hours before the earthquake in Meckering in Australia. In China rise of water level in wells was observed before earthquakes of Tangshan Liu- quiao and Shanyin.

Experiments in water level variations have been conducted in Kurile Islands to predict the earthquakes of 4 and more on Richter scale. For this purpose wells upto 410-670 metres depth at epicentral distances upto 700 km are used. This is an effective technique for observing the deformation of the earth's crust. The model on which the forecasts of earthquakes is based shows that 3 to 10 days before an earthquake, the water level begins to fall. After a short period, it starts rising when the earthquake strikes.

Radon Gas

Radon is a radioactive gas which is discharged from rock masses prior to earthquake. It is dissolved in the well water and its concentration in the water increases. Such an increase was reported in Tashkent in 1972 where increase in concentration varying from 15 to 200 per cent was noticed about 3 to 13 days prior to an earthquake.

In China, 50% and 70% increase in radon concentration was reported 18 and 6 days respectively before the Tangshan and Luhuo at Langfang and Guzan stations which were located 130 and 200 km epicentral distances for two cases. In a correlation in radon anomalies at four sites in Kangra and one site in Amritsar with the time of occurrence of Uttarkashi earthquake was reported.

Oil Wells

Large scale fluctuations of oil flow from oil wells prior to earthquakes were reported in Israel, northern Caucasus (Europe) and China. These earthquakes which occurred in 1969, 1971 and 1972 gave rise to increased flow of oil before their occurrence. It has been suggested that when the tectonic stress accumulates to a certain level, the pore pressure within a deep oil bearing strata reach its breaking strength causing oil to sprout along the oil wells.

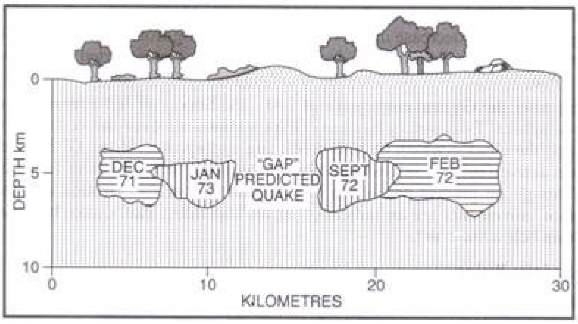
Theory of Seismic Gap

Seismicity gap is a region where earthquake activity is less compared with its neighbourhood along plate boundaries. Soviet seismologist S. A. Fedotov studied the seismic record of 12 large earthquakes which rocked northern Japan between 1904 and 1963. By plotting the size of each tremor- struck area, he found that each quake segment abutted the next contiguous one without overlapping, as if each deep seated crack had been shut off by a barrier at the ends of the fracture zone.

Each large earthquake was in a segment that was quiet for the last 39 years or so. Fedotov predicted that those segments which were quiet for some time will be hit by earthquake sooner or later. Three of these blocks in Kurile Island were struck where according to Fedotov an earthquake was due. Thus evolved the theory of seismic gap in earthquake prediction.

Based on this theory Dr. Kiyo Mogi of Tokyo succeeded in predicting a few earthquakes in Japan. Three geophysicists—Masakazu Ohtake, Tosimatu Matumoto and Gary V. Latham—working at Taxas University's Marine Science Institute had predicted a major earthquake in southern Mexico around the town of Puerto Angel based on the theory of seismic gap.

On 29 November, a severe earthquake measuring 7.9 on the Richter scale with an epicentre within a kilometre of the predicted site struck the area. A seismic gap predicted quake also occurred along the San Andreas Fault.



A 4 km stretch of seismic gap was identified along the san andreas fault in california in which an earthquake occurred as predicted.

In India, three seismic gaps have been identified—one in Himachal Pradesh which lies along the plate boundary between earthquakes of Kangra and Kinnaur the second called 'Central gap' between and earthquakes, third called 'Assam Gap' between earthquakes of 1897 and 1950. Identification of these gaps can go a long way in predicting the earthquakes in these areas.

Foreshocks

Generally major earthquakes are preceded by minor shocks known as foreshocks. These foreshocks provide valuable dues to the occurrence of a strong earthquake.

Some of the earthquakes have been successfully predicted on the basis of study of foreshocks. In addition to unusual behaviour of animals, the Haichang earthquake in China was predicted by studying the increased seismicity from December 1974 to February 1975.

The Oaxaca, Mexico earthquake of November 1978 was also successfully predicted on the basis of foreshock observations. Foreshocks have been detected a few days to a month in advance with the help of closely located seismic stations in Himachal Pradesh for several earthquakes like Anantnag Dharmasala, Kashmir, Kinnaur and a few others. Uttarkashi earthquake of October 20, 1991 was preceded by foreshocks on October 15 and 16 with magnitude larger than 3.5 on Richter scale.

The most recent Bhuj earthquake of January 26, 2001 was also preceded by foreshocks in December 2000. But there are some other earthquakes which are preceded by foreshocks. Therefore, this is not a flawless method and has to be supplemented by other methods of earthquake prediction.

Changes in Seismic Wave Velocity

We know that P, S, and L waves originate from the focus of an earthquake. P and S are called body waves because they travel through the body of the earth, while L waves are known as surface waves because they move along the upper crust of the earth. P waves are faster than the S waves and reach seismographs first.

The time lag between the arrival of P and S waves is called lead time. Russian seismologists found that this lead time began to decrease significantly for days, weeks and even months before the earthquake. But just before the quake hit the area the lead time was back to normal. A longer period of abnormality in wave velocity presaged a larger quake.

Taking the cue from the Russians, Lynn Sykes, Scholz and Aggarwal conducted laboratory, experiments on rock samples in 1973. These experiments showed abnormal change of ratio of velocities of P waves and S waves before the earthquake.

This ratio is expressed as V_p/V_s. The duration of V_p/V_s anomaly depends upon the fault or dimensions of the aftershock area. After the Garm region of the former USSR, V_p/V_s anomalies were noticed in Blue Mountain Lake earthquake in the USA in 1973. The velocity anomaly period for this earthquake was about 5 days and the decrease in velocity was about 12 per cent.

Similar decrease in velocity ratio was reported before the damaging, and earthquakes in China. In Japan, 7 to 40% decrease in the velocity ratio ranging from 50 to 700 days before the main earthquakes were recorded. In Tehran 14% decrease in velocity was reported 1 to 3 days before three earthquakes in 1974.

Immediately after the Gujarat earthquake of 2001, the Survey of India mooted a network of 300 permanent Geographical Positioning System (GPS) stations all over the country to monitor earth movements round the clock—which help in predicting earthquakes.

If the GPS systems are located along the known active faults, it is possible to monitor movements of active faults or breaks in the earth's crust. Though no precise prediction can be made about the location and magnitude of an earthquake, minor movements are an indication of an impending earthquake because it reflects the force coming from below the crust.

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3

Volcano Hazards

The probability of eruption of a volcano or the occurrence of a related geophysical event within a particular time frame is called volcano hazard. This chapter closely examines the different types of volcanic eruptions as well as the types of lava flows to provide an extensive understanding of the subject.

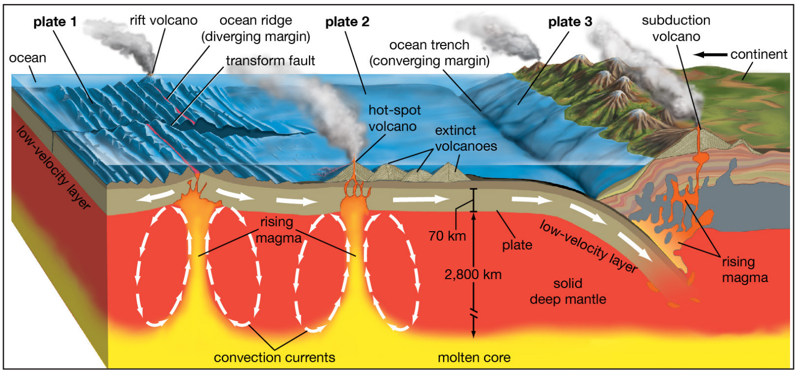
Volcano

Volcano is a vent in the crust of the Earth or another planet or satellite, from which issue eruptions of molten rock, hot rock fragments, and hot gases. A volcanic eruption is an awesome display of the Earth's power. Yet while eruptions are spectacular to watch, they can cause disastrous loss of life and property, especially in densely populated regions of the world. Sometimes beginning with an accumulation of gas-rich magma (molten underground rock) in reservoirs near the surface of the Earth, they can be preceded by emissions of steam and gas from small vents in the ground. Swarms of small earthquakes, which may be caused by a rising plug of dense, viscous magma oscillating against a sheath of more-permeable magma, may also signal volcanic eruptions, especially explosive ones. In some cases, magma rises in conduits to the surface as thin and fluid lava, either flowing out continuously or shooting straight up in glowing fountains or curtains. In other cases, entrapped gases tear the magma into shreds and hurl viscous clots of lava into the air. In more violent eruptions, the magma conduit is cored out by an explosive blast, and solid fragments are ejected in a great cloud of ash-laden gas that rises tens of thousands of metres into the air. One feared phenomenon accompanying some explosive eruptions is the nuée ardente, or pyroclastic flow, a fluidized mixture of hot gas and incandescent particles that sweeps down a volcano's flanks, incinerating everything in its path. Great destruction also can result when ash collects on a high snowfield or glacier, melting large quantities of ice into a flood that can rush down a volcano's slopes as an unstoppable mudflow.

Strictly speaking, the term *volcano* means the vent from which magma and other substances erupt to the surface, but it can also refer to the landform created by the accumulation of solidified lava and volcanic debris near the vent. One can say, for example, that large lava flows erupt from Mauna Loa volcano in Hawaii, referring here to the vent; but one can also say that Mauna Loa is a gently sloping volcano of great size, the reference in this case being to the landform. Volcanic landforms have evolved over time as a result of repeated volcanic activity. Mauna Loa typifies a shield volcano, which is a huge, gently sloping landform built up of many eruptions of fluid lava. Mount Fuji in Japan is an entirely different formation. With its striking steep slopes built up of layers of ash and lava, Mount Fuji is a classic stratovolcano. Iceland provides fine examples of volcanic plateaus, while the seafloor around Iceland provides excellent examples of submarine volcanic structures.

Mount Fuji, Japan

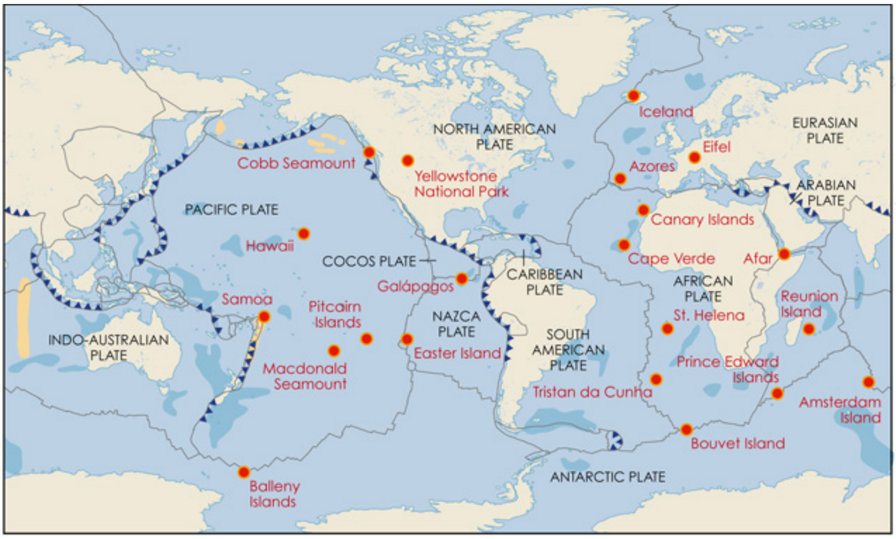
Volcanoes figure prominently in the mythology of many peoples who have learned to live with eruptions, but science was late in recognizing the important role of volcanism in the evolution of the Earth. As late as 1768, common misconception by defining volcanoes as "burning mountains, which probably are made up of sulphur and some other matter proper to ferment with it, and take fire." Today geologists agree that volcanism is a profound process resulting from the thermal evolution of planetary bodies. Heat does not easily escape from large bodies such as the Earth by the processes of conduction or radiation. Instead, heat is transferred from the Earth's interior largely by convection—that is, the partial melting of the Earth's crust and mantle and the buoyant rise of magma to the surface. Volcanoes are the surface sign of this thermal process. Their roots reach deep inside the Earth, and their fruits are hurled high into the atmosphere.



Volcanic activity and the Earth's tectonic plates.

In figure, stratovolcanoes tend to form at subduction zones, or convergent plate margins, where an oceanic plate slides beneath a continental plate and contributes to the rise of magma to the surface. At rift zones, or divergent margins, shield volcanoes tend to form as two oceanic plates pull slowly apart and magma effuses upward through the gap. Volcanoes are not generally found at strike-slip zones, where two plates slide laterally past each other. "Hot spot" volcanoes may form where plumes of lava rise from deep within the mantle to the Earth's crust far from any plate margins.

Volcanoes are closely associated with plate tectonic activity. Most volcanoes, such as those of Japan and Iceland, occur on the margins of the enormous solid rocky plates that make up the Earth's surface. Other volcanoes, such as those of the Hawaiian Islands, occur in the middle of a plate, providing important evidence as to the direction and rate of plate motion.



The study of volcanoes and their products is known as volcanology, but these phenomena are not the realm of any single scientific discipline. Rather, they are studied by many scientists from several specialties: geophysicists and geochemists, who probe the deep roots of volcanoes and monitor signs of future eruptions; geologists, who decipher prehistoric volcanic activity and infer the likely nature of future eruptions; biologists, who learn how plants and animals colonize recently erupted volcanic rocks; and meteorologists, who determine the effects of volcanic dust and gases on the atmosphere, weather, and climate.

Clearly the destructive potential of volcanoes is tremendous. But the risk to people living nearby can be reduced significantly by assessing volcanic hazards, monitoring volcanic activity and forecasting eruptions, and instituting procedures for evacuating populations. In addition, volcanism affects humankind in beneficial ways. Volcanism provides beautiful scenery, fertile soils, valuable mineral deposits, and geothermal energy. Over geologic time, volcanoes recycle the Earth's hydrosphere and atmosphere.

A helicopter-borne “smart spider” sensor sitting on a ridge of Mount Saint Helens, an active volcano in the Pacific Northwest. This sensor is part of a wireless network of such devices designed to monitor the tremors, ground deformation, explosions, and ash emissions associated with volcanoes.

Types of Volcanoes

A volcano is an opening in the Earth’s surface where molten rock can escape from underneath. The Earth’s surface is made up of tectonic plates, which are spreading apart, crunching into each other, or sliding beside one another. Volcanoes are typically found at the fault lines between these plates. There can be active volcanos, which are currently, or have recently erupted. There are also dormant volcanoes, which haven’t erupted recently, and extinct volcanoes, which will never erupt again. There are 4 major types of volcanoes:

Cinder Cone Volcanoes

These are the simplest type of volcano. They occur when particles and blobs of lava are ejected from a volcanic vent. The lava is blown violently into the air and the pieces rain down around the vent. Over time, this builds up a circular or oval-shaped cone, with a bowl-shaped crater at the top. Cinder cone volcanoes rarely grow larger than about 1,000 feet above their surroundings.

Composite Volcanoes

Composite volcanoes or stratovolcanoes make up some of the world’s most memorable mountains: Mount Rainier, Mount Fuji, and Mount Cotopaxi, for example. These volcanoes have a conduit system inside them that channels magma from deep within the Earth to the surface. They can have clusters of vents, with lava breaking through walls, or issuing from fissures on the sides of the mountain. With all this material coming out, they can grow thousands of meters tall. As we’ve seen with the famous Mount Saint Helens, composite volcanoes can explode violently.

Shield Volcanoes

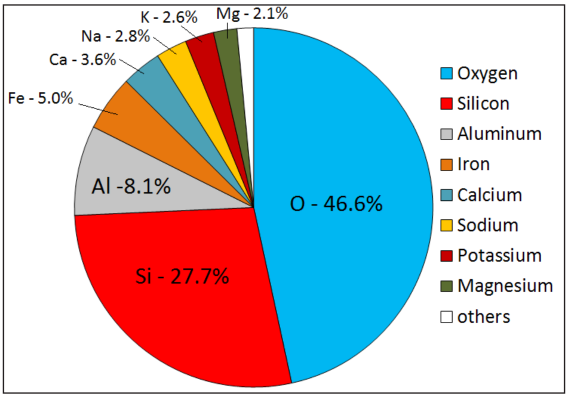
These are large, broad volcanoes that look like shields from above – hence the name. The lava that pours out of shield volcanoes is thin, so it can travel for great distances down the shallow slopes of the volcano. These volcanos build up slowly over time, with hundreds of eruptions, creating many layers. They're not likely to explode catastrophically. Perhaps the best known shield volcanoes are the ones that make up the Hawaiian Islands, especially Mauna Loa and Mauna Kea.

Lava Domes

Volcanic or lava domes are created by small masses of lava which are too viscous (thick) to flow very far. Unlike shield volcanoes, with low-viscosity lava, the magma from volcanic domes just piles up over and around the vent. The dome grows by expansion of the lava within, and the mountain forms from material spilling off the sides of the growing dome. Lava domes can explode violently, releasing a huge amount of hot rock and ash.

Magma

Magmas can vary widely in composition, but in general they are made up of only eight elements; in order of importance: oxygen, silicon, aluminum, iron, calcium, sodium, magnesium, and potassium. Oxygen, the most abundant element in magma, comprises a little less than half the total, followed by silicon at just over one-quarter. The remaining elements make up the other one-quarter. Magmas derived from crustal material are dominated by oxygen, silicon, aluminum, sodium, and potassium.



Average elemental proportions in Earth's crust, which is close to the average composition of magmas within the crust.

The composition of magma depends on the rock it was formed from (by melting), and the conditions of that melting. Magmas derived from the mantle have higher levels of iron, magnesium, and calcium, but they are still likely to be dominated by oxygen and silicon. All magmas have varying proportions of elements such as hydrogen, carbon, and sulphur, which are converted into gases like water vapour, carbon dioxide, and hydrogen sulphide as the magma cools.

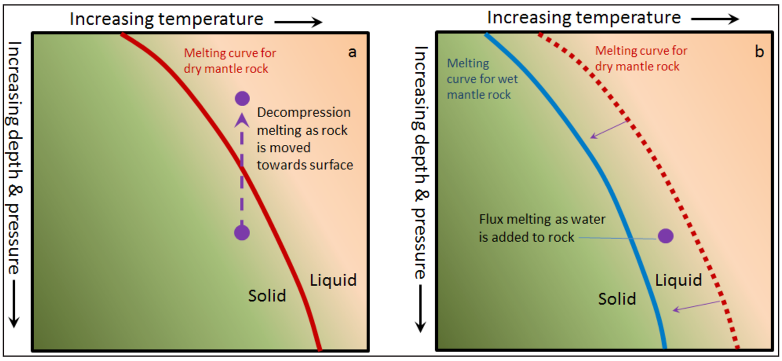
Virtually all of the igneous rocks that we see on Earth are derived from magmas that formed from partial melting of existing rock, either in the upper mantle or the crust. Partial melting is what happens when only some parts of a rock melt; it takes place because rocks are not pure materials. Most rocks are made up of several minerals, each of which has a different melting temperature. The wax in a candle is a pure material. If you put some wax into a warm oven (50 °C will do as the melting temperature of most wax is about 40 °C) and leave it there for a while, it will soon start to melt. That's complete melting, not partial melting. If instead you took a mixture of wax, plastic, aluminum, and glass and put it into the same warm oven, the wax would soon start to melt, but the plastic, aluminum, and glass would not melt. That's partial melting and the result would be solid plastic, aluminum, and glass surrounded by liquid wax. If we heat the oven up to around 120 °C, the plastic would melt too and mix with the liquid wax, but the aluminum and glass would remain solid. Again this is partial melting. If we separated the wax/plastic "magma" from the other components and let it cool, it would eventually harden. As you can see from figure, the liquid wax and plastic have mixed, and on cooling, have formed what looks like a single solid substance. It is most likely that this is a very fine-grained mixture of solid wax and solid plastic, but it could also be some other substance that has formed from the combination of the two.

In figure, partial melting of "pretend rock": (a) the original components of white candle wax, black plastic pipe, green beach glass, and aluminum wire, (b) after heating to 50 ˚C for 30 minutes only the wax has melted, (c) after heating to 120 ˚C for 60 minutes much of the plastic has melted and the two liquids have mixed, (d) the liquid has been separated from the solids and allowed to cool to make a "pretend rock" with a different overall composition.

In this example, we partially melted some pretend rock to create some pretend magma. We then separated the magma from the source and allowed it to cool to make a new pretend rock with a composition quite different from the original material (it lacks glass and aluminum).

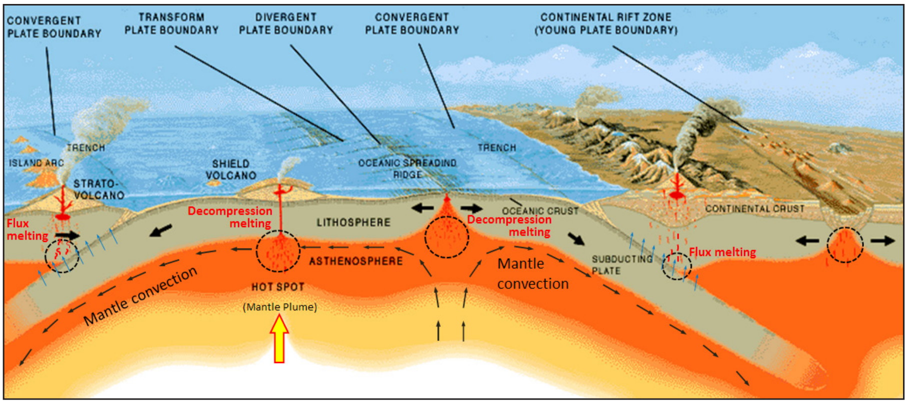
Of course partial melting in the real world isn't exactly the same as in our pretend-rock example. The main differences are that rocks are much more complex than the four-component system we used, and the mineral components of most rocks have more similar melting temperatures, so two or more minerals are likely to melt at the same time to varying degrees. Another important difference is that when rocks melt, the process takes thousands to millions of years, not the 90 minutes it took in the pretend-rock example.

Contrary to what one might expect, and contrary to what we did to make our pretend rock, most partial melting of real rock does not involve heating the rock up. The two main mechanisms through which rocks melt are decompression melting and flux melting. Decompression melting takes place within Earth when a body of rock is held at approximately the same temperature but the pressure is reduced. This happens because the rock is being moved toward the surface, either at a mantle plume (a.k.a., hot spot), or in the upwelling part of a mantle convection cell. The mechanism of decompression melting is shown in figure. If a rock that is hot enough to be close to its melting point is moved toward the surface, the pressure is reduced, and the rock can pass to the liquid side of its melting curve. At this point, *partial* melting starts to take place. The process of flux melting is shown in figure. If a rock is close to its melting point and some water (a flux that promotes melting) is added to the rock, the melting temperature is reduced (solid line versus dotted line), and partial melting starts.



Mechanisms for (a) decompression melting (the rock is moved toward the surface) and (b) flux melting (water is added to the rock) and the melting curve is displaced.

The partial melting of rock happens in a wide range of situations, most of which are related to plate tectonics. The more important of these are shown in figure. At both mantle plumes and in the upward parts of convection systems, rock is being moved toward the surface, the pressure is dropping, and at some point, the rock crosses to the liquid side of its melting curve. At subduction zones, water from the wet, subducting oceanic crust is transferred into the overlying hot mantle. This provides the flux needed to lower the melting temperature. In both of these cases, only partial melting takes place — typically only about 10% of the rock melts — and it is always the most silica-rich components of the rock that melt, creating a magma that is more silica-rich than the rock from which it is derived. (By analogy, the melt from our pretend rock is richer in wax and plastic than the "rock" from which it was derived.) The magma produced, being less dense than the surrounding rock, moves up through the mantle, and eventually into the crust.



Common sites of magma formation in the upper mantle. The black circles are regions of partial melting. The blue arrows represent water being transferred from the subducting plates into the overlying mantle.

As it moves toward the surface, and especially when it moves from the mantle into the lower crust, the hot magma interacts with the surrounding rock. This typically leads to partial melting of the surrounding rock because most such magmas are hotter than the melting temperature of crustal rock. (In this case, melting is caused by an increase in temperature.) Again, the more silica-rich parts of the surrounding rock are preferentially melted, and this contributes to an increase in the silica content of the magma.

At very high temperatures (over 1300 °C), most magma is entirely liquid because there is too much energy for the atoms to bond together. As the temperature drops, usually because the magma is slowly moving upward, things start to change. Silicon and oxygen combine to form silica tetrahedra, and then, as cooling continues, the tetrahedra start to link together to make chains (polymerize). These silica chains have the important effect of making the magma more viscous.

Volcanic Eruptions

Deep within the Earth it is so hot that some rocks slowly melt and become a thick flowing substance called magma. Since it is lighter than the solid rock around it, magma rises and collects in magma chambers. Eventually, some of the magma pushes through vents and fissures to the Earth's surface. Magma that has erupted is called lava.

Some volcanic eruptions are explosive and others are not. The explosivity of an eruption depends on the composition of the magma. If magma is thin and runny, gases can escape easily from it. When this type of magma erupts, it flows out of the volcano. A good example is the eruptions at Hawaii's volcanoes. Lava flows rarely kill people because they move slowly enough for people to get out of their way. If magma is thick and sticky, gases cannot escape easily. Pressure builds up until the gases escape violently and explode. A good example is the eruption of Washington's Mount St. Helens. In this type of eruption, the magma blasts into the air and breaks apart into pieces called tephra. Tephra can range in size from tiny particles of ash to house-size boulders.

Explosive volcanic eruptions can be dangerous and deadly. They can blast out clouds of hot tephra from the side or top of a volcano. These fiery clouds race down mountainsides destroying almost everything in their path. Ash erupted into the sky falls back to Earth like powdery snow. If thick enough, blankets of ash can suffocate plants, animals, and humans. When hot volcanic materials mix with water from streams or melted snow and ice, mudflows form. Mudflows have buried entire communities located near erupting volcanoes.

Types of Volcanic Eruptions

Hawaiian Eruption

In a Hawaiian eruption, fluid basaltic lava is thrown into the air in jets from a vent or line of vents (a fissure) at the summit or on the flank of a volcano. The jets can last for hours or even days, a phenomenon known as fire fountaining. The spatter created by bits of hot lava falling out of the fountain can melt together and form lava flows, or build hills called spatter cones. Lava flows may also come from vents at the same time as fountaining occurs, or during periods where fountaining has paused. Because these flows are very fluid, they can travel miles from their source before they cool and harden.

Hawaiian eruption: In a Hawaiian eruption, fluid lava is ejected from a vent as fire fountains or lava flows. The 1969 eruption at Mauna Ulu, a vent of Kilauea Volcano in Hawaii, was a spectacular example of fire fountaining.

Hawaiian eruptions get their names from the Kilauea Volcano on the Big Island of Hawaii, which is famous for producing spectacular fire fountains. Two excellent examples of these are the 1969-1974 Mauna Ulu eruption on the volcano's flank, and the 1959 eruption of the Kilauea Iki Crater at the summit of Kilauea. In both of these eruptions, lava fountains reached heights of well over a thousand feet.

Strombolian Eruption

Strombolian eruptions are distinct bursts of fluid lava (usually basalt or basaltic andesite) from the mouth of a magma-filled summit conduit. The explosions usually occur every few minutes at regular or irregular intervals. The explosions of lava, which can reach heights of hundreds of meters, are caused by the bursting of large bubbles of gas, which travel upward in the magma-filled conduit until they reach the open air.

Strombolian eruption. Short bursts of glowing lava, created from the bursting of large gas bubbles at the summit vent of a volcano typify a Strombolian eruption. This photo, taken from the summit of Stromboli, a volcano in the Aeolian Islands, Italy, shows a classic example of this activity.

What Determines Eruption Type

This kind of eruption can create a variety of forms of eruptive products: spatter, or hardened globs of glassy lava; scoria, which are hardened chunks of bubbly lava; lava bombs, or chunks of lava a few cm to a few m in size; ash; and small lava flows (which form when hot spatter melts together and flows downslope). Products of an explosive eruption are often collectively called tephra.

Strombolian eruptions are often associated with small lava lakes, which can build up in the conduits of volcanoes. They are one of the least violent of the explosive eruptions, although they can still be very dangerous if bombs or lava flows reach inhabited areas. Strombolian eruptions are named for the volcano that makes up the Italian island of Stromboli, which has several erupting summit vents. These eruptions are particularly spectacular at night, when the lava glows brightly.

Vulcanian Eruption

A Vulcanian eruption is a short, violent, relatively small explosion of viscous magma (usually andesite, dacite, or rhyolite). This type of eruption results from the fragmentation and explosion of a plug of lava in a volcanic conduit, or from the rupture of a lava dome (viscous lava that piles up over a vent). Vulcanian eruptions create powerful explosions in which material can travel faster than 350 meters per second (800 mph) and rise several kilometers into the air. They produce tephra, ash clouds, and pyroclastic density currents (clouds of hot ash, gas and rock that flow almost like fluids).

Vulcanian eruption. Relatively small but violent explosions of viscous lava create columns of ash and gas and occasional pyroclastic flows, as seen at this eruption of the Santiaguito volcanic dome complex in Guatemala.

Vulcanian eruptions may be repetitive and go on for days, months, or years, or they may precede even larger explosive eruptions. They are named for the Italian island of Vulcano, where a small volcano that experienced this type of explosive eruption was thought to be the vent above the forge of the Roman smith god Vulcan.

Plinian Eruption

Plinain eruption. The largest and most violent of all explosive eruptions, Plinian eruptions send columns of pulverized rock, ash, and gases that rise miles into the atmosphere in a matter of minutes. Mount St. Helens in Washington State experienced a Plinian eruption following a major flank collapse in 1980.

The largest and most violent of all the types of volcanic eruptions are Plinian eruptions. They are caused by the fragmentation of gassy magma, and are usually associated with very viscous magmas (dacite and rhyolite). They release enormous amounts of energy and create eruption columns of gas and ash that can rise up to 50 km (35 miles) high at speeds of hundreds of meters per second. Ash from an eruption column can drift or be blown hundreds or thousands of miles away from the volcano. The eruption columns are usually shaped like a mushroom (similar to a nuclear explosion) or an Italian pine tree; Pliny the Younger, a Roman historian, made the comparison while viewing the 79 AD eruption of Mount Vesuvius, and Plinian eruptions are named for him.

Plinian eruptions are extremely destructive, and can even obliterate the entire top of a mountain, as occurred at Mount St. Helens in 1980. They can produce falls of ash, scoria and lava bombs miles from the volcano, and pyroclastic density currents that raze forests, strip soil from bedrock and obliterate anything in their paths. These eruptions are often climactic, and a volcano with a magma chamber emptied by a large Plinian eruption may subsequently enter a period of inactivity.

Lava Domes

Lava domes form when very viscous, rubbly lava (usually andesite, dacite or rhyolite) is squeezed out of a vent without exploding. The lava piles up into a dome, which may grow by inflating from the inside or by squeezing out lobes of lava (something like toothpaste coming out of a tube). These lava lobes can be short and blobby, long and thin, or even form spikes that rise tens of meters into the air before they fall over. Lava domes may be rounded, pancake-shaped, or irregular piles of rock, depending on the type of lava they form from.

Lava dome. Lava domes, such as this example in the crater of Mount St. Helens, are piles of viscous lava that are too cool and sticky to flow far. Domes grow and collapse in cycles, and often form at volcanoes that also experience Plinian eruptions.

Lava domes are not just passive piles of rock; they can sometimes collapse and form pyroclastic density currents, extrude lava flows, or experience small and large explosive eruptions (which may even destroy the domes.) A dome-building eruption may go on for months or years, but they are usually repetitive (meaning that a volcano will build and destroy several domes before the eruption ceases). Redoubt volcano in Alaska and Chaiten in Chile are currently active examples of this type of eruption, and Mount St. Helens in the state of Washington spent several years building several lava domes.

Surtseyan Eruption

Surtseyan eruptions are a kind of hydromagmatic eruption, where magma or lava interacts explosively with water. In most cases, Surtseyan eruptions occur when an undersea volcano has finally grown large enough to break the water's surface; because water expands when it turns to steam, water that comes into contact with hot lava explodes and creates plumes of ash, steam and scoria. Lavas created by a Surtseyan eruption tend to be basalt, since most oceanic volcanoes are basaltic.

Surtseyan eruption: Lava erupting through water creates the dramatic plumes of scoria and billowing ash-and-gas clouds of a Surtseyan eruption. The type example of this eruption occurred at Surtsey, a volcanic island off the coast of Iceland.

The classic example of a Surtseyan eruption was the volcanic island of Surtsey, which erupted off the south coast of Iceland between 1963 and 1965. Hydromagmatic activity built up several square kilometers of tephra over the first several months of the eruption; eventually, seawater could no longer reach the vent, and the eruption transitioned to Hawaiian and Strombolian styles. More recently, in March 2009, several vents of the volcanic island of Hunga Ha'apai near Tonga began to erupt. The onshore and offshore explosions created plumes of ash and steam that rose to more than 8 km (5 miles) altitude, and threw plumes of tephra hundreds of meters from the vents.

Volcanic Hazards

Volcanoes can be exciting and fascinating, but also very dangerous. Any kind of volcano is capable of creating harmful or deadly phenomena, whether during an eruption or a period of quiescence. Understanding what a volcano can do is the first step in mitigating volcanic hazards, but it is important to remember that even if scientists have studied a volcano for decades, they do not necessarily know everything it is capable of. Volcanoes are natural systems, and always have some element of unpredictability.

Volcanologists are always working to understand how volcanic hazards behave, and what can be done to avoid them. Here are a few of the more common hazards, and some of the ways that they are formed and behave.

Lava Flows

Lava is molten rock that flows out of a volcano or volcanic vent. Depending on its composition and temperature, lava can be very fluid or very sticky (viscous). Fluid flows are hotter and move the fastest; they can form streams or rivers, or spread out across the landscape in lobes. Viscous flows are cooler and travel shorter distances, and can sometimes build up into lava domes or plugs; collapses of flow fronts or domes can form pyroclastic density currents.

Most lava flows can be easily avoided by a person on foot, since they don't move much faster than walking speed, but a lava flow usually cannot be stopped or diverted. Because lava flows are extremely hot - between 1,000-2,000°C (1,800 - 3,600° F) - they can cause severe burns and often burn down vegetation and structures. Lava flowing from a vent also creates enormous amounts of pressure, which can crush or bury whatever survives being burned.

Pyroclastic Density Currents

Pyroclastic density currents are an explosive eruptive phenomenon. They are mixtures of pulverized rock, ash, and hot gases, and can move at speeds of hundreds of miles per hour. These currents can be dilute, as in pyroclastic surges, or concentrated, as in pyroclastic flows. They are gravity-driven, which means that they flow down slopes.

Pyroclastic flow deposits covering the old city of Plymouth on the Caribbean island of Montserrat.

A pyroclastic surge is a dilute, turbulent density current that usually forms when magma interacts explosively with water. Surges can travel over obstacles like valley walls, and leave thin deposits of ash and rock that drape over topography. A pyroclastic flow is a concentrated avalanche of material, often from a collapse of a lava dome or eruption column, which creates massive deposits that range in size from ash to boulders. Pyroclastic flows are more likely to follow valleys and other depressions, and their deposits infill this topography. Occasionally, however, the top part of a pyroclastic flow cloud (which is mostly ash) will detach from the flow and travel on its own as a surge.

Pyroclastic flow at Mount St. Helens, Washington.

Pyroclastic density currents of any kind are deadly. They can travel short distances or hundreds of miles from their source, and move at speeds of up to 1,000 kph (650 mph). They are extremely hot - up to 400 °C (750 °F). The speed and force of a pyroclastic density current, combined with its heat, mean that these volcanic phenomena usually destroy anything in their path, either by burning or crushing or both. Anything caught in a pyroclastic density current would be severely burned and pummeled by debris (including remnants of whatever the flow traveled over). There is no way to escape a pyroclastic density current other than not being there when it happens.

One unfortunate example of the destruction caused by pyroclastic density currents is the abandoned city of Plymouth on the Caribbean island of Montserrat. When the Soufrière Hills volcano began erupting violently in 1996, pyroclastic density currents from eruption clouds and lava dome collapses traveled down valleys in which many people had their homes, and inundated the city of Plymouth. That part of the island has since been declared a no-entry zone and evacuated, although it is still possible to see the remains of buildings which have been knocked over and buried, and objects that have been melted by the heat of the pyroclastic density currents.

Pyroclastic Falls

Pyroclastic falls, also known as volcanic fallout, occur when tephra - fragmented rock ranging in size from mm to tens of cm (fractions of inches to feet) - is ejected from a volcanic vent during an eruption and falls to the ground some distance away from the vent. Falls are usually associated with Plinian eruptive columns, ash clouds or volcanic plumes. Tephra in pyroclastic fall deposits may have been transported only a short distance from the vent (a few meters to several km), or, if it is injected into the upper atmosphere, may circle the globe. Any kind of pyroclastic fall deposit will mantle or drape itself over the landscape, and will decrease in both size and thickness the farther away it is from its source.

Mount Pinatubo, Philippines: View of World Airways DC-10 airplane setting on its tail because of weight of June 15, 1991 ash. Cubi Point Naval Air Station.

Tephra falls are usually not directly dangerous unless a person is close enough to an eruption to be struck by larger fragments. The effects of falls can be, however. Ash can smother vegetation, destroy moving parts in motors and engines (especially in aircraft), and scratch surfaces. Scoria and small bombs can break delicate objects, dent metals and become embedded in wood. Some pyroclastic falls contain toxic chemicals that can be absorbed into plants and local water supplies, which can be dangerous for both people and livestock. The main danger of pyroclastic falls is their weight: tephra of any size is made up of pulverized rock, and can be extremely heavy, especially if it gets wet. Most of the damage caused by falls occurs when wet ash and scoria on the roofs of buildings causes them to collapse.

Pyroclastic material injected into the atmosphere may have global as well as local consequences. When the volume of an eruption cloud is large enough, and the cloud is spread far enough by wind, pyroclastic material may actually block sunlight and cause temporary cooling of the Earth’s surface. Following the eruption of Mount Tambora in 1815, so much pyroclastic material reached and remained in the Earth’s atmosphere that global temperatures dropped an average of about 0.5 °C (~1.0 °F). This caused worldwide incidences of extreme weather, and led 1816 to be known as ‘The Year Without A Summer.’

Lahars

Lahars are a specific kind of mudflow made up of volcanic debris. They can form in a number of situations: when small slope collapses gather water on their way down a volcano, through rapid melting of snow and ice during an eruption, from heavy rainfall on loose volcanic debris, when a volcano erupts through a crater lake, or when a crater lake drains because of overflow or wall collapse.

Large boulder carried in lahar flow, Muddy River, east of Mount St. Helens, Washington.

Lahars flow like liquids, but because they contain suspended material, they usually have a consistency similar to wet concrete. They flow downhill and will follow depressions and valleys, but they can spread out if they reach a flat area. Lahars can travel at speeds of over 80 kph (50 mph) and reach distances dozens of miles from their source. If they were generated by a volcanic eruption, they may retain enough heat to still be 60-70 °C (140-160 °F) when they come to rest.

Lahars are not as fast or hot as other volcanic hazards, but they are extremely destructive. They will either bulldoze or bury anything in their path, sometimes in deposits dozens of feet thick. Whatever cannot get out of a lahar's path will either be swept away or buried. Lahars can, however, be detected in advance by acoustic (sound) monitors, which gives people time to reach high ground; they can also sometimes be channeled away from buildings and people by concrete barriers, although it is impossible to stop them completely.

Gases

Volcanic gases are probably the least showy part of a volcanic eruption, but they can be one of an eruption's most deadly effects. Most of the gas released in an eruption is water vapor (H_2O), and relatively harmless, but volcanoes also produce carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), fluorine gas (F_2), hydrogen fluoride (HF), and other gases. All of these gases can be hazardous - even deadly - in the right conditions.

Carbon dioxide is not poisonous, but it displaces normal oxygen-bearing air, and is odorless and colorless. Because it is heavier than air, it collects in depressions and can suffocate people and animals who wander into pockets where it has displaced normal air. It can also become dissolved in water and collect in lake bottoms; in some situations, the water in those lakes can suddenly 'erupt' huge bubbles of carbon dioxide, killing vegetation, livestock and people living nearby. This was the case in the overturn of Lake Nyos in Cameroon, Africa in 1986, where an eruption of CO_2 from the lake suffocated more than 1,700 people and 3,500 livestock in nearby villages.

Lake Nyos, Cameroon, Gas Release. Dead cattle and surrounding compounds in Nyos village.

Sulfur dioxide and hydrogen sulfide are both sulfur-based gases, and unlike carbon dioxide, have a distinct acidic, rotten-egg smell. SO_2 can combine with water vapor in the air to form sulfuric acid (H_2SO_4), a corrosive acid; H_2S is also very acidic, and extremely poisonous even in small amounts. Both acids irritate soft tissues (eyes, nose, throat, lungs, etc.), and when the gases form acids in large enough quantities, they mix with water vapor to form vog, or volcanic fog, which can be dangerous to breathe and cause damage to the lungs and eyes. If sulfur-based aerosols reach the upper atmosphere, they can block sunlight and interfere with ozone, which have both short and long-term effects on climate.

Sulfur dioxide issuing from fumaroles of the Sulfur Banks at the summit of Kilauea Volcano, Hawaii.

One of the nastiest, although less common gases released by volcanoes is fluorine gas (F_2). This gas is yellowish brown, corrosive and extremely poisonous. Like CO_2, it is denser than air and tends to collect in low areas. Its companion acid, hydrogen fluoride (HF), is highly corrosive and toxic, and causes terrible internal burns and attacks calcium in the skeletal system. Even after visible gas or acid has dissipated, fluorine can be absorbed into plants, and may be able to poison people and animals for long periods following an eruption. After the 1783 eruption of Laki in Iceland, fluorine poisoning and famine caused the deaths of more than half the country's livestock and almost a quarter of its population.

Lava Flows

Lava flows are the least hazardous of all processes in volcanic eruptions. How far a lava flow travels depends on the flows temperature, silica content, extrusion rate, and slope of the land. A cold lava flow will not travel far and neither will one that has high silica content. Such a flow would have a high *viscosity* (a high resistance to flow). A basalt flow like those in Hawai'i have low silica contents and low viscosities so they can flow long distances. Such a flow can move as far away as 4 km from its source and have a thickness of 10 m. These flows can move at rates of several kilometers per hour. More silica-rich flows can move as far away as 1.3 km from their sources and have thicknesses of 100 m. These flows can move at rates of a few to hundreds of meters per hour. If a lava flow is channelized or travels underground in a lava tube then the distance it travels is greatly extended.

Lava flows as you can see don't move very fast so people rarely get killed by them. However, lava flows are very hot (between 550 degrees C and 1400 degrees C) and can therefore cause injuries. People have burnt their skin, charred their eyebrows, and melted the soles of their boots from being near or on a hot lava flow. Lava flows don't cool instantaneously. It can take days to years for a lava flow to completely cool.

The biggest hazard of lava flows is that they destroy property. In the late 1980's, the town of Kalapana in Hawai'i was destroyed by lava flows. Lava flows buried cars and burnt homes, buildings, and vegetation. Electric power, water, and communications were cut off from the community.

Another hazard associated with lava flows (as well as other hot volcanic material) is they can melt snow and ice which can produce flooding. Melting of ice beneath a glacier may produce very large floods called *jokulhlaups* or glacier bursts Lava flows can also dam rivers which may in the future produce flooding if the dam were to break, though most lava flows are fairly porous.

The main concern with lava flows is how far they will ultimately extend. Equations have been used to estimate this distance. But how do you stop a lava flow if you know it’s heading toward your property? Different methods have been used including: breaching the sides of a lava tube or channel, diverting the flow, constructing barriers, and bombing the lava flow. Another way to stop a lava flow is to increase the lava flow’s viscosity by spraying it with water, increasing the rate at which gas escapes from the flow, stirring the flow, or seeding the flow with foreign nuclei.

Dynamics of Lava Flows

Lava flows form when molten or partially molten rock is erupted onto the surface of Earth or other rocky planets. Eruptions are forced by buoyancy caused by density differences between the melt and surrounding rock and by the pressures generated by exsolution of volatiles. The melt spreads on the surface as a gravity current, forming a lava flow. The lava is not a simple liquid but generally a mix of silicate liquid, crystals, and gas bubbles, with additional increases in crystal and bubble fractions during the evolution of the flow. Surface heat fluxes from the lava are generally large enough to cause rapid quenching of a thin surface layer to an amorphous glassy solid, and the slower process of crystallization leads eventually to complete solidification of the flow. The behavior of lava flows, their structure, rate of flow frontal advance, and instabilities vary depending on the properties of the erupted magma, the effusion rate, the ground topography over which the lava flows, and its new environment (which primarily determines the rate of heat loss). The flow front eventually comes to a halt, in some cases before the vent supply shuts off.

Although this review focuses on theoretical and experimental studies of flow dynamics, it is worthwhile briefly outlining for the interested fluid mechanician some of the motivation for and broader background to such studies. These naturally include a desire to assess the direct hazards posed to people and property by advancing lava flows, a recurring threat of frequently erupting volcanoes such as Etna, in Sicily, and Kilauea, in Hawaii, and by the much more destructive forces of pyroclastic flows, which give less warning, as at Merapi, in Indonesia, in 1994, and during the eruption of Unzen, in Japan, in 1991–1995. Lava also melts snowcaps, as at Redoubt Volcano, in Alaska, in 1989, and can lead to flash floods and mud flows. These hazards depend on such factors as the rheology of the lava, its effusion rate, the existing ground topography, the distance the flow front advances before it solidifies, and the steepness and stability of lava domes. A further motivation to understand lava flow dynamics is the interpretation of observations of ancient or remote flows, in which the flow shape, structure, and surface features (its morphology) can hold clues to the eruption rates and lava rheology. For extraterrestrial flows, estimates of the rheology and eruption rates have already been made, based on flow morphology. These, in turn, are used to infer chemical composition of the magmas and the nature of the tectonic mechanisms responsible for the volcanism. In submarine flows, lava composition can be obtained by direct measurement, but the eruptions are rarely observed during their active phase, and so information on eruption rates might again be obtained from the form of the solidified flows. Other aims of lava flow modeling are to understand the formation of nickel-iron-copper sulfide ore deposits from ancient high-temperature (komatiite) flows and the emplacement of particularly remarkable surface features, such as very large rhyolite flows on Earth, large “pancake” domes observed on the surface of Venus, and basalt flows over 100 km long on Earth, the Moon, and Mars.

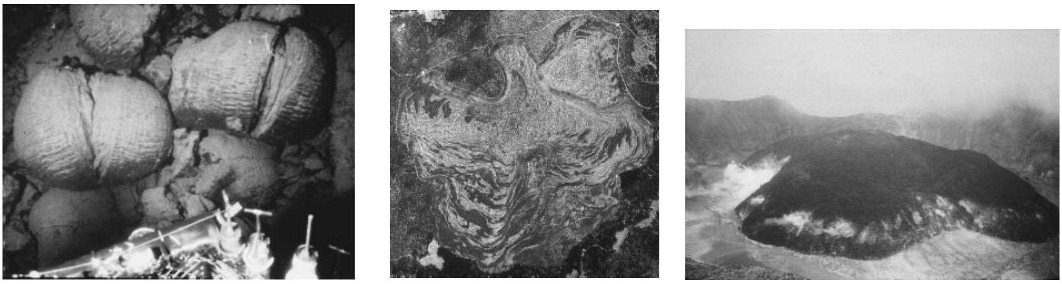
In the modeling of lava flows, both process-oriented models and the computational-simulation approach have a useful role, although particular care must be taken to ensure that the formulations of complicated numerical models have a sound physical basis. Simplified isothermal models of low-Reynoldsnumber and viscoplastic flows have demonstrated the way in which slow eruptions of lava would advance in the absence of cooling, and recently these have provided the basis for models that include heterogeneous rheology and rheological change caused by cooling and solidification. Results from models of melting of the underlying base and erosion by turbulent lavas are providing an improved basis for understanding contamination of the lava by the underlying rocks and the deposition of metal ores. Laboratory analog models have provided tests for the simplest of flow models, as well as a means of exploring a range of instabilities and complex flow regimes that have not yet been addressed by theoretical or computational models.

We focus on the flow of lava on the surface (neglecting the equally interesting dynamics beneath the surface, which force the eruption of magma). Fluid-dynamical problems by briefly summarizing the observed range of styles of lava flows. The physical properties of lavas and the nature of the surface heat fluxes, both of which determine the rates at which the lavas cool, increase in viscosity, and solidify. The range of dynamical-flow regimes is discussed along with results from isothermal models of extremely viscous and plastic flows. We turn to the role of thermal effects, particularly solidification at the free surface in both creeping flows and long lava flows, and of thermal erosion of underlying ground in turbulent flows. Concluding comments on progress toward understanding lava flows and the challenge ahead. The review includes some references to observational work, field data, and laboratory experiments on the properties of lava samples. However, there is no intent to be complete in these areas, because a review of observations would require far more space than is available here, and the purpose is to focus on theoretical and experimental studies of the relevant dynamics.

Observed Styles of Flow

There are a number of styles of lava flow, each presumably reflecting a different dynamical regime. Some examples are shown in figure. The style of flow is related, through lava composition, eruption temperature, and effusion rate, to the class of volcano. On some volcanoes the effusion of melt is the dominant form of activity, whereas explosive eruptions are common in other cases. Lava flows are generally dominant for basaltic volcanism at volcanic “hotspots” (notably oceanic-island chains, of which Hawaii and Iceland are examples) and at midocean ridges (where the seafloor plates are moving apart, causing the underlying mantle to upwell and undergo small degrees of partial melting, giving rise to a more-or-less continuous supply of mid-ocean ridge basalts). In these cases the lavas, at their vents, are among the hottest and least viscous on Earth today. Their effusion rates can also be large, producing rapid channelized flows that may be turbulent and travel for long distances. Ancient eruptions of even hotter and less viscous lavas called komatiites [generally thought to originate from hotspots in the Archaean and proterozoic eras, $>2 \times 210^9$ years ago], and enormous outpourings of flood basalts, which flowed hundreds of kilometers and generated large plateaus on both continents and ocean floors, have been preserved in regions of the Earth’s crust. These testify to flows much faster and more turbulent than any historically recorded.


(a) (b) (c)



(d) (e) (f)

In figure, examples of some lava flow forms. (a) Channelized basalt flow from Kilauea Volcano, Hawaii (flow channel ~ 20 m wide); (b) and (c) “ropy pahoehoe” and “toey pahoehoe,” respectively, from Kilauea (“ropes” have wavelength ~ 20 cm; “toes” are typically 30 cm across); (d) submarine-pillow basalts, each ~ 1 m across, on the East Pacific Rise; (e) Little Glass Mountain rhyolite flow, northern California, showing flow around an obstacle on a gentle slope and transverse surface ridges of ~ 5 m in height (image 2.8 km across); (f) a lava dome 850 m across and 130 m high in the crater of La Soufrière, St. Vincent, 1979.

The largest of present-day flows are those of Hawaii, which often commence their journey on the mountain slopes as rapid, open-channel “pahoehoe” flows. They commonly change their form some kilometers from the vent to become slowly creeping flows (called `a`a) with a capping of solid blocks and a thick ($\leq$10-m) flow front In both forms they produce their own channel by construction of levees of solidified lava. Outbreaks from a channel or flow front can tap the hot interior fluid and commonly produce shallow flows with thin glassy surfaces (also called “pahoehoe” lava). Some of these flows advance with smooth surfaces, others with their surface folded into a “ropy” appearance, others in toelike protrusions. Rapid channel flows can also form lava tubes, which are roofed channels in which the flowing melt is completely surrounded by solidified lava and therefore well insulated against surface heat loss .Submarine mid-ocean ridge eruptions of basalt, although of similar viscosity, are often much slower, and the Reynolds number can be small. These types of lava are also much more rapidly cooled by the water. Slow submarine eruptions give rise to fields of “pillow basalts, each composed of a slowly spreading mound of meter-sized lobes. “Pillow” morphology is known to have occurred even in ancient high-temperature komatiite flows now exposed in Western Australia.

At volcanoes found above the scene of active subduction of the sea floor (e.g. western North America, Indonesia, the Philippines, and Japan), lavas have lower temperatures and much greater apparent viscosity. In these cases a relatively slow effusion of lava is sometimes sustained for months or years (often between explosive eruptions), and the resulting flows have extremely low Reynolds numbers. Examples are large rhyolite flows and 100-m– to 1-km–sized mounds referred to as lava domes, the most viscous of which tend to grow slowly over months or years. These domes have a solid surface layer but remain mobile for days to months, with the solid undergoing plastic or brittle deformation. On occasions, a section of a lava dome may collapse down the mountain slope either as a block-and-ash flow or, if there is an explosive release of pressure, as a destructive pyroclastic flow. Domes show obvious non Newtonian behavior, including fractures (or “creases”) in the vent region at which the lava slowly opens and diverges as it is extruded, smooth extrusion surfaces where one part of the lava slid past another, and tall angular spines.

Lava Rheology

The rheology of lava as it is erupted from a vent depends on composition, temperature, crystal content, and bubble content. It is therefore time dependent as a result of cooling, crystallization, and vesiculation. If the lava is viewed as a viscous fluid, four different shear viscosity coefficients can be defined: the melt viscosity η_m of the liquid phase alone; the (actual) lava viscosity $\eta (= d\sigma / d\dot{\varepsilon}$, where σ is the applied shearing stress, and $\dot{\varepsilon}$ is the strain rate) of the liquid- e˙ crystal-bubble mixture that makes up the lava; the apparent lava viscosity $\eta_A \; (= \sigma / \dot{\varepsilon})$ of this mixture; and an apparent flow viscosity η_F that is an effective viscosity for a whole lava flow and which, in some way, averages over potentially large differences in g and η_A from place to place within the flow (and over time if desired). The melt viscosity governs the microphysics of the growth, migration, coalescence, and deformation of bubbles. It is identical to the actual lava rheology for small crystal and bubble fractions. It is temperature dependent but likely to be close to Newtonian. Both the actual and apparent lava viscosities, η and η_A , on the other hand, are a result of the microphysics of the liquid-crystal-bubble mixture and are the relevant macroscopic viscosities governing the flow. Lava flows have wide-ranging crystal contents at the vent (from <5% in many basalts and rhyolites to commonly 30%– 50% for andesite and dacites), and these increase with distance from the vent. Bubbles typically occupy anything from a few percent by volume to .90% in highly vesiculated portions of a flow. The actual and apparent viscosities will in general differ as a result of a finite yield stress or a nonlinear relation between shearing stress and strain rate. Use of an apparent flow viscosity η_F ignores the actual nature of the rheology and is used to characterize the whole of a thermally and rheologically heterogeneous flow in terms of a single rheological variable. It therefore represents little of the actual mechanics of flow.

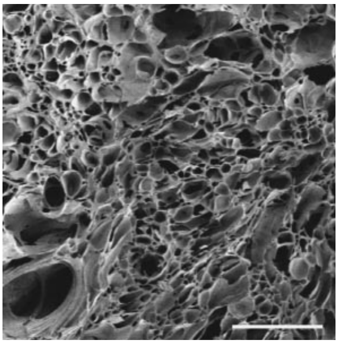


Figure shows images of (a) crystallinity in an `a`a sample taken from an active lava channel 2 km from its vent on Kilauea Volcano, Hawaii, in, and thought to be responsible for a yield strength (this back-scattered electron micrograph shows an area of ~0.4 mm across and a crystal volume fraction of ~45%; and (b) vesiculation in a common form of pumice produced by pyroclastic eruptions (this scanning electron micrograph shows an area of ~0.5 mm across; sample from Mt. Mazama, USA. Additional fascinating images indicating changing crystallinity and effects of shear on vesicles are to be seen in these references.

An approximation that is sometimes used to describe lava rheology is the Bingham flow law, in which the shearing stress σ and strain rate are related by:

$$\sigma = \sigma_0 \;\; \eta\dot{\varepsilon},$$

Where σ_o is the yield stress and g is a constant viscosity (referred to as the plastic viscosity). When the applied stress is below the yield stress, there is no deformation [other than brittle or elastic, which are neglected here, but once this limit is exceeded, the flow may be characterized by an apparent viscosity $\eta_A = \eta \; + \; \sigma_0 / \dot{\varepsilon}$. Thus, for small strain rates, the yield stress can give rise to an apparent viscosity that is very much greater than the actual viscosity. We neglect elastic deformation because the important length scale of shearing in lava flows is small (on the order of the flow depth) and because, on all but small pahoehoe flows, the solid parts are observed to be highly fractured. The fracturing is a result of brittle failure under thermal and flow stresses and tends to produce a carapace of plates, blocks, or rubble.

The viscosity of lava is a function of the temperature *T*, the volume fraction of crystals ϕ, and, to a lesser extent, the size and shape of the crystals. Thus a single relation is not likely to be accurate for a range of lava types having different compositions, temperatures, and histories. However, for basaltic lavas the apparent viscosity is often taken to follow the Einstein-Roscoe relation.

$$\eta_A(T,\phi) = \eta_0 \left(1 - \phi / \phi_{\max}\right)^{-2.5} e^{\gamma(To - T)},$$

Where $\phi_{\max}$ is the maximum crystal fraction that will allow flow γ is a constant [$\gamma \approx 0.04$] and T_o and η_0 are reference values (such as those at the vent). Highly silicic magma has greater melt viscosity by virtue of its composition and generally cooler temperature. It might or might not have higher crystallinity, depending on water content, because the crystal fraction ϕ is related to the temperature and composition of the lava. One approach might be to model the crystallinity of basaltic magmas by:

$$\phi(x) = \phi_0 + \phi_f \left(T_0 - T\right)\left(T_0 - T_{sol}\right)$$

Where ϕ_o is the initial (vent) crystal fraction, ϕ_f is the total further amount of crystallization that occurs during flow, and T_{sol} is the solidus temperature. Here $\phi_0 + \;\; \phi_f \;\; \leq 1$.

An alternative is to use an effective solidification temperature and $\phi_0 + \phi_f = \phi_{\max}$ in equation $\phi(x) = \phi_0 + \phi_f (T_0 - T)(T_0 - T_{sol})$.

Equation $\eta_A(T,\phi) = \eta_0 (1 - \phi / \phi,_{\max})^{-2.5} e^{\gamma(To-T)}$ illustrates the expectation that all lavas reach a limit of extremely large apparent viscosity caused by the onset of a yield stress for a critical crystal content $\phi_{\max}$. Early experimental evidence suggested that $\phi_{\max} \approx 0.55 - 0.6$ for silicate melts. More recent results confirm that the use of this value in equation $\eta_A(T,\phi) = \eta_0 (1 - \phi / \phi,_{\max})^{-2.5} e^{\gamma(To-T)}$ is appropriate, although the latter results also show the onset of non-Newtonian behavior for $\phi_{\max}$ ’ 0.4 (at which η_A . 10^9 Pas, and yield stress is on the order of 2 ×2 10^6 Pa). Independent evidence from Hawaiian samples indicates that basalt flows become controlled by a yield strength at $\phi \approx$ 45%–50%. These are the crystal contents at which the relative motion of the crystals begins to be inhibited by their overlapping and interlocking. In situ instrumental measurements of the yield strength for basalts on Mt. Etna have given values of 400– 6000 Pas.

The effects of bubbles on lava rheology are less well understood but will generally be less important than crystals. Very small bubbles are effectively rigid under surface tension forces and can increase the viscosity. Larger bubbles, on the other hand, deform in shear, providing slippage and leading to shear-thinning behavior. A similar response may occur if elongated crystals become aligned with the shear. Such shear-thinning behavior can be modeled by using a simple power-law stress-strain rate relation or the Herschel-Bulkley generalization of the Bingham rheology:

$$\phi_{if} = \left(K\dot{\varepsilon}^{n-1} + \sigma_0 / \dot{\varepsilon}\right)\varepsilon_{ij} \quad \text{for}\, \sigma > \sigma_0,$$

$$\varepsilon_{ij} = 0 \ \text{ for } \ \sigma \le \sigma_0,$$

Where, σ_{ij} are the deviatoric stresses, $\sigma = \surd\left(1/2\,\sigma_{jk}\,\sigma_{jk}\right), \varepsilon_{ij}$ are elements of the rate of strain tensor, $\dot{\varepsilon} = \surd\left(1/2\,\varepsilon_{jk}\,\sigma_{jk}\right)$ is the shear rate, *K* is the consistency (a measure of the resistance to shear), *n* is an index characterizing the nonlinearity, and σ_0 is again the yield stress. For *n* = 1, we have a Bingham fluid in which the deviatoric stresses are proportional to the shear rate and K = η , the plastic viscosity. When η < 1, shear leads to reduction of the applied stress required to achieve that shear rate (as in shear-thinning, vesicle-rich lava), whereas, if *n* > 1, as suggested by Smith for crystal-rich lava near the solidus, the fluid would be shear thickening.

Given the range of influences on lava rheology, it is not surprising that lava flows can be heterogeneous. Heterogeneity within a flow occurs owing to cooling, crystallization or exsolution of volatiles during flow, or a change in magma properties when a stratified magma chamber is progressively tapped during an eruption. All of these causes can be important. Cooling leads to a very complex surface layer that may subsequently inhibit flow of the hotter lava of the flow interior. The surface layer consists largely of glassy lava formed by rapid cooling to the glass transition temperature of ~700°C, as well as, presumably, some cooled but not yet solidified underlying lava. This layer might be viewed as a more viscous one or an elastic shell having a tensile strength. However, it seems more likely that the highly fractured and blocky carapace on large flows might be better described by either an internal friction coefficient (a Coulomb rheology, assuming a 'dry' blocky layer, as in the flow of sand) or a yield stress for shearing motion that will eventually bring the flow to a halt.

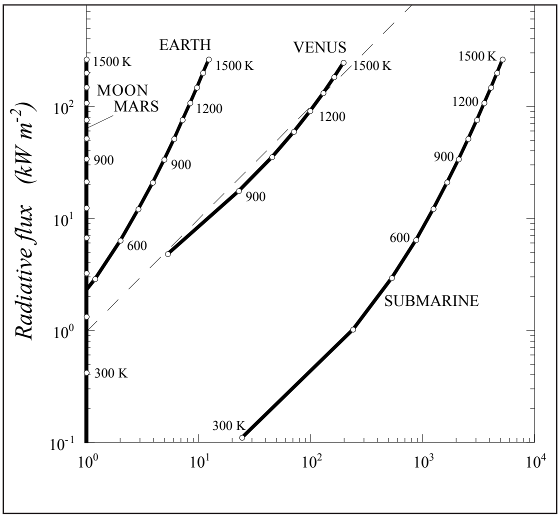
Lava Temperatures and Cooling Mechanisms

Lava is erupted onto the surface with temperatures and viscosities that largely relate to its composition. The hottest lava (komatiite, with low silica and high magnesium content) has had eruption temperatures of 1400–1600 °C. The basaltic lava at volcanic hotspots such as Hawaii emerges at <1200 °C, and mid-ocean ridge basalts erupt at 1100 °C. These basalts have viscosities $\eta_A \approx \eta$ ~10^2 –10^3 Pas on eruption and have no significant yield stress before cooling and crystallization occur. At the other end of the scale are the relatively silicic and more viscous types of magma (andesite and dacite) erupted at around 900 °C above zones of lithosphere subduction and caused by melting of a fraction of the down-going lithosphere. These types of magma have η_A ~ $10^5 - 10^8$ Pas (a value not to be confused with the apparent flow viscosity η_F, which for one dome is estimated to be on the order of 10^{11} Pas; Huppert et al.)

When lava is extruded with eruption temperature T_e into an environment at ambient temperature T_a, the temperature difference $\Delta T = T_e - T_a$ implies a surface heat flux $F_s(t)$, the magnitude of which depends on the heat transfer mechanisms on each side of the surface. The surface flux and surface (or contact) temperature $T_c(t)$ are strongly coupled, each adjusting to the other and to heat transfer within the lava. The contact temperature is generally much less than the interior temperature of the lava, and both T_c and F_s can be estimated by matching the heat fluxes on both sides of the surface. Heat loss from the surface is caused by radiation and convection.

The radiative flux F_R from the surface is readily calculated as a function of T_c from Stefan's law $F_R = e\Sigma\left(T_c^4 - T_a^4\right)$ where *e* is the surface emissivity (generally e > 0.9), Σ is the Stefan-Boltzmann constant, and T_a is the ambient temperature. The convective heat flux F_C [whether buoyancy-driven, $F_C \propto \left(T_c - T_a\right)^{4/3}$, or wind-forced, $F_C \propto T_c - T_a$] can be found by using parameterizations well established in other contexts. For submarine eruptions the calculation is complicated by the large temperature differences, boiling (at lower pressures), and highly nonlinear properties of seawater at high temperatures and pressures (which lie near the critical point under water depths of >2 km).

Representative fluxes are plotted in figure. Radiation dominates under the thin atmospheres of Earth and Mars, whereas the Earth's atmosphere has sufficient heat capacity that convection provides a comparable flux once the surface temperature has fallen to < ~ 200 °C. Radiation is less important than convection for temperatures of < 900 °C under the dense atmosphere of Venus (where Ta ≈750 °C). Underwater radiation is always negligible relative to the very rapid convective transport.



Convective flux (kW m^{-2})

Figure shows estimated surface fluxes from lavas, owing to radiation (vertical axis) and free buoyancy-driven turbulent convection (horizontal axis), as functions of the lava surface temperature (in Kelvin). Recall that this temperature is much less than that of the interior. Fluxes from lavas on the Moon and Mars are shown along the vertical axis, because their atmospheres are too thin to give significant convective fluxes. The results for Venus are terminated at 800 K, because the lowland surface temperature is 750 K. Submarine fluxes are much larger than the others as a consequence of the large heat capacity of water. The oblique line represents $F_R = F_C$.

Surface cooling leads to solidification, which occurs through formation of an amorphous glass when quenching is rapid [cooling faster than 20–30 °C s^{-1} to the glass transition at 700 °C. If cooling is slower, solidification occurs by crystallization at temperatures below the solidus (around 1100 °C). If crystallization is rapid (owing to either cooling or the exsolution of volatiles and the consequent increase in the liquidus temperature after eruption), the latent heat of crystallization may add significantly to the heat budget. As an example, crystallization in a Hawaiian channel flow traveling at 1–2 m s^{-1} was found to occur primarily by nucleation of new crystals, at the rate of 10^4 crystals m^{-3} s^{-1} (or 0.2–0.5 volume fraction h^{-1}) in response to a cooling rate of 22–50 °C h^{-1}. This illustrates a rapid cooling rate in the flow interior caused by stirring in a fast, highly disrupted flow and is in contrast to more viscous flows, in which the much slower cooling rates are controlled by conduction. However, quenching of the surface temperature for all flows is rapid, taking only 0.1 or 100 s to fall below the glass transition under water or air, respectively.

Cooling also occurs from the base of a flow by conduction into underlying rocks, leading to solidification at the bottom of the flow (if the flowing lava is cool enough or short lived) or to melting and erosion of the substrate (if the flow is sufficiently hot relative to the melting temperature of the base and advection continues long enough to supply sufficient heat). Melting is more readily accomplished by turbulent flows, because heat is drawn from throughout the flow depth. The latter scenario is relevant to komatiites, to lava tubes at channel bends and abrupt changes in slope, and to basalt channels not far from the vent.

Flow Regimes without Cooling

Relevant Conditions

The first step in the formulation of useful dynamical models for lava flows is a consideration of the relevant dynamical regimes. Consider an eruption of lava from a localized vent at volume flux *Q(t)*, with viscosity η, yield stress σ_0, and density ρ into an environment having ambient density ρ_a. The developing flow with have depth *h(x,y,t)* and plan form area *A(t)*. The eruption may be onto a horizontal plane, a sloping plane, or a more complicated topography such as a valley or mountain summit. Assuming the viscosity is constant (i.e. a Bingham fluid), the horizontal and vertical momentum equations can be written as:

$$\rho Du_i / Dt = -\partial p / \partial x_i + \left(\partial / \partial y + \partial / \partial z\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right]$$

$$\rho Dw / Dt = \rho g - \partial P / \partial z + \left(\partial / \partial x + \partial / \partial y\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right]$$

where, u_i and w are horizontal and vertical components of velocity, $D\mathrm{u}/\mathrm{Dt} = \mathrm{u}_t + \mathrm{u}\cdot\nabla\mathrm{u}$ and $\mathrm{g} = \mathrm{g}^*\ \left(\rho - \rho_a\right)/\rho$ is the reduced gravity (the gravitational acceleration g* is in the negative z direction), *P* is pressure, $\varepsilon_{ij} = 1/2\pi\left[\left(\partial u_i / \partial x_j\right)\right] + \left(\partial u_j / \partial x_i\right)$ are components of the rate of strain tensor, $\dot{\varepsilon}$ is again the magnitude of $\dot{e}$ the shear rate, and δ_{ij} is the delta function. For flow on a plane of slope β from the horizontal, it will normally be convenient to recast these equations into coordinates parallel and normal to the slope, which changes the gravitational term in equation,

$$\rho Dw / Dt = \rho g - \partial P / \partial z + \left(\partial / \partial x + \partial / \partial y\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right]$$

to $\rho g cos\beta$ and introduces a term $\rho g \sin\beta$ into equation,

$$\rho Du_i / Dt = -\partial p / \partial x_i + \left(\partial / \partial y + \partial / \partial z\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right].$$

In a suitably non-dimensionalized form and dropping for convenience the final term representing the strain associated with compressibility (although this may be significant in flows with large bubble contents), equation $\rho Du_i / Dt = -\partial p / \partial x_i$ $+\left(\partial / \partial y+\partial / \partial z\right)\left[2\left(\eta+\sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij}-1/3\nabla.u\delta_{ij}\right)\right]$ becomes:

$$\mathrm{Re}\,Du_i / Dt = G\left(H / L\right)\partial P / \partial x_i + \left(H / L\partial / \partial y + \partial / \partial z\right)\left[2\left(1+B\right)\varepsilon_{ij}\right]$$

Where velocities have been scaled by U, vertical lengths by H, horizontal lengths by L, time by H/U, and pressure by ρgH. The dimensionless parameters are the Reynolds number $\mathrm{Re} = \rho UH / \eta$, the ratio of buoyancy to viscous stresses $G = \rho gH^2 / \eta U$, the aspect ratio H/L of the flow, and the Bingham number $B = \sigma_0 / \eta\dot{\varepsilon} = \sigma_0 H / \eta U$. For $\mathrm{Re} \ll 1 + B$ the inertia effects are negligible, and the internal stresses are balanced by the gravitationally induced stress ($G \approx 1$). The aspect ratios of lava flows range from $H/L \approx 0.2$–0.3 for most lava domes (based on their radius) and ~0.1 for pahoehoe toes to very small values (< 0.01) for long-channel and sheet flows.

The Reynolds number can be evaluated from estimated speeds, depths, and viscosities of flows observed while they were active. For the slow effusion of very viscous lavas forming domes, which on Earth are tens of meters high and 10^2 –10^3 m across, Re ~ 10^{-10}-10–10^{-4}. Hence modeling of these flows has started with solutions for the spreading of very viscous Newtonian fluid creeping over horizontal or sloping planes. The relatively rapid channel flows on Hawaii, on the other hand, have velocities on the order of 10 $\mathrm{ms^{-1}}$ near the vent and 0.1 $\mathrm{ms^{-1}}$ near the flow front, depths of 1–10 m, and viscosities near the vent on the order of 10^3 Pas, hence Re ~ 1–10^2 , becoming smaller downstream as the viscosity increases and slope decreases. Ancient eruptions of very hot komatiite lavas are thought to have had velocities on the order of 10 $\mathrm{ms^{-1}}$, viscosities of ~1 Pa, and depths of ~10 meters, which suggest values of Re possibly as large as 10^6. Hence these ancient flows would have been turbulent with efficient mixing throughout the depth of a flow, whereas the largest of present-day flows, although not fully turbulent, are strongly agitated by irregularities in the channel and by blocks of solid lava carried by the flow. Thus the modeling of long basalt flows has started from the assumption of well-mixed channel flows having properties that are uniform in the vertical. An additional consideration for flows with large Re is that surface gravity waves can propagate without immediate dissipation. Hence the Froude number $\mathrm{Fr} = U / \surd\left(gH\right)$ [= $(Re/G)^{1/2}$ in 6] is a relevant parameter, and, if $Fr > 1$, the lava flow potentially involves control points, supercritical flow, and hydraulic jumps.

Evidence for non-Newtonian flow regimes is obvious on many lava flows, including linear crevasse structures, along which the material parts as it is slowly extruded, irregular surfaces sometimes dominated by tall angular spines, smooth striated extrusion surfaces, tearing of the surface lava in channel flows, and the formation of solidified levees that channelize Hawaiian lavas. In the Bingham fluid approximation, the significance or otherwise of a yield stress is determined by the value of the Bingham number B in few previous equation. For Newtonian flow, B = 0, whereas B $\rightarrow \infty$ for those parts of a flow having very small shear rate $\dot{\varepsilon} \ll \sigma_0 / \eta$ or a large yield stress $\sigma_0 \gg \dot{\varepsilon}\eta$. For small Re, $B \ll 1$ implies a viscous-gravity balance, whereas $B \gg 1$ implies a balance of yield stress and gravity in which the flow depth scales as $H \sim \left(\sigma_0 L / \rho g\right)^{1/2}$.

Lava flows lie across the full range of *B*. For example, the dome of basaltic andesite that was erupted on La Soufrière volcano on the island of St. Vincent in, had a height of 100 m, a front velocity of 3×10^{-5} ms^{-1} (400 m in 150 days), and an interior apparent viscosity $\eta_A \sim 2 \times 10^7$ Pas (a petrologic prediction given the observed 45% crystallinity and eruption temperature of 1000 °C). If the yield stress is on the order of $\sigma_0 \sim 10^5$ Pa (consistent with values obtained in the laboratory for similar lava samples, we estimate B ~ 10^4. There are of course uncertainties of an order of magnitude in both the viscosity and yield stress used here. Nevertheless, it is clear that B$\gg$ 1 for this dome. Measurements available for a number of other lava domes lead to a similar conclusion—that silicic domes tend to grow so slowly that the viscous stresses are very small compared with the yield stress, and therefore the domes are effectively, at any moment, in a static equilibrium between gravity and yield stress. When the effects of cooling are taken into account, a carapace yield stress may be much greater than the interior strength used above, and it has been argued that this further increases the effective value of B by several orders of magnitude.

At the other end of both the flow rate and rheologic spectrum, large basaltic channel flows have strain rates $U / H\ ;\ 0.1 - 1\ s^{-1}$, viscosity of ~$10^3$ Pas, and a small or vanishing yield stress. Hence $B \ll 1$, as long as $\sigma_0 \ll 10^3$ Pa, and the flow can be considered to be viscous. This is the case near the vent and, for Hawaiian flows, a kilometer or two down-channels. However, the crystallinity will eventually reach the critical value of 45%–50% as a result of cooling and stirring. This can be hastened by the exsolution of volatiles. Hence the onset of a yield stress >10^3 Pa can be expected, and there may be a transition in flow regime. The viscous stresses may remain important in regions of greatest shear, but plastic deformation at $\dot{\varepsilon} < \sigma_0 / \eta$ will dominate in cooler and slower parts of the channel. Note that Hulme estimated transitional flow strengths of 10^2 –10^4 Pa on many basaltic channel flows using the height of levees, ground slope, and lava density in an isothermal model. A similar conclusion applies to smaller breakouts from these channels, forming relatively shallow pahoehoe flows characterized by a thin glassy skin. In these the shearing rate is closer to 0.1 s^{-1}, and the critical yield stress (that giving B= 1) for the interior is ~10^2 Pa. Again, however, cooling of the surface may dominate, and in this case it is unclear whether the glass is best treated as a much more viscous layer or as a thin, strong boundary layer containing the underlying low-viscosity fluid. The results of Bingham flow models applied to lava flows have been fruitful in accounting for various aspects of real flow behavior.

Axisymmetric Viscous Flow

Under the assumptions of small Re, constant viscosity, hydrostatic pressure, $H/L \ll 1$, and axisymmetric motion on a horizontal plane, equations

$$\rho Du_i / Dt = -\partial p / \partial x_i + \left(\partial / \partial y + \partial / \partial z\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right]$$

and reduce $\rho Dw / Dt = \rho g - \partial P / \partial z + \left(\partial / \partial x + \partial / \partial y\right)\left[2\left(\eta + \sigma_0 / \dot{\varepsilon}\right)\left(\varepsilon_{ij} - 1/3\nabla.u\delta_{ij}\right)\right]$ to:

$$\partial P / \partial r = \rho g \partial h / \partial r = \eta \partial^2 u / \partial z^2,$$

where *u(r,z,t)* is the radial velocity. The problem is closed by continuity and the conditions of zero velocity at the base z = 0 and zero stress at the top of the flow z = h. It is straightforward to find the dependence of flow radius R and depth *H* on time implied by Equation $\partial P / \partial r = \rho g \partial h / \partial r = \eta \partial^2 u / \partial z^2$ by comparing the integrated gravitational driving force $F_B \sim \rho g H^2 R$ to the retarding force $F_\eta \sim \dot{\varepsilon}\eta R^2$ caused by shear stress acting over the basal area. Under the self-similarity assumption, continuity implies $V \sim HR^2$. For dome volumes varying with time as $V = St^\alpha$, where *S* and a are constants ($\alpha \geqq 0$),

$$R \sim \left(\rho g S^3 / \eta^{t(3\alpha+1)}\right)^{1/8}, \mathrm{H} \sim \left[\eta S / \rho g\, t^{(\alpha-1)}\right]^{1/4}$$

These expressions also give the speed u_f of flow front advance and a relation between height and radius:

$$u_f \sim \left[\rho g S^3 / \eta\, t^{(3\alpha+7)}\right]^{1/8},\ H \sim \left[\left(\eta / \rho g\right)^\alpha SR^{(2\alpha-2)}\right]^{1/3(3\alpha+1)}$$

A complete similarity solution that provides values for the constants of proportionality omitted in equation $R \sim \left(\rho g S^3 / \eta^{t(3\alpha+1)}\right)^{1/8}$, $\mathrm{H} \sim \left[\eta S / \rho g^{t(\alpha-1)}\right]^{1/4}$, as well as the flow shape *h(r)*, was given by Huppert and Huppert et al. The solution agrees well with laboratory experiments using viscous oil spreading on a plane. Interesting conclusions from equation above are that the radius of a flow of constant volume ($\alpha = 0$) increases as $t^{1/8}$, so that the rate of advance of the front becomes extremely slow after a short time, while the height decreases. For a constant source flux ($\alpha = 1$), the radius increases as $t^{1/2}$, velocity decreases as $t^{-1/2}$, and the height is constant at $\left(\eta S \rho g\right)^{1/4}$. Dome height increases with time only if the source flux (or viscosity) increases with time. Flow from the vent in such a viscous model is largely accommodated by divergent radial motion near the flow surface, and the flow front advances through upper levels of the fluid moving to the flow front, where they are subsequently over run.

In an application of the results to the Soufrière dome by Huppert et al, the dome volume during the first 90 days of dome growth was fitted by the powerlaw expression $V \sim t^{1.36}$ (i.e. $\alpha = 1.36$). Based on this fit the predicted behavior of the radius is $R \sim t^{0.63}$, whereas the measurements give $R \sim t^{0.58}$. If this is taken as a reasonable agreement, a rearrangement of Equation $R \sim \left(\rho g S^3 / \eta^{t(3\alpha+1)}\right)^{1/8}$, H~ $\left[\eta S / \rho g\, t^{(\alpha-1)}\right]^{1/4}$ into the form $\eta \sim \rho g S^3 t^{(3\alpha+1)} / R^8$ can be used to estimate the viscosity, giving $\eta \sim 2\times10^{11}$ Pas.

However, this approach is problematic. The viscosity obtained is inaccurate because it is proportional to high powers of the measured volumes and radii. The mean value obtained is also ~4 orders of magnitude greater than that given by petrologic methods. In addition, the dome height increased more rapidly than the model predicts. These discrepancies were attributed to non-Newtonian properties; the effect of a cooled skin or the effects of a flow front composed of cooled lava and avalanched blocks. On the other hand, this implies that application of the uniform viscosity solution does not capture the essence of the controls on the spread of the lava. We will also see below that the similarity between the predicted and measured power-law exponents for the dome radius does not discriminate well between differing mechanisms of deformation.

Viscous Flow on a Slope

The spreading of a Newtonian fluid on a sloping plane can be described under the same approximations, but this time the flow is not axisymmetric, and it becomes necessary to solve for the flow outline as well as the three dimensional depth distributions. Analyses of the shape of an evolving flow from point and line sources on a plane of slope angle θ are given by Lister and tested by laboratory experiments using various viscous fluids. The similarity solutions for a point source show that the flow becomes strongly influenced by the slope at a time *T** or a volume $V^* \sim ST^{*\alpha} \sim S\left[\left(\rho g / 3\eta S\right)^{-1} \cot^5\theta / \sin\theta\right]^{1/(\alpha+3)}$, where the notation is that used in previous equation. At larger times the across-slope flow width *W* increases as $W \sim \left(S \cot\theta t^{\alpha}\right)^{1/3}$, whereas the down-slope length increases as $L \sim \left(\rho g / 3\eta\right)^{1/3}\left[S^4 t^{4\alpha-3} \sin^5\theta / \cos^2\theta\right]^{1/9}$. The corresponding flow depth near the vent varies as $H \sim \left(\rho g / 3\eta\right)^{-1/3}\left[S^2 t^{2\alpha-3} / \left(\cos\theta \sin^2\theta\right)\right]^{1/9}$. The ratio of a cross-slope width to down-slope length varies with time as $W / L \sim t^{(\alpha+3)9}$ and can be expressed in terms of the total volume released onto the slope:

$$W / L \sim \left(\rho g / 3\eta S^{1/\alpha}\right)^{1/3}\left(\sin^{s}\theta / \cos^5\theta\right)^{1/9} V^{(\alpha+3)9\alpha}$$

Thus, for the particular case of a constant source flux $\left(\alpha = 1\right)$, we have $L \sim t^{7/9}, W \sim t^{1/3}$, and $H \sim t^{-1/9}$. In this case we also have $W \sim L^{3/7}$ and W/*L* proportional to $\eta^{-1/3}$, $Q^{-1/3}$, and $V^{4/9}$. For larger viscosity and larger volume flux, the flow is more elongated, whereas it grows wider (compared with its length) as the volume increases. These results provide a useful basis for comparison when assessing the results of theories or experiments with different fluid rheology or the effects of cooling, and they may help to understand the shape of, for example, large rhyolite flows on slopes.

Surface tension was found to have significant effects at large times in the experiments of Lister, leading to a surface tension–dominated rivulet at the down-slope extremity of the flow or to bifurcation in fingering-style instability. However, surface tension is negligible on scales greater than a few centimeters in real lava flows, and it will not influence flow spreading for all but perhaps small pahoehoe “toes.” Flow branching is instead caused by rheology variations from cooling.

Axisymmetric Viscoplastic Flow

The introduction of yield strength into the simplest flow problem above—the slow axisymmetric spreading of a thin layer of fluid from a small vent—is highly instructive. Blake proposed that the material of highly silicic lava domes possesses yield strength and replaced equation $\partial P/\partial r=\rho g\partial h/\partial r=\eta\partial^2 u/\partial z^2$ with the static balance obtained from equation:

$$\rho Du_i/Dt=-\partial p/\partial x_i+\left(\partial/\partial y+\partial/\partial z\right)\left[2\left(\eta+\sigma_0/\dot{\varepsilon}\right)\left(\varepsilon_{ij}-1/3\nabla.u\delta_{ij}\right)\right] \text{ and}$$

$$\rho Dw/Dt=\rho g-\partial P/\partial z+\left(\partial/\partial x+\partial/\partial y\right)\left[2\left(\eta+\sigma_0/\dot{\varepsilon}\right)\left(\varepsilon_{ij}-1/3\nabla.u\delta_{ij}\right)\right]$$

for $B \gg 1$:

$$\partial P/\partial r=\rho g\partial h/\partial r=\sigma_0/h.$$

This model is based on the assumption that the fluid does not deform anywhere but at its base, where the pressure is greatest and, for the fluid to have reached its current shape, equal to the yield stress. The solution to equation $\partial P/\partial r=\rho g\partial h/\partial r=\sigma_0/h$, originally given by Nye in the context of ice sheet dynamics, with $h=0$ at $r = R$, is simply,

$$h^2=\left(2\sigma_0/\rho g\right)\left(R-r\right),$$

which implies that the central height $H = h(0)$ and the radius R are always related by $H=C\left(\sigma_0 R/\rho g\right)^{1/2}$, where $C=\sqrt{2}$. Using slurries of kaolin powder in water, Blake found excellent agreement for the shape, except at the origin— where transition from vertical flow in the small vent to lateral flow outside necessarily involves strain rates large enough for viscous stresses to become significant and the surface slope discontinuity disappears—and at the flow front where the flow is steeper than the solution.

Scaling analysis starting from the integrated force balance $g\rho H^2 R \sim \sigma_0 R^2$ and the self-similar continuity relation $V \sim HR^2$, and again assuming dome volume varies as $V = St^{\alpha}$, leads to:

$$R \approx 0.65\left(\sigma_0 / \rho g\right)^{-1/5} S^{2/5} t^{2\alpha/5}, \quad H \approx\sim 1.4\left(\sigma_0 / \rho g\right)^{2/5} S^{1/5}\, t^{\alpha/5},$$

$$H \approx 1.76\left(\sigma_0\, R / \rho g\right)^{1/2}$$

where the constants shown are the empirical values (obtained for constant volume flux), and we note that, in *HI*, the value C ≈ 1.76 is somewhat larger than predicted. These scaling laws are also consistent with results obtained from isothermal experiments with slurries of kaolin in polyethylene glycol wax spreading under water (recall that g is the reduced gravity), but in that case σ_0 and C were not evaluated independently. The most interesting aspect of this solution is that the relation between *H* and *R* is independent of time and also independent of *S* and α—the solution is a static one. Thus, when the vent flow is stopped in the experiments, the dome does not continue to flow as it does in the viscous case. Also in contrast to the viscous flows, marked elements of the flow surface moved radially but did not approach the flow front, and the same material remained at the front throughout the spreading. There are two sets of slip planes ilometres out from the summit, which divide the surface into small roughness elements. The surface roughness remained small under air as a result of surface tension but was several ilometres high under water for the slurries used.

Since shear rates are larger near the vent, viscous stresses can be more important when *R/H* is small. Hence there can be a transition from viscous flow (B >> 1) at small times to plastic flow (B << 1) at large times. From the results for Newtonian flow, we see that $B \ll 1$ for $t \ll \left[\left(g^3\, \rho^3 \eta^5\, S\right)\sigma_0^8\right]^{1/5(5-\alpha)}$ and that transition to plastic flow will always occur for a < 5.

Application of this uniform-yield stress model to the Soufrie`re lava dome is straightforward, because the volume and time are not needed; the measurements give $H \sim R^{0.52}$, in very good agreement with equation:

$$R \approx 0.65\left(\sigma_0 / \rho g\right)^{-1/5} S^{2/5} t^{2\alpha/5}, \quad H \approx\sim 1.4\left(\sigma_0 / \rho g\right)^{2/5} S^{1/5}\, t^{\alpha/5}$$

and

$$H \approx 1.76\left(\sigma_0\, R / \rho g\right)^{1/2}$$

Using the power-law relation for *V(t)* as fitted to the measurements by Huppert et al, equation $R \approx 0.65\left(\sigma_0 / \rho g\right)^{-1/5} S^{2/5} t^{2\alpha/5}$, $H \approx\sim 1.4\left(\sigma_0 / \rho g\right)^{2/5} S^{1/5}\, t^{\alpha/5}$ and $H \approx 1.76\left(\sigma_0\, R / \rho g\right)^{1/2}$ also predicts $R \sim t^{0.544}$ and $H \sim t^{0.272}$, both of which are closer to the observed trends than are those predicted by the Newtonian model.

Given this agreement, evaluation of the yield stress from $H/R^{1/2}$ by using equation $R \approx 0.65\left(\sigma_0 / \rho g\right)^{-1/5} S^{2/5} t^{2\alpha/5}$, $H \approx\sim 1.4\left(\sigma_0 / \rho g\right)^{2/5} S^{1/5}\, t^{\alpha/5}$ and $H \approx 1.76\left(\sigma_0\, R / \rho g\right)^{1/2}$ gives $\sigma_o = 2.6 \times 10^5$ Pa for Soufrière and similar values for a number of other domes. Thus the plastic model appears to describe lava domes better than does the viscous model.

The axisymmetric solutions for viscous and plastic flows have been extended to visco-plastic (Bingham) flow at B < 1, conditions in which both viscous stresses and yield stress are significant. These authors also investigated the effects of shear thinning of a power-law fluid by using the Herschel Bulkley rheology, and they concluded, from numerical solutions for constant volume flux, that it may be difficult to differentiate between the effects of yield stress and shear thinning. However, as we have seen above, the Bingham numbers for lava domes (based on crude estimates for the yield stress and viscosity) are so large that viscous stresses, whether linear or dependent on a higher power of the shear rate, are expected to be negligible. Note also that the isothermal experiments by Griffiths & Fink (carried out as isothermal comparisons to cooling flows) gave final static shapes that did not alter when the source flux was turned off and that recent experiments on a slope involved constructing a large dome with a series of small incremental extrusions separated by long repose periods and yet gave identical dome shapes (at the same volumes) to runs with continuous extrusion. Thus the dome shape appears independent of volume flux history and shear rate so long as extrusion rates are small. As quantified above, lava domes too have very small extrusion rates, and some are similarly constructed by many sequential extrusions.

An interesting aspect of radially expanding Bingham flows is that the pressure gradient is assumed to be too small everywhere to cause deformation except at the base, where the yield stress is attained. Hence a plug flow is predicted. How-ever, the motion described by the continuity equation, integrated over the depth to give:

$$\partial h / \partial t + 1 / r\ \partial / \partial r\left(rU\right) = w_s,$$

where $U\left(r.t\right) = \int_0^h u\left(r, z, t\right) dz$ and w_s is the vertical velocity at the free surface, is actually extensional in the azimuthal direction and compressional in the radial direction. Hence there is no true plug flow, and the fluid is deforming everywhere. And Balmforth et al addressed this paradox and showed, through an expansion in the aspect ratio $H/L << 1$, that the plug flow is valid only at leading order. The fluid is actually weakly yielding throughout its depth, to compensate for the radial expansion, and $\partial u / \partial z \sim O\left(H / L\right)$.

Another axisymmetric non-Newtonian model, one that incorporates a heterogeneous rheology resulting from heat loss, consists of a uniform (viscous) interior capped by a thin brittle shell having a tensile strength. In this case, the static balance between gravity and tensile strength in the shell gives an elliptic height profile that is wider and lower for smaller tensile strengths. The model does not include the thermodynamics, which control the crust thickness, but the dome is proposed to grow with added volume input through brittle failure of the crust followed by quenching to form a crust in equilibrium with the new volume.

Viscoplastic Flow on a Slope

Early realization that the levee banks created by long basalt flows implied non Newtonian flow led Hulme to consider the unconfined motion of a Bingham fluid down a plane of slope β. He considered long flows and assumed that all quantities are independent of the distance x down-slope. Near the edges of the flow its depth $h(y)$ becomes small, and the lateral flow is assumed to cease when the cross-slope pressure gradient is balanced by the basal-yield stress, as expressed in Equation $\partial P / \partial r = \rho g \partial h / \partial r = \sigma_0 / h$. (with the radial coordinate r replaced by the cross-slope distance y). The cross-slope depth profile near the edges is then fixed and given by Equation $h^2 = (2\sigma_0 / \rho g)(R - r)$ (with the radius R replaced by the cross-slope width W of the whole flow). This balance also gives the depth $H = C(\sigma_0 W / \rho g)^{1/2}$ on the center line of the flow. If the flow depth is assumed to be constant in the down-slope direction at any value of y, then motion requires $\rho g h(y) \sin\beta > \sigma_0$. Hence there is a critical depth,

$$h_s = \sigma_0 / \rho g \sin\beta$$

below which there will be no down-slope motion. Substituting this depth into the cross-slope balance (Equation $\partial P / \partial r = \rho g \partial h / \partial r = \sigma_0 / h$) gives the width of the region of stationary fluid along the edge of the flow:

$$w_s = \sigma_0 / 2\rho g \sin^2\beta = h_s / 2\sin\beta$$

Between these two stationary regions, there is free viscoplastic flow down-slope, which Hulme approximated as the two-dimensional flow between a parallel stressfree surface and the bottom plane, leading to the depth-averaged velocity:

$$u = \left(\rho g \sin\beta h_s^2 / 3\eta\right)\left[\left(h / h_s\right)^3 - 3/2\left(h / h_s\right)^2 + 1/2\right].$$

A problem with the analysis is that, for the cross-slope motion to cease, it is necessary to consider more than the cross-slope component of the basal stress; the total stress $\sigma = \rho g h[\sin^2\beta + \left(\partial h / \partial y\right)^2]^{1/2}$ at the base (where the down-slope thickness gradient is neglected) must become equal to the yield stress.

Hulme's laboratory experiments with kaolin-water slurry on a slope revealed the presence of stationary levees bounding long down-slope flows. The height of the levees was consistent with the formula, which was then applied to lava flows to find yield strengths (of ~ 10^3 Pa for low silica contents to 10^5 Pa for higher silica contents) for various flows given the height of levees (5–30 m) and the underlying topographic slope. This much of the behavior of long flows, and particularly the observed levees, can therefore be explained in terms of isothermal flows having yield strength. The levee-derived correlation between silica content and strength for terrestrial flows, along with remote measurements of levee heights, was even used to estimate compositions of lunar flows. In detail the real flow levees are formed of cooled flow-front or surface material pushed aside by the advancing flow front, so that only the levees are required to have yield strength. However, the principle and the application of equation $h_s = \sigma_0 / \rho g \sin\beta$ are unchanged.

A more difficult problem is posed by large lava domes on slopes; these are not the very long flows described by Hulme. Instead, the challenge is to predict the fully three-dimensional shapes, including the extent of up-slope flow from the vent. A solution can be found for the three-dimensional case in the limit of slow flows ($B \rightarrow \infty$) and gives the final width of very long down-slope flows independent of the viscosity. We again assume $H/L \ll 1$, a hydrostatic gradient in the vertical, and a static balance between gravity and yield stress (this time in the plane parallel to the base slope), and we obtain an equation for flow thickness h(*x,y*) normal to the base.

$$\left(\partial h / \partial x = \tan\beta\right)^2 + \left(\partial h / \partial y\right)^2 = \left(\sigma_0 / \rho g h \cos\alpha\right)^2 .$$

Assuming symmetry about the down-slope *(x)* axis through the source implies [$\partial h / \partial y$ (y = 0) = 0 (except at *x* = 0, where] $\partial h / \partial y$ must be discontinuous to force radial flow from the vent). Then above equation can be solved for the thickness profile h(*x,0*). Scaling thickness *h* by h_s (Equation $h_s = \sigma_0 / \rho g \sin\beta$) and distance x parallel to the slope by h_s/sinβ leads to the dimensionless thickness profiles,

$$x = h - H + \mathrm{In}\left|(1-h)/(1-H)\right|, \quad x \geq 0$$

$$= h - H - \mathrm{In}\left|(1+h)/(1+H)\right|, \quad x \leq 0,$$

on the down-slope (x > 0) and up-slope (x < 0) sides, where *h* = *H* at *x* = *0*. The leading edges of the flow are found at h 4 0, and from above equation we have:

$$x_d = -H - \mathrm{In}\left|1-H\right|, \; x_u = -H + \mathrm{In}\left|1+H\right|,$$

or a total flow length $L = -\mathrm{In}\left|1-H^2\right|$. The cross-slope thickness profile of the dome can be approximated by neglecting $\partial h / \partial x$ in equation $\left(\partial h / \partial x = \tan\beta\right)^2 + \left(\partial h / \partial y\right)^2 = \left(\sigma_0 / \rho g h \cos\alpha\right)^2$ in the region of maximum width (down-slope from x = 0), and the maximum width is given by $W \approx 2\left[1 - \surd\left(1 - H^2\right)\right]$. It tends to be more useful to describe these flows in terms of their volume *V* at any time, where *V* is normalized by the volume scale $\sigma_0^3/(\rho g)^3(\sin^5\beta)$ the dome is not much influenced by the topography for $V \ll 1$ but strongly influenced and displaced somewhat down-slope from the vent for $V < 1$.

When $V \gg 1$ (and the thickness *H* tends to 1), the down-slope length of the dome tends to infinity. This reflects the fact that Hulme's critical thickness h_s (Equation $h_s = \sigma_0 / \rho g \sin\beta$) is the maximum dome thickness that can be supported on the slope in a static balance. For $V \ll 1$ (i.e. $H \ll 1$ as a result of small volume, large yield strength, small slope, or reduced gravity), the dome is not influenced by the base slope and is close to axisymmetric, and the solution approaches the quadratic profile. To obtain the dome perimeter and contour plots of flow thickness as a function of H (or of total flow volume V) Equation $(\partial h/\partial x = \tan\beta)^2 + (\partial h/\partial h)^2 = (\sigma_0/\rho g h \cos\alpha)^2$ was solved numerically. [A very similar problem is treated through numerical simulation by Miyamoto & Sasaki.] The solutions can be compared with isothermal experiments with slurries of kaolin in polyethylene glycol wax as well as kaolin in water, both on a sloping base. For $V \approx 0.1$ ($H \approx 0.7$), the flow margin begins to depart noticeably from circular, and the down-slope length is more than twice the up-slope length from $x = 0$. For $V \approx 1.5$ ($H \approx 0.95$), the down-slope length is eightfold greater than the up-slope length and nearly twice the full width. The stationary levees of Hulme are seen to form along the edges of the down-slope flow at very large flow elongations. The laboratory flows tended to spread farther across slope and were less elongated than predicted, but are otherwise consistent with the theoretical solution. Two sets of slip planes again curve out from the summit as in Blake's experiments on a horizontal base, but this time they are asymmetric in the *x* direction. In the analysis the assumption of the static balance everywhere implies that the origin is to be identified with the vent from which the fluid was supplied. There is no implication that fluid volumes having histories different from this will take similar shapes; the static shape will be different if the base slope is changed after the volume is emplaced or if the flow is viscous for a time before taking on yield strength.

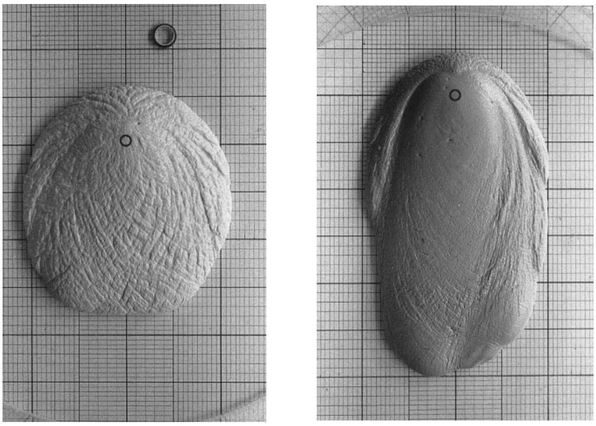


Figure show isothermal laboratory flows of Bingham fluid on a planar slope. The fluid was extruded in many small-volume increments from a 1-cm-diameter hole in the smooth base. The domes were static between increments. The white circle shows the location of the source. (a) Kaolin/water slurry, slope β =12°, volume 900 cm^3, σ_o = 92 Pa, dimensionless volume $V \approx 0.8$ (b) Kaolin/polyethylene glycol slurry, β = 18°, 1000 cm^3, σ_o = 84 Pa, $V \approx 12$. 'Levees' develop for $V > 10$, when further spreading is largely down-slope.

Effects of Cooling and Solidification

Dimensionless Parameters

Since lavas are far from thermal equilibrium with the overlying atmosphere or ocean and relatively close to their solidus temperatures, cooling induces very large changes in rheology that eventually bring flows to a halt. It is therefore important to investigate thermal effects in flow models. These effects depend on whether the flow is laminar or turbulent and on the rate of cooling and rheological change compared with the rate of spreading of the flow. Comparing the conductive transport of heat within the lava to the advection of heat with the flow gives Peclet (Pe) numbers Pe 4 UH/k (k is the diffusivity) ranging from 10^2 to 10^5 for slow growing lava domes to $>10^6$ for faster channelized basalts and turbulent komatiite flows. As a measure of the rate of cooling, we could take the global Nusselt (Nu) number, $Nu = F_s^* H / \rho c_p \, k \Delta T$, based on the surface heat flux F^*_s that would occur if the contact temperature remained at the eruption temperature $T_{e.}$ This Nu number can be rewritten as Nu ~ H/ δ_T, where δ_T is the thickness of a steady-state conductive layer that can supply the surface flux. (Alternatively, the ratio $\mathrm{Nu_A} = F_s^* / \left(\rho c_p \Delta T U \right) = \mathrm{Nu/Pe}$ based on the advective heat transport might be used.) Taking as an example an eruption temperature $T_e \approx 1150$°C, Ta ≈ 0°C and the fluxes from figure, we find Nu~ 10^3 (for all subaerial flows) (and Nu_A ~ 1 or 10^{-3} for domes and fast-flowing basalts, respectively). The large values of Pe and Nu indicate that active flows, whether they are laminar or turbulent, will involve only thin thermal boundary layers. The small values of NuA indicate that the surface fluxes are sufficiently small that lavas can flow a large distance (if the velocity U is sustained) before being completely cooled. For laminar flows (while they remain shorter than $L \sim H\,\mathrm{Pe}^{1/2}$), the interior is not cooled, and the flow must become thermally and rheologically stratified. For turbulent flows, mixing of the surface boundary layer into the interior may be possible (if mixing is not inhibited by rheological contrasts) and will cool the interior with distance downstream. When the flow involves crystallization (or melting of the floor), the latent heat of fusion L_h can be significant compared with the specific heat, as measured by the Stefan number $S = L_h / c_p \, \Delta T$, and should be included in any complete heat budget. However, it is generally a small effect.

Note that cooling has its influence through variations in the lava rheology, whereas the Pe and Nu numbers concern only the temperature distribution. The strong dependence of rheology on temperature near the solidification temperature introduces a complexity but increases the validity of the simplifying thin-boundary-layer-and-isothermal-interior approximation for both laminar and well-mixed flows. Because the most dramatic rheological changes with temperature are caused by solidification, they occur at temperatures close to the glass transition temperature (under rapid cooling) or at temperatures for which the crystallinity passes through the critical range 40%–60% (for slow cooling). We are concerned with rapid surface quenching and a glassy crust on all flows. For turbulent flows there are, in addition, the effects of mixing and relatively slow distributed cooling, hence crystallization and consequent change of rheology, in the bulk of the flow. An important parameter that determines the extent of solidification is $\Theta_s \left(T_S - T_a\right)\left(T_e - T_a\right)$, the proximity of the eruption temperature T_e to the solidification temperature T_s. For $\Theta_s \ll 1$, a large amount of cooling is required to reach solidification, whereas, for $\Theta_s \leq 1$, there is rheological change with little cooling. Basaltic lavas (with $T_e \approx$ 1150 °C, $T_a \approx$ 0 °C, and a glass transition at $T_s \approx$ 700 °C) have $\Theta_s \approx 0.6$, and highly silicic lavas (with T_e‘ 900 °C) have $\Theta_s \approx 0.8$.

Although the set of thermal parameters (Θ_s, Nu, and Pe) are sufficient to define a cooling and solidifying flow at small Re and given rheology, it is possible to define a dimensionless parameter that provides a more ready indication of the extent and effects of solidification. In the thin boundary layer regime, surface solidification commences at a distance $d_s \approx ut_s$ from the vent, where u is the surface velocity and t_s is the time taken for the surface temperature T_c to cool from the vent temperature T_e to the solidification temperature T_s. Scaling distance by H and velocity by a suitable scale U, we define the dimensionless parameter.

$$\Psi = Ut_s / H = t_s / t_A$$

or, equivalently, $d_s / H \approx \Psi$, , where $t_A = H/U$ is the time scale for lateral flow through a distance H. The value of t_s depends on Θ_s and the surface heat flux and it must be obtained from a heat transfer calculation, accounting for radiation and convection from the surface. This solidification time is on the order of 0.1 s for submarine lavas, 100 s for subaerial basaltic lavas (on Earth and Mars), and ~60 s for the cooler highly silicic lavas under air. The parameter Ψ is defined for extrusions of constant volume flux Q in terms of the advective time scale t_A appropriate to the corresponding isothermal Newtonian gravity currents. A similar parameter Ψ_B can be defined, again by Equation $\Psi = Ut_s / H = t_s / t_A$, when the flow is plastic. For the Newtonian case (and point source), a global velocity scale $U \sim Q / H^2 \sim \left(\rho g Q / \eta\right)^{1/2}$ and depth scale $H \sim \left(Q\eta / \rho g\right)^{1/4}$ give $t_A = \left(\eta / \rho g\right)^{3/4} Q^{-1/4}$. The dimensionless solidification time becomes:

$$\sigma = \sqrt{}\left(1/2\,\sigma_{jk}\,\sigma_{jk}\right), \varepsilon_{i}$$

For the plastic case, $U \sim Q\left(\rho g / \sigma_0\right)^3 Qt_s$ and $H \sim \sigma_0 / \rho g$ lead to:

$$\Psi_B = \left(\rho g / \sigma_0\right)^3 Qt_s .$$

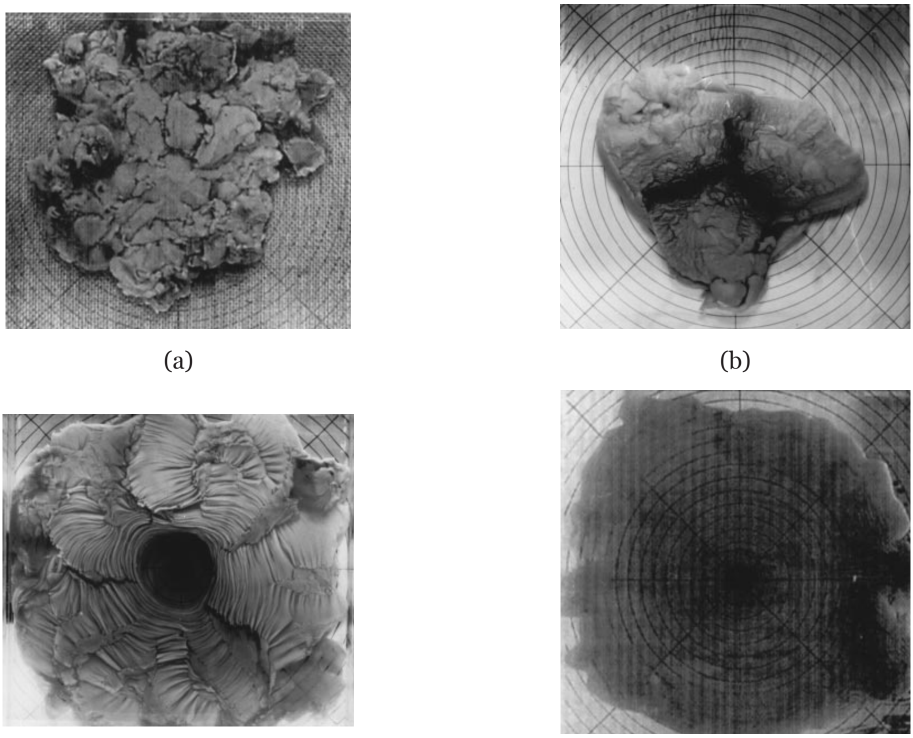
These definitions represent an attempt at describing a flow in a global sense, recognizing that the advection velocity at a given radius can vary with time (as the depth changes or the flow becomes non-axisymmetric) and depends on distance from the vent. Thus there remains scope for time dependence of the effects of solidification within a flow having a fixed value of η. Of course, variations of source volume flux lead to changes in Ψ.

At distances from the vent greater than d_s, the layer of solid crust will thicken in a manner that, again, can be calculated by coupling conduction in the lava to the surface heat flux through the surface temperature T_c(t). Note that, in terms of the external dimensionless parameters, $\approx$ and Ψ_B provide a general indication of whether the crust thickens quickly or slowly relative to the lateral motion, and they are more relevant to the thickness of the rheological boundary layer than is Pe, at least at early times, because the latter relates only to the thickness of the thermal boundary layer (given by $\delta_T \sim \left(\Psi / \mathrm{Pe}^{1/2}\right) H$) at the location of the onset of solidification).

Finally, the effects of cooling on flow dynamics depend on the magnitude of the rheological changes. A surface layer is most simply characterized by a constant crust viscosity η_c and yield strength σ_c . These (taken with crust thickness) suffice to parameterize a more continuous variation with depth, but are crude approximations when the properties may vary with time or location on the surface. On the other hand, they lead to a better representation of the dynamics than does the use of a single apparent (bulk) flow viscosity η_F that increases with time as the flow enlarges. It can also be argued that the surface temperature of creeping flows is everywhere far below the solidification temperature so that the crust properties (but not crust thickness) will be roughly constant. The contrasts with the flow interior $\left(\eta_c / \eta \text{ and } \sigma_c / \sigma_0\right)$, along with crust thickness, will determine whether the crust remains passive or inhibits motion of the underlying fluid.

Creeping Flows with Cooling

Laboratory analog experiments serve to test the hypothesis that the primary effects of cooling and solidification for slow laminar flows are captured by Ψ , which can be seen as the ratio of the rate of lateral advection of fluid to the rate of solidification. The experiments used viscous polyethylene glycol (PEG) wax, which freezes at a convenient temperature of 18–19 °C, extruded from a small (or linear) vent under cold water onto a horizontal or sloping base. The cold water gave a suitable turbulent convective heat flux and solidification times comparable to horizontal advection times. The results revealed a sequence of flow regimes, and these correlated with intervals of Ψ. At Ψ <0.7, where cooling is rapid or extrusion is slow, the flow was fully encased in solid and spread through many small bulbous outgrowths reminiscent of submarine lava “pillows”; at $0.7 < \Psi < 2.5$ thick solid extended over most of the surface and formed rigid plates separated by divergent rifts, complete with transform faults, where solid continued to accrete onto the plates; at $2.5 < \Psi < 6$, solid became more widely distributed (except over the vent) but was thin and tended to buckle or fold, forming many small transverse ridges and ropy structures; at $6 < \Psi < 16$, crust was seen only around the margins of the flows, where it formed levees; and at $\Psi > 16$, no solid crust formed before the flow front reached the side walls of the container (the values of W given here are smaller, by a factor of $10^{2/3}$, than those originally reported because an incorrect value for the water viscosity was originally used). In addition, the flows ceased to spread when the source flux was turned off if $< \Psi 6$, indicating control by the strength of the solid. The forms of surface deformation and flow morphology observed are similar to some of the main characteristics found on basaltic (low-viscosity) lava flows and traditionally used to categorize them. In particular, they include submarine pillow basalts, submarine jumbled plates, and subaerial ropy and sheet pahoehoe flows.



(a) (b)

(c) (d)

The effect of a sloping base shifts the regime transitions to smaller values of Ψ and leads to a flow elongated down slope. The down-slope flow can be channelized by solidified edges in the levee and surface folding regimes, and it can form covered lava tubes at smaller Ψ . An identical sequence of flow regimes was found for PEG flows spreading from a line source (after allowing for appropriate redefinition of Ψ in terms of the flow rate per unit length of the vent; Fink & Griffiths) Thus the regimes of behavior are robust. However, experiments with different fluids are needed to test for possible dependence on material properties.

Figure shows examples of solidifying gravity currents showing four flow types in laboratory experiments with polyethylene glycol wax flowing over a horizontal floor. The Newtonian liquid was extruded from a small hole onto the base of a tank of cold water. Some of the surface subsequently solidified. (a) Pillow growth at $\Psi = 0.11$; (b) rifting flow with separating rigid surface plates at $\Psi = 2.7$; (c) folded flow at $\Psi = 3.0$; (d) largely axisymmetric flow with solid confined to levees along the flow front at $\Psi = 7.3$ [these values of Ψ have been corrected for a previous numerical mistake; all values reported by Fink & Griffiths must be divided by $10^{2/3}$].

Laboratory experiments have also been carried out with the spreading of a high-temperature corium melt (mainly hafnia, zirconia, silica, and wustite), which is similar to a melt that may be formed if a severe accident in a pressurized-water nuclear reactor leads to melting of the reactor core. In experiments designed to investigate the flow of corium over the floor of the reactor vessel, 17 kg of melt at 2200 K were released to flow under air. The surface of the material cooled by radiation and solidified rapidly, producing a thin thermal and rheological boundary layer. Folding produced a surface appearance similar to ropy pahoehoe lava, all the way from the flow margin to the source. The flow front stopped spreading after ~8 $_s$. unfortunately, values of Ψ cannot be obtained because surface cooling (by 300 K) had taken place before the melt left the source.

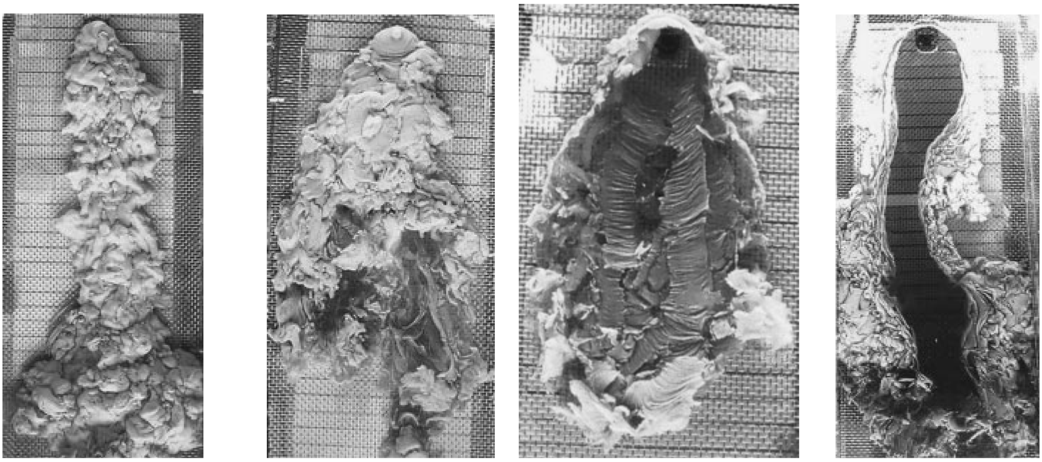
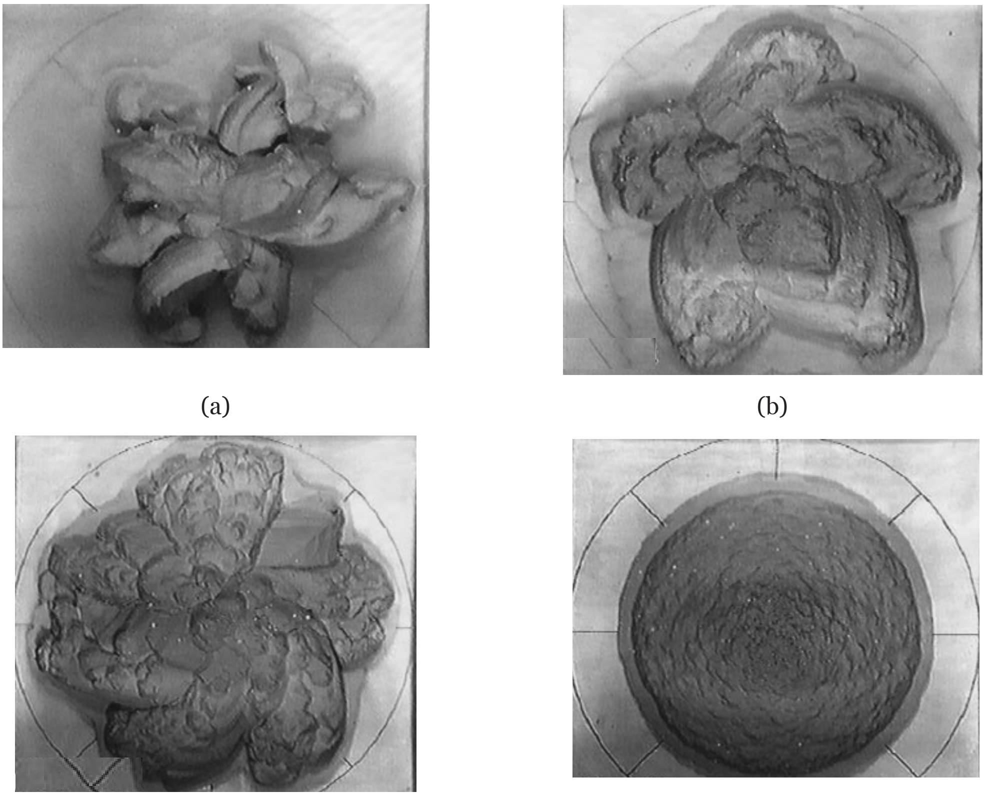

(a) (b) (c) (d)

Figure shows laboratory experiments with polyethylene glycol wax flowing from a small source on a planar slope under cold water. The base slopes downward to the right and is covered with mesh to make a rough floor. (a) Pillow flow, (b) rifting flow, (c) folded flow, (d) leveed flow.(c) and (d) are similar to ropy pahoehoe and long channelized flows observed in Hawaiian lava flows.

Experiments similar to the wax studies above but with a kaolin–PEG slurry, which has both a yield strength and the freezing temperature of the PEG, reveal a different sequence of morphologies. Hence the rheology of the interior fluid plays a role in controlling the forms of flow and deformation, even though the rate of solidification, expressed in Ψ_B, again determined which of the morphologies occurred. At $\Psi_B > 15$ (fast extrusion and slow cooling), the slurry spread axisymmetrically almost as if there were no cooling; at $0.9 < \Psi_B < 15$, there were strong rigid plates over most of the surface and later upward extrusion of ridges with smooth striated sides; at $0.12 < \Psi_B < 0.9$, the flow commenced as a set of four to six (most often five) radially moving lobes having a weak tendency to spiral. Under rapid cooling or very slow effusion, $\Psi_B < 0.12$, the lobes were more like vertical spines and were extruded upward from the vicinity of the source. In these experiments the transitions between regimes were more gradual than those for the viscous fluid. The morphologies strongly resemble qualitative characteristics of many highly silicic lava domes.



(a) (b)

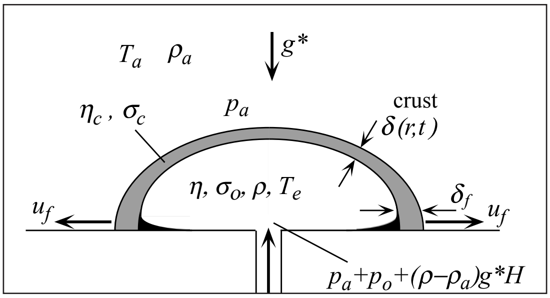
(c) (d)

Figure show solidifying flows of a Bingham fluid using a slurry of kaolin in polyethylene glycol. Apart from the fluid rheology, the experiments were similar to those of figure. (a) A spiny extrusion at $\Psi_B = 0.09$, (b) a lobate extrusion showing a typical 5-lobe pattern at $\eta_A \sim= 0.79$, (c) a flow without distinct lobes but surfaced by solid plates with curving segments, $\Psi_B = 1.3$, (d) an axisymmetric flow almost unaffected by cooling at $\Psi_B =30$.

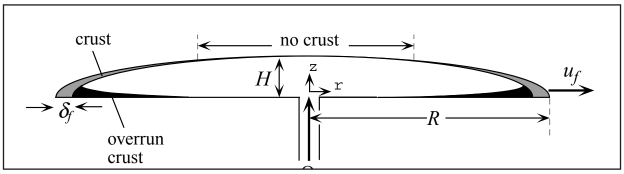
There has been no adequate theoretical description of the above cooling and solidifying flows or of the various instabilities that lead to asymmetric spreading and irregular structure. Only a gravitational instability in a density-stratified lava dome and the surface buckling instability have been ilometr. There is good quantitative agreement between the wavelengths of observed folds (on ropy pahoehoe and the laboratory wax flows) and that predicted for the buckling of layers of differing viscosity or yield strength subjected to a compressive stress.

Scaling relationships for the growth of solidifying flows in several dynamical regimes have been proposed based on a simplified two-component description. The flow is reduced to an isothermal and rheologically uniform interior (viscous or plastic) and a thin surface layer having different rheological properties—a larger viscosity or yield strength. The surface layer is viewed as largely solidified material (because the solid gives to the greatest rheological difference), and, therefore, it begins at a distance of ~d_s from the vent if the advection is fast enough, or it may completely encompass the flow if the volume flux is small. In addition, the surface layer thickness δ on each element of surface is assumed to increase approximately as $\delta \sim (kt)^{1/2}$, which translates to a changing thickness δ I with distance from the vent and an increasing crust thickness δ_f(t) at the flow front. Observation shows that the crust is highly fractured and blocky and therefore is ilometr as viscoplastic, with most of its influence on the flow arising from the thickest crust at the flow front.

The flow is driven by gravity (integrated force $F_B \sim \rho g H^2 R$) or overpressure (a pressure P_o in excess of the hydrostatic, giving $F_P \sim P_0 R^2$) and is retarded by both basal stress ($\rho Dw / Dt =$if Newtonian, $F_\sigma \sim \sigma_0 R^2$e if plastic) and crustal stresses ($F_{\eta c} \sim \eta_c \dot{\varepsilon} R \delta_f$ for a viscous crust and $F_B \sim \rho g H^2 R$for a plastic crust). The usual geometric relation $V \sim R^2 H$ is used to express continuity under the assumption of self-similarity while a flow is within a given regime. Volume is assumed to increase as $V \sim St^\alpha$. From these scalings, solutions can be found for various crustcontrolled asymptotic regimes, extending the previous solutions for homogeneous flows to cases in which the dominant balance is between buoyancy and crust viscosity, buoyancy and crust yield strength, or overpressure and any of the crustal or interior retarding forces. The conditions for transitions between regimes during flow can also be found.



Lava dome or pillow



Rapid, extensive lava flow

A two-component model for cooling lava flows at small Re. Scaling analysis of the force balances in this model provides predictions for the spreading of flows from point and line sources.

The balance of buoyancy with the yield strength of the crust gives:

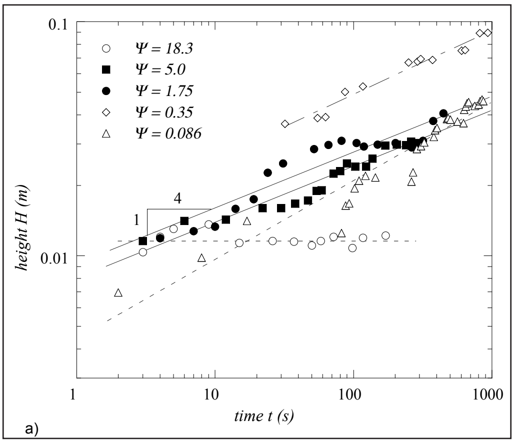
$$R \sim \left(\sigma_c / \rho g\right)^{-1/4} k^{-1/8} S^{1/2} t^{(4\alpha-1)8}, \; H \sim \left[\left(\sigma_c / \rho g\right)^{2\alpha} k^{\alpha} S^{-1} R^{2}\right]^{1/(4\alpha-1)},$$

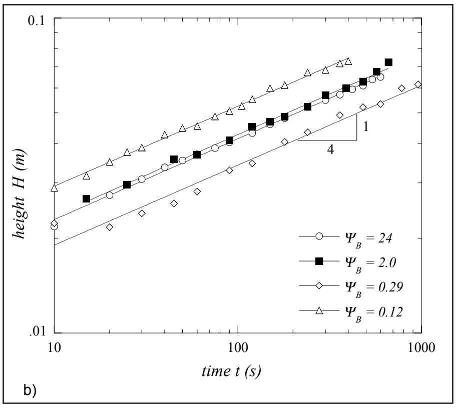
and

$$H \sim \left(\sigma_c / \rho g\right)^{1/2} \left(kt\right)^{1/4}.$$

In both this model and the uniform plastic flow (Equation $R \approx 0.65\left(\sigma_0 / \rho g\right)^{-1/5} S^{2/5} t^{2\alpha/5,}$ $H \approx 1.4\left(\sigma_0 / \rho g\right)^{2/5} S^{1/5} t^{\alpha/5}$ and $H \approx 1.76\left(\sigma_0 R / \rho g\right)^{1/2}$), the height increases with time. This contrasts with a dominant viscous crust or viscous interior, for which the height is constant (for constant volume flux) or decreases (for α , 1). Of greater interest is the result that the flow height in above equation is independent of both internal properties (η and σ_0) and source flux (S and α), whereas, for constant-volume fluxes, isothermal viscous flows have a height increasing with volume flux: $H \sim Q^{1/4}$ and isothermal plastic domes have $H \sim (Qt)^{1/5}$, where $Q = S$ (α = 1). The absence of Q in above equation follows from the fact that a smaller-volume flux allows greater time for cooling and formation of thicker crust, which inhibits lateral flow more and gives a flow depth as great as that for larger-volume fluxes. This important result is also illustrated by the variation of height H with overall radius R; for various models with α = 1, isothermal viscous flow has $H \sim Q^{1/4}$, viscous crust control gives $H \sim Q^{1/7}$, both independent of R, whereas crust strength control gives the inverse variation with volume flux $H \sim Q^{-1/3}R^{2/3}$. Thus a larger-volume flux creates a deeper flow for the purely viscous case but a shallower flow for a strong crust. The difference is again the result of a shorter time available for cooling at larger-volume flux, which implies a thinner crust and less inhibition of spreading. Likewise, slower cooling gives a smaller flow depth.

The experiments of confirmed this behavior for solidifying wax flows, the results being consistent with the viscous solutions for $\Psi > 20$ (where there is little or no solid crust), but consistent with the opposite trend (previous equation) for $\Psi < 6$ (where crust is obvious). Similarly, the experiments with slurries confirmed that previous equation applied to solidifying flows having an interior yield stress, despite the different morphologies. Other experimental results with corn syrup spreading under cold water, in which cooling produced an increase in viscosity but no solidification or yield strength, have been ilometr in terms of a single value of an apparent (bulk) flow viscosity η_B over the period of observation of the spreading flow (for which the thermal boundary layer was thin). This is in effect a time-averaged form of the flow viscosity η_F and, as in Huppert et al, was defined as the viscosity necessary to fit the form to the measured *R(t)*. This global viscosity coefficient was found to depend on Pe and the ratio of $\eta_c / \eta_{e,} / \eta_c$ being the viscosity at the vent. The result was shown to be consistent with the similarity solution for flow with a cooling viscous boundary layer and the simpler relation $\eta_B \sim \eta_{e,} \mathrm{Pe}^{-4/7}$.





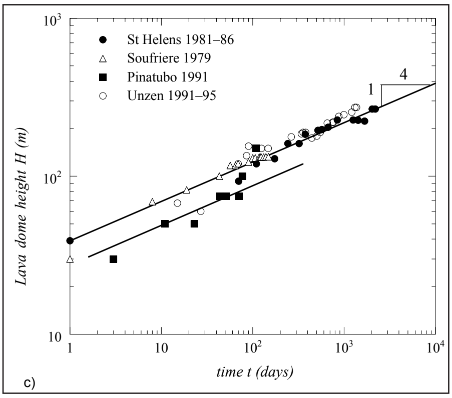


Figure shows data for the growth of dome height with time in (a) experiments with solidifying polyethylene glycol (PEG) wax and a source of constant volume flux, (b) experiments with solidifying kaolin/PEG slurry having a yield stress, solidification temperature of 178C, and constant volume flux, (c) four lava domes that grew on La Soufrie`re, In (a) an experiment with no cooling is included (the run having constant H), the run at the smallest Ψ shows effects of overpressure (broken line, $H \sim t^{1/3}$) and the run having $\bar{\eta} = 0.35$ gives $H \sim t^{0.27}$. Solid lines have slope ¼. Variability tends to be large under the intermediate conditions. In (b) the flow with largest Ψ_B had solid only at its margins; that with smallest WB was encapsulated in thick solid and grew through upward spines. The height in these experiments had a trend consistent with the ¼-power, but there was unexplained scatter in the absolute height and radius at small Ψ_B (possible causes include solid strengths differing between batches of slurry or with ambient water temperatures and the effects of instabilities). In (c) data for the Unzen dome were supplied by S. Nakada and are presented here for the first time—they lie slightly above the straight line fitted previously to the Soufrie`re and Mt. St. Helens data; data for the other domes are from. The height shown for the Unzen dome, which grew on a slope, is the difference between the highest and lowest reaches of the dome. The four lava domes, the laboratory Bingham domes, and flows of viscous wax having a moderate spreading rate ($0.2 < \Psi < 6$) all evolved in a way consistent with equation $H \sim \left(\sigma_c / \rho g\right)^{1/2} \left(kt\right)^{1/4}$ in the text.

Comparison of the theoretical scaling with the few available measurements for active lava domes is very useful. Data from four lava domes give the heights, widths, and volumes as functions of time. These can be used to evaluate the exponent α in each case from the volume estimates. The data from Mt. Unzen, whose lobate dome eruption was described by is presented here for the first time. For the values of α so obtained, the predicted trends of dome radius with time given by the various models are not greatly different. However, the models of spreading controlled by the yield strength of a developing crust compare most ilometres with the data. The predicted trends for dome height with time (or radius) in the various asymptotic regimes are more clearly different and allow a more definite conclusion about which of the models best describes the data. For flow dominated by basal viscous stresses we predict a height decrease with time in each case (except for the first 20 days of growth of the Soufrière dome), whereas the measured dome heights increased. Hence the viscous models are discounted (unless the crust near the flow front is characterized by an apparent viscosity that increases with time). On the other hand, the model of flow controlled by crustal-yield strength is in good agreement with the data, and the best agreement is with the buoyancy-crust strength balance: The predicted $H \sim t^{1/4}$ relations provides a reasonable fit for all four lava domes.

Given the good agreement between the scaling analysis and trend of the data in figure, equation $H \sim \left(\sigma_c / \rho g\right)^{1/2} \left(kt\right)^{1/4}$ is readily applied to evaluate the crustal yield strengths for real lava domes, giving $\sigma_c \sim 1.3\times10^8$ Pa for Mt. St. Helens (70 < t < 2200 days after commencement of dome growth), 1.5 × 10^8 Pa for Soufrire and 0.9 × 10^8 Pa for the Pinatubo dome. For Mt. Unzen dome (15 < t < 1373 days), we find σ_0 ~ 1.6 × 10^8 Pa. These four strengths are remarkably similar given the different dome compositions, basal topography, extrusion rates, eruption durations, and dome morphologies. They may therefore reflect a maximum yield strength achieved by a fractured, jumbled carapace of solidified lava relatively close to the ambient atmospheric temperature. Note that the strength estimate does not require measurements sufficient to estimate the dome volume or exponent α.

The internal lava yield stress has also been estimated by applying the isothermal Bingham model to the first 20 days of growth of the Soufrière dome and measurements of the dimensions of a small lobe that grew (over a period of 160 minutes) on the Mt. St. Helens dome: the values are σ_0 ~ 2.8 × 10^5 Pa and 1.1 × 10^5 Pa, which are similar to the estimate σ_0 ~ 2.6 × 10^5 Pa obtained by applying the same model to the Soufrie`re dome at times t > 40 days. An independent but less direct estimate of the internal strength of a number of domes is based on classifying each dome by its dominant qualitative morphology and applying the laboratory relationship between morphology and Ψ_B to evaluate Ψ_B . The resulting Ψ_B , taken in conjunction with an estimate of the volume flux and the calculated solidification time t_s for each dome, were then used in Equation $\Psi_B = (\rho g / \sigma_0)^3 Q t_s$. to obtain σ_0 . For all of the 14 cases considered, $R \approx\sim$ (0.5–5) × 10^5 Pa. The consistency between these different estimates of internal strength lends weight to the hypothesis that the internal yield stress influences the flow instabilities and morphology found in lava domes, whereas the height and overall spreading are controlled by the crust. The estimates also give σ_c / σ_0 ~ 10^3. With this strength a crust thickness as small as $R \approx>$ 10^{-3} R (e.g. 1 m in 1000 m) is required for the crust strength to dominate.

Long Lava Flows

Turning to long basalt flows that extend for many ilometres from their vent, the flow behavior again reflects, albeit in ways that remain poorly understood, differing vent fluxes, eruption duration, underlying topography, and whether they flow under air or water. Field evidence indicates that surface cooling leads to the formation of a glassy crust, whereas internal mixing can cause disruption or entrainment of this crust, cooling, and rheological changes in the interior. Development of side levees removes mass from the advancing flow front and represents formation of a flow-defined channel. In some circumstances, cooling produces such a strong crust that it forms a rigid connected roof beneath which rapid, thermally insulated flow continues in a lava tube. There are so many processes involved that, in past attempts to model these flows, some of them are approximated by empirical parameterizations. A key factor that has proved particularly difficult to model in a predictive manner is the effect of cooling, which depends on the amount and rate of disruption, of cooled surface crust. The disruption of crust has been described in terms of an empirical fraction of the surface representing exposed incandescent fluid from the flow interior. This fraction has been expressed as a function of the mean flow velocity but awaits a theoretical model. The aim is again to predict factors such as the rate of cooling with distance downstream, flow thickness, the speed of advance of the flow front, changes in flow regime, and the final length of a flow. Given the complexities of long lava flows, simple theoretical results and complex parameterized computational models are both valuable. Arguably, they lend more understanding than do computational simulations with primitive equations but finite spatial resolution. However, there is a need to remove empirical approximations from models, replacing them with parameterizations based on testable and predictive physical models of the relevant processes.

Many of the processes and studies mentioned above in the context of creeping flows are equally relevant to long flows, so long as these are slow, as for \`a\`a or shallow breakouts from the main channel or flow front. Most models of large basalt flows, on the other hand, have taken a different approach and assumed vertically uniform temperature within the flow, in some cases including a thin crust that offers thermal insulation and appears in the model heat equation but has no mechanical influence in the momentum equations. They also assume flow down a prescribed channel.

For a thermally mixed flow having no temperature or velocity variations with depth, a control-volume formulation for the local temperature *T(x,t)* gives:

$$DT/Dt = \left(L/c_p\right) d\phi/dt - F_s/\rho c_P h,$$

where *h(x, t)* is the local flow depth. The rate of latent heat release is small (generally < 1 % of the surface flux). The surface heat loss F_s is largely radiative, and has been expressed in terms of the internal temperature T (as opposed to the surface temperature T_c) as $F_s = e\sum fT^4$, where f is an effective fraction of the surface over which high-temperature incandescent lava is exposed. Hence the characteristic timescale for cooling is $\Gamma = \left(\rho c_p \mathrm{H}\right)/\left(e\sum fT_e^3\right)$. If we further assume no variation in along-stream velocity U and a constant mass flux q per unit width, above equation reduces to the simple form,

$$\partial u/\partial z \sim O\left(H/L\right)$$

which has the solution $T\left(x\right)T_e = \left[\left(3/\mathrm{U}\Gamma\right)x + 1\right]^{1/3}$, or $\mathrm{T} \sim x^{-1/3}$ at large x. The timescale Γ (with f = 1) is on the order of 1 day, whereas observed flow emplacement times are only 1- to 10-fold longer. This comparison is evidence that Γ is a relevant timescale and that emplacement times are limited by cooling rather than vent supply duration. Observed values of f (~0.001–0.1) imply larger values of Γ. However, the temperature need only decrease from $T_e \approx 1150$ °C to ~1100 °C before the crystallinity reaches the critical value of ~45% for onset of a yield strength and ; 50%–60% for cessation of flow. This amount of cooling requires only a small fraction of the time ∂t. A more detailed thermal model allows for heat loss from the low-temperature crust covering a fraction 1-*f* of the surface and conductive cooling at the base. In the limit f =- 0, the flow interior is completely insulated by a conductive crust, and Γ is replaced by a much longer timescale based on the heat flux from a relatively low surface temperature.

Thermal models have been linked to the dynamic by assuming steady, hydrostatic, two-dimensional motion (i.e. a prescribed channel of uniform width and slope, with no cross-channel variations) and neglecting the pressure gradients owing to the gradient of flow depth *dh/dx* relative to those caused by the topographic slope β (i.e. $H/L \ll \sin \beta$). The application of a Bingham flow law to motion along the down-slope channel yields.

$$u(x.y) = \left[(\rho g \sin \beta)/2\eta\right] z(2h - z) - 2\sigma_0 z, \quad 0 < z < h - h_s$$

$$\left[(\rho g \sin \beta)/2\eta\right] h^2 (1 - \sigma_0 / \sigma_b)^2, \; h - h_s < z < h,$$

where $\eta\,(x)$ is the plastic viscosity as before, $\sigma_b\,(x) = \rho g \sin \beta$ is the shear stress at the base of the flow, and $h_s(x)$ is the critical depth. The latter represents the thickness of the undeformed plug at the top of the flow, in which the shear stress is less than $\sigma_o(x)$. Expressions such as Equations $\eta_A(T,\phi) = \eta_0 (1\text{-}\ \phi/\phi_{\max})^{-2.5}\ e^{\gamma(To-T)}$ and $\phi(x) = \phi_0 + \phi_f (T_0 - T)(T_0 - T_{sol})$ relate the viscosity and yield strength to temperature and crystallinity. Cooling causes the apparent viscosity $\eta_a = \eta + \sigma_0 / \dot{\varepsilon}$ to increase downstream, in turn causing the velocity to decrease and the flow to deepen with distance downstream. The model flows attain a very large apparent viscosity (especially with the onset of yield strength) at some distance from the vent and effectively come to a halt with a very large flow thickness. The flow depth near the vent is greater than h_s but eventually becomes equal to h_s as the critical depth increases downstream. Comparison with sparse available data from lava flows shows qualitative agreement, with flows cooling and slowing at distances 10^2 to 10^4 m from the vent, and predicted advection times of hours to days for realistic volume fluxes and rheological parameter values. The behavior, particularly the flow depth downstream, is very sensitive to volume flux. As found in the scaling for laminar flows, the flow thickness can be larger for smaller-volume fluxes, a consequence of the effects of smaller advection velocity relative to the rate of cooling. The results are also sensitive to the assumption of either efficient vertical mixing or thermal stratification.

Although the available models capture the gross features of long channelized flows, there are many factors yet to be included. The control-volume formulations are not time-dependent, so they do not indicate that subsequent volumes from a steady eruption come to a halt at different distances from the vent, and changes in eruption rate are not allowed for. Hence these models do not allow a full investigation of flow front advance or of the effect of cooling relative to the effect of erupted volume. The thin flow approximation also cannot capture processes occurring near the flow margins, where the depth variation $dh/dx > \sin\beta$. Importantly, long cooling flows without a prescribed channel have not received much theoretical attention. In this case flow may spread across slope, form levees, or branch (as in numerical experiments with complex distributary systems.

Excellent qualitative results relevant to long lava flows are obtained from the laboratory analog experiments for cooling flows on a horizontal base and on planar slopes. Results obtained with freezing PEG wax on a slope show that four characteristic regimes occur, as on a horizontal base, but with down-slope elongation and channelization. The regimes again appear to be delineated by ranges of the dimensionless solidification time (or advection speed) Ψ , with an added dependence on slope angle.

In these experiments the solidifying flow determines its own channel width, the width may vary with distance downstream and with time, and the mass flux decreases with distance down the channel as a result of continuous levee building, branching, or roof construction. These are laminar flows. Conditions for the disruption and mixing of surface crust under stresses imposed by the underlying flow and conditions for stable crust are not known for either laminar or turbulent flows, yet they determine the distance down channel at which vertically mixed flow gives way to the onset of a thickening surface layer and stratified flow. Also remaining unpredicted are the mechanical and thermal conditions required for formation of lava tubes

Flows with Melting of the Base

Thermal erosion caused by melting of underlying sediments or rock by basaltic lava flows has been investigated as the cause of sinuous rilles observed on the moon. Similar erosion by much hotter (> 1400 °C) and very low-viscosity (0.1- to 10-Pa) komatiite lavas has been invoked to explain channels and embayments beneath terrestrial komatiite flows. Rich Fe-Ni-Cu ilometr deposits are found at the foot of the latter embayments and are thought to have formed by thermal erosion of ilomet-rich rocks by metal-rich lavas, followed by the segregation and accumulation of dense immiscible metal ilometr melts. Theoretical ilometre by Huppert et al, Huppert & Sparks, and Turner et al has suggested that komatiites erupted and flowed for large distances as turbulent currents, had high cooling rates under seawater, and could have produced thermal erosion 10–100 km from their sources. The extent of melting may have led to significant contamination of the flow by the assimilated melt. Huppert ilometr the time-dependence to show that there will always be some initial solidification at the cool boundary (if T_s is greater than the initial boundary temperature), followed by a remelting phase and then melting of the original boundary (if the flow is hotter than the boundary melting temperature). The geometry of erosion channels has been addressed by Jarvis and predicted to involve undercutting of the edges. Mathematical ilometre by Williams et al indicates that erosion is strongly dependent on the nature of the base material, with hydrous sediment being fluidized by vaporized seawater and strongly eroded, whereas relatively little erosion is predicted to occur for consolidated anhydrous sediment.

The modeling involves solution of a heat equation similar to equation $DT / Dt = \left(L / c_p\right) d\phi / dt - F_s / \rho c_P h,$ but having two additional terms to account for the turbulent heat flux to the base and the heat required to raise melted substrate to the lava temperature. The surface flux term is replaced by the turbulent flux at the bottom of a solid crust, where the steady-state crust temperature is given by an independent relation equating the turbulent heat flux into the crust from the interior lava to the surface heat loss through buoyancy-driven convection in the overlying water. The steady-state crust thickness is then found by equating the conductive flux through the crust to the convective flux into the water. The crust provides good insulation to the flowing lava. The steady-state thermal erosion rate u_m into the substrate is given by equating heat fluxes at the melting interface:

$$u_m = \mathrm{C}_T \left(T - T_m\right) / E_m$$

where C_T is the turbulent heat transfer coefficient in the lava, T is the lava temperature, T_m is the melting temperature of the ground, and E_m is the energy (per unit volume) required to melt the ground. The flow velocity in this two-dimensional control-volume formulation for moderate to large Re is simply u = 2 $L = -\mathrm{In}\left|1 - H^2\right|$, where g is the reduced gravity and C_D (Re) is a suitable friction coefficient.

The calculations indicate that submarine komatiite lava, erupted at its liquidus temperature and initially 10 m thick, could have flowed hundreds of ilometres from its source, a result consistent with field observations. If the eruption durations were < 2 weeks, only small extents of thermal erosion (on the order of meters) are likely to have occurred. However, this model is based on the questionable assumption that a solid crust is able to form at the lava-water interface despite agitation by the underlying turbulent flow. No models have taken into account the potentially large effects on heat transfer of a more viscous melt boundary layer or morphological instabilities on the melting boundary, and the value of the heat transfer coefficient from the lava to the base is very uncertain owing to a number of such boundary-related effects. The model could potentially be applied to the somewhat cooler basaltic sheet flows that are found to be ~ 100 km long on the present sea floor and to submarine flood basalt flows. On land, the cooler and much smaller flows of channelized basalt on Hawaii show clear evidence for thermal erosion by melting of the underlying rocks. On the other hand, field observations of long flows indicate that well-insulated flow in lava tubes or inflated sheets capped by crust provides a mechanism for long-distance travel of small-to-moderate volume fluxes without significant cooling. This appears to rule out the requirement of very high eruption rates previously postulated for flood basalts and calls into question the occurrence of fully turbulent flows. The field observations also highlight the need for models of flows at transitional Reynolds numbers and transitional thermal regimes.

Types of Lava Flows

Lava flow is a surficial outpouring of molten rocks. The same name is also given to already solidified rock bodies that formed as molten or semi-molten flows of rocky material. Lava flows are the most common volcanic feature on Earth. They cover roughly 70% of the Earth and are also very common on other terrestrial planets, covering 90% of Venus and 50% of Mars.

1. Red hot basaltic lava flow. Hawaii. 2. Blocky lava. La Palma. 3. Slowly solidifying pahoehoe lava flow. Hawaii. 4. Pillow lava. Iceland. 5. Transition from smooth pahoehoe to rubbly aa. Hawaii. 6. Columnar lava. Northern Ireland.

Lava flows are very common features on planet Earth although the vast majority of them are hidden from us in the deep ocean basins. The lava type associated with submarine volcanism – pillow lava, is therefore underrepresented where ordinary people have a chance to see it.

The most common way to divide lava flows into distinct types is following: Pahoehoe lava flow, Aa lava flow, Blocky lava flow, and also Pillow lava flow. Sometimes Turbulent lava flow is also added, but the latter is only of theoretical interest to scientist because we will not see that type of lava flow in the nature.

Lava surface is cooling very rapidly. The temperature of glowing lava is at least 475 °C. Bright yellow is hotter (over 1000 °C) and orange cooler (800-900 °C). Dull red colors indicates a temperature in the range of 600-700 °C. Lava surface may cool from bright yellow to dull red within minutes. Pu'u O'o vent, Kilauea volcano.

Turbulent lava flows may have been present billions of years ago when the interior of the Earth and consequently lava flows as well were significantly hotter and the composition of lava was less siliceous. That enabled the lava to flow more easily and turbulently. The most common subaerial lava flows today are pahoehoe, aa, and blocky lavas.

Pahoehoe Lava

Pahoehoe is a smooth and continuous lava crust. Pahoehoe forms when the effusion rate is low and consequently the velocity of lava flow is slow. Pahoehoe lava flow is usually at least 10 times slower than typical aa lava flow. Higher effusion rate results in lava flow being shattered which is how the rubbly and clinkery aa lava surface forms. Pahoehoe and aa lava are strikingly different in appearance, but their composition may be identical or very similar. Lava flow that was originally pahoehoe may transform into aa lava but the reverse is impossible — once lava crust is broken it cannot return back to smooth and continuous form.

Only low-viscosity (usually basaltic) lava can form pahoehoe. Aa lava is much more common and is not as picky about the composition of lava flow. Aa lava can be basaltic, andesitic, tephritic, etc. Blocky lava needs more felsic compositions (silica content generally over 55%). Blocky lava is composed of larger blocks than aa lava and these blocks have much smoother surface.

Best known examples of pahoehoe lava flows are from the Big Island of Hawaii and the term 'pahoehoe' itself (just as 'aa') originates from the Hawaiian language.

Pahoehoe is also known as ropy lava and it has several more varieties named entrail, festooned, filamented, sharkskin, shelly, etc.

Forming basaltic pahoehoe lava flow in Hawaii. Such lava flows move slowly and are not overly dangerous when compared with some other volcanic phenomena.

However, their destructive power is practically unstoppable. You can easily walk away from a lava flow like that in most cases, but you will not be able to save your house if it happens to be on the way of such a slow-moving disaster. Here is all that is left of a house engulfed by a pahoehoe lava flow. Although it is possible to predict which regions are in danger of being covered by lava flows, people, if allowed, stubbornly continue to build their houses in these districts. Destruction that inevitably follows keeps the attention of public focused on these flows and provides money for scientists studying them.

Hawaiian lava from the Kilauea volcano (Pu'u O'o vent).

Lava flows are often imagined as fiery rivers of molten rock. That is indeed often the case, but it is also very common that there is no easily defined boundary of an active lava flow. The lava often flows largely underground.

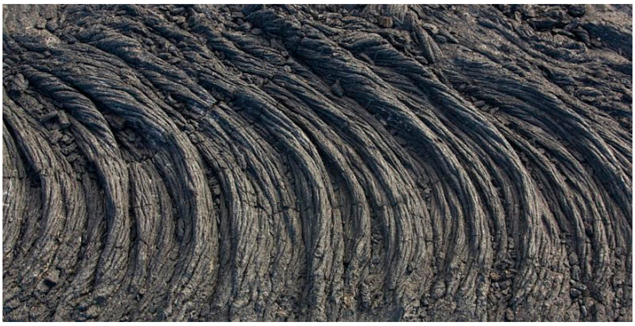
This is potentially very dangerous situation not so much because of lava itself because it moves slowly and contrary to popular belief it is impossible to sink into it. But because of toxic volcanic gases that are involved with all types of lava flows. I tried to be very careful, trying to observe the flows so that the wind was blowing the gas away from me. Here is a picture of volcanic gas seeping out from the ground. If you are also trying to find flowing lava, always try to keep a safe distance with such a thick cocktail of hazardous gases and pay attention to the wind direction.

Pahoehoe lava flows form a beautiful and otherworldly barren landscape in southern part of Hawai’i.

Walking on a pahoehoe lava flow is relatively easy, especially when compared with walking on an aa-type lava flow which is practically impossible undertaking. However, hiking on a smooth lava surface is not without some nasty surprises. As mentioned earlier, lava crust solidifies quickly, but the interior keeps moving which often leaves empty space beneath the thin surface. It can easily break when you step on it which may result in badly scratched legs because the edges of a broken lava flow are razor sharp. Or even worse, you might have a broken leg which understandably is a major problem if you are miles away from nearest roads. Through practice hikers will learn relatively quickly where it is safer to step and where it pays to be extra careful.

Generally speaking, smaller lava lobes are safer and larger gently sloping, but otherwise relatively smooth parts are the most dangerous ones.

This image shows also that voids in lava flows are a common feature. Such a long tunnel-like caves are called lava tunnels. Large amount of lava can move through these tunnels which make it easier for a volcano to grow itself laterally larger. This is a Thurston lava tunnel in Hawaii. Lava tunnels are especially common within silica-poor basaltic lavas.



This lava flow formed on La Palma, Canary Islands during the eruption of Cumbre Vieja rift in 1949 (Hoyo del Banco vent). Examples like that can be also described as ropy lava which is a subtype of pahoehoe. The wrinkled surface of ropy lava is a result of the interior of the lava flow moving more quickly than the exterior.

The formation process of basaltic ropy pahoehoe lava.

Coulée is a volcanic landform which is an intermadiate stage between lava dome and lava flow. The lava that forms coulée is too thick to flow like a normal lava flow. However, it may resemble huge pahoehoe flow (this coulée is more than 50 meters wide) when gravity forces it to flow downhill just a little and the slightly more easily flowing interior warps the surface just like it does in a ropy pahoehoe flow. Light-colored mound in the foreground is composed of pumiceous lapilli. Picture taken in Tenerife, Canary Islands.

Aa Lava

Aa lava is a rough rubbly crust of a lava flow. It is a major lava flow type. Other important subaerial lava flow types are pahoehoe and blocky lava.

Here you can see both smooth pahoehoe and irregular aa lava types. Hawaii.

Aa and pahoehoe are terms that were brought to geological terminology from the Hawaiian language. Aa is according to native Hawaiians a sound one makes if he or she tries to walk barefoot on such a lava flow. There are different spelling versions, ‘a’a, a’a, a-aa are used as well as simple aa. Pahoehoe means in Hawaiian “on which one can walk”.

This beautiful cascade of lava in Hawaii is largely composed of pahoehoe type lava flow, but in the left-hand side some lava tongues have broken to form aa instead of pahoehoe.

Walking on it is very slow and potentially dangerous even if one has good hiking boots. It is such a miserable experience because the uppermost part of aa lava is composed of loose clinkery unstable blocks. You can never be sure that the rocks you are stepping on do not move. They often do. This means that ground beneath your feet is unstable and you may easily lose balance. It is no good if that happens because the edges of fresh aa lava rubble may be very sharp. Sometimes aa lava blocks are so big that one has to climb over them. It makes moving progress very slow and bare hands will get scratched for sure.

Pahoehoe lava flow in the center that have partially covered the aa-type flow in Hawaii.

One thing that in my opinion is often poorly understood is the fact that aa and pahoehoe are terms that only describe the upper part of a lava flow. It is more correct to say that aa lava is a type of lava flow crust, not lava flow itself. Both aa lava and pahoehoe are usually massive beneath the crust which may be smooth (pahoehoe) or rubbly (aa). Massive part usually contains vesicles (gas bubbles) which will fill with secondary minerals like zeolites in older lava flows. This process takes considerable time and requires low-temperature hydrothermal alteration. There are no amygdules (vesicle filling mineral masses) in historic lava flows.

Lava flow formed in 1949 on La Palma in the foreground. It is almost completely aa lava. Pahoehoe forms only small part of it.

Aa lava is more common than pahoehoe. Special conditions are needed for pahoehoe to form: lava with low viscosity (high temperature, low silica content), low effusion rate, and gentle slope. Aa lava is free of such restrictions and therefore forms instead of pahoehoe if the conditions are not right. It is usually the speed of advancing lava flow that determines whether aa or pahoehoe forms and that depends on the effusion rate and steepness of the slope. It has been shown that flow rates exceeding 5-10 m^3/s clearly favors the formation of aa lava over pahoehoe on Hawaii. Once aa lava is formed it never reverts back to smooth pahoehoe form.

Aa lava in the foreground near the western coast of La Palma, Canary Islands.

Aa lava and The Atlantic Ocean near the southern tip of La Palma.

Pyroclastic Flow

A pyroclastic flow (also known as a pyroclastic density current or a pyroclastic cloud) is a fast-moving current of hot gas and volcanic matter (collectively known as tephra) that moves away from a volcano about 100 km/h (62 mph) on average but is capable of reaching speeds up to 700 km/h (430 mph). The gases can reach temperatures of about 1,000 °C (1,830 °F).

Pyroclastic flows sweep down the flanks of Mayon Volcano, Philippines, in 1984.

Pyroclastic flows are a common and devastating result of certain explosive eruptions; they normally touch the ground and hurtle downhill, or spread laterally under gravity. Their speed depends upon the density of the current, the volcanic output rate, and the gradient of the slope.

Rocks from the Bishop tuff, uncompressed with pumice (on left); compressed with fiamme (on right).

The word *pyroclast* is derived from the Greek πῦρ, meaning "fire", and κλαστός, meaning "broken in pieces".A name for pyroclastic flows which glow red in the dark is *nuée ardente* (French, "burning cloud"); this was first used to describe the disastrous 1902 eruption of Mount Pelée on Martinique.

Pyroclastic flows that contain a much higher proportion of gas to rock are known as "fully dilute pyroclastic density currents" or pyroclastic surges. The lower density sometimes allows them to flow over higher topographic features or water such as ridges, hills, rivers and seas. They may also contain steam, water and rock at less than 250 °C (482 °F); these are called "cold" compared with other flows, although the temperature is still lethally high. Cold pyroclastic surges can occur when the eruption is from a vent under a shallow lake or the sea. Fronts of some pyroclastic density currents are fully dilute; for example, during the eruption of Mount Pelée in 1902, a fully dilute current overwhelmed the city of Saint-Pierre and killed nearly 30,000 people.

A pyroclastic flow is a type of gravity current; in scientific literature they are sometimes abbreviated to PDC (pyroclastic density current).

Causes

There are several mechanisms that can produce a pyroclastic flow:

- *Fountain collapse* of an eruption column from a Plinian eruption (e.g. Mount Vesuvius' destruction of Herculaneum and Pompeii). In such an eruption, the material forcefully ejected from the vent heats the surrounding air and the turbulent mixture rises, through convection, for many kilometers. If the erupted jet is unable to heat the surrounding air sufficiently, convection currents will not be strong enough to carry the plume upwards and it falls, flowing down the flanks of the volcano.
- *Fountain collapse* of an eruption column associated with a Vulcanian eruption (e.g., Montserrat's Soufrière Hills volcano has generated many of these deadly

pyroclastic flows and surges). The gas and projectiles create a cloud that is denser than the surrounding air and becomes a pyroclastic flow.

- Frothing at the mouth of the vent during degassing of the erupted lava. This can lead to the production of a rock called ignimbrite. This occurred during the eruption of Novarupta in 1912.
- Gravitational collapse of a lava dome or spine, with subsequent avalanches and flows down a steep slope (e.g., Montserrat's Soufrière Hills volcano, which caused nineteen deaths in 1997).
- The directional blast (or jet) when part of a volcano collapses or explodes (e.g., the eruption of Mount St. Helens in May 18, 1980). As distance from the volcano increases, this rapidly transforms into a gravity-driven current.

Size and Effects

Building remnant in Francisco Leon destroyed by pyroclastic surges and flows during eruption of El Chichon volcano in Mexico 1982. Reinforcement rods in concrete bent in the direction of the flow.

Flow volumes range from a few hundred cubic meters (yards) to more than 1,000 cubic kilometres (~240 cubic miles). Larger flows can travel for hundreds of kilometres (miles), although none on that scale has occurred for several hundred thousand years. Most pyroclastic flows are around 1 to 10 km^3 (about ¼ to 2½ cubic miles) and travel for several kilometres. Flows usually consist of two parts: the *basal flow* hugs the ground and contains larger, coarse boulders and rock fragments, while an extremely hot ash plume lofts above it because of the turbulence between the flow and the overlying air, admixing and heating cold atmospheric air causing expansion and convection.

A scientist examines pumice blocks at the edge of a pyroclastic flow deposit from Mount St. Helens.

The kinetic energy of the moving cloud will flatten trees and buildings in its path. The hot gases and high speed make them particularly lethal, as they will incinerate living organisms instantaneously or turn them into carbonized fossils:

- The cities of Pompeii and Herculaneum, Italy, for example, were engulfed by pyroclastic surges on August 24, 79 AD with many lives lost.
- The 1902 eruption of Mount Pelée destroyed the Martinique town of St. Pierre. Despite signs of impending eruption, the government deemed St. Pierre safe due to hills and valleys between it and the volcano, but the pyroclastic flow charred almost the entirety of the city, killing all but two of its 30,000 residents.
- A pyroclastic surge killed volcanologists Harry Glicken and Katia and Maurice Krafft and 40 other people on Mount Unzen, in Japan, on June 3, 1991. The surge started as a pyroclastic flow and the more energised surge climbed a spur on which the Kraffts and the others were standing; it engulfed them, and the corpses were covered with about 5 mm (0.2 in) of ash.
- On 25 June, 1997 a pyroclastic flow travelled down Mosquito Ghaut on the Caribbean island of Montserrat. A large, highly energized pyroclastic surge developed. This flow could not be restrained by the Ghaut and spilled out of it, killing 19 people who were in the Streatham village area (which was officially evacuated). Several others in the area suffered severe burns.

The casts of some victims in the so-called “Garden of the Fugitives”, Pompeii.

Interaction with Water

Testimonial evidence from the 1883 eruption of Krakatoa, supported by experimental evidence, shows that pyroclastic flows can cross significant bodies of water. However, that might be a pyroclastic surge, not flow, because the density of gravity current means it cannot move across the surface of water. One flow reached the Sumatran coast as much as 48 km (30 mi) away.

When the reconstructed pyroclastic flow (stream of mostly hot ash with varying densities) hit the water, two things happened: the heavier material fell into the water, precipitating out from the pyroclastic flow and into the liquid; the temperature of the ash caused the water to evaporate, propelling the pyroclastic flow (now only consisting of the lighter material) along on a bed of steam at an even faster pace than before.

During some phases of the Soufriere Hills volcano on Montserrat, pyroclastic flows were filmed about 1 km (0.6 mi) offshore. These show the water boiling as the flow passed over it. The flows eventually built a delta, which covered about 1 km^2 (250 acres).

A pyroclastic flow can interact with a body of water to form a large amount of mud, which can then continue to flow downhill as a lahar. This is one of several mechanisms that can create a lahar.

On the Moon

In 1963, NASA astronomer Winifred Cameron proposed that the lunar equivalent of terrestrial pyroclastic flows may have formed sinuous rilles on the Moon. In a lunar volcanic eruption, a pyroclastic cloud would follow local relief, resulting in an often sinuous track. The Moon's Schröter's Valley offers one example

Ash and Pumice Falls

Just as dissolved gas bubbles out of a fizzy drink when it is opened, so gas dissolved in magma escapes when pressure is released as it reaches the surface.

If the magma contains a lot of dissolved gases, then it will tend to "froth up" as the pressure is released during an eruption. This is how pumice (right) is formed.

The most powerful volcanic eruptions occur when magma starts to froth up as it erupts, forcing pumice out of the vent under pressure, just as happens when you shake up a bottle of fizzy drink and open it.

Exploding gas bubbles shatter the pumice into tiny fragments which we call volcanic ash. Ash clouds are driven high into the atmosphere by the force of these eruptions; the finest particles may spread for hundreds of miles before falling back to Earth.

This type of eruption took place at Vesuvius in Italy in 79 AD. Towards the end of the eruption, the column of gas and ash started to collapse and form pyroclastic flows.

These mixtures of super-hot gas and choking ash can flow downhill at speeds of over 100 km/h, killing everything in their paths.

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4

Weather Hazards and Thunderstorms

There are numerous hazards which are related to weather such as droughts, dust storms, heat waves, wildfires, tropical cyclones, blizzards, hailstorms and hurricanes. A thunderstorm is another weather hazard which features lightning and thunder. The topics elaborated in this chapter will help in gaining a better perspective about these weather hazards.

Weather Hazards

Weather is the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity. The average weather of a region over decades is its climate. Although weather can vary day-to-day or year-to-year, the climate of a region is relatively stable because it represents the average weather over a long period of time. Extra-warm summers and extra-cold winters, when combined with typical seasonal change, result in a moderate average temperature over long periods of decades or centuries. Proximity to a large body of water can also decrease the temperature range of a geographic region. While the Midwest is far from an ocean, it is in close proximity to the Great Lakes; nevertheless, states in this area experience a considerable range of temperatures over the course of a year. The greatest temperature ranges are found during the winter: The average winter temperature of northern Minnesota is -13 °C (8 °F) while that of areas around the Ohio River is 2 °C (35 °F). Weather hazards can occur fairly frequently, such as several times a year, or relatively infrequently, such as once every century.

Extreme Temperature

Extreme temperatures can create dangerous conditions for people and may lead to property damage. Heat waves are periods of excessively hot weather that may also accompany high humidity. Temperatures of just 3 °C (6 °F) to 6 °C (11 °F) above normal are enough to reclassify a warm period as a heat wave. Under these conditions, the mechanism of sweating does little to cool people down because the humidity prevents sweat from evaporating and cooling off the skin. Heat waves have different impacts on rural and urban settings. In rural settings, agriculture and livestock can be greatly affected. Heat stress recommendations are issued to help farmers protect their animals, particularly pigs and poultry, which, unlike cattle, do not have sweat glands.

The impacts of heat waves on urban settings include a combination of the natural conditions of excessive heat and the social conditions of living in a densely populated space. Cities contain a considerable amount of pavement, which absorbs and gives off more heat than vegetation-covered land does. Air conditioning units that cool down the inside of buildings produce heat that is released outside. Pollution from cars and industrial manufacturing also elevate the outdoor temperatures in cities. This phenomenon, in which cities experience higher temperatures than surrounding rural communities do, is known as the heat island effect. Other social conditions can cause an increase in the hazards associated with heat waves in urban areas. People who are in poor health, live in apartment buildings with no air conditioning, or are unable to leave their houses are at greatest risk of death during heat waves. In 1995, a heat wave impacted the Midwest, leading to nearly 740 heat-related deaths in Chicago alone. In addition to causing widespread illness from dehydration and exposure to extreme heat, the high temperatures buckled road pavement and warped train rails.

Recently, a different extreme temperature phenomenon has made the news: the polar vortex. As the name implies, a polar vortex is a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere. Typically, the polar vortex hovers above Canada. However, a pocket of the counter-clockwise rotating low-pressure center can break off and shift southward at a lower altitude, covering the Midwest with frigid air. The jet stream then shifts to a more southward flow than usual, chilling the Midwest and even the southern states. A polar vortex can lock the jet stream in this new pattern for several days to more than a week. Extreme low temperatures can endanger livestock, and precautions should be taken regarding travel on roadways. Although the cold temperatures of a polar vortex can be uncomfortable and make traveling dangerous in the winter, the Midwest has not yet experienced any major economic or health-related impacts from this extreme weather event.

Seasonal Severe Storms

Several types of severe storms present challenges to people living in the Midwest. Summer brings severe thunderstorms associated with cold fronts. Fall and spring can bring ice storms, and winter brings the challenge of snow and, in some cases, blizzard conditions. Although rare, hurricanes moving north from the Gulf of Mexico can impact the weather in the Midwest as well. Severe thunderstorms are a common occurrence for people living in the Midwest because the conditions over the Great Plains are perfect for the development of severe weather. The flat, open fields are warmed by the summer sun, which sits high in the sky during this time of year. This results in large temperature differences when cold air masses move across the country. The boundary between the warm air and the cold air moving into a region creates a cold front.

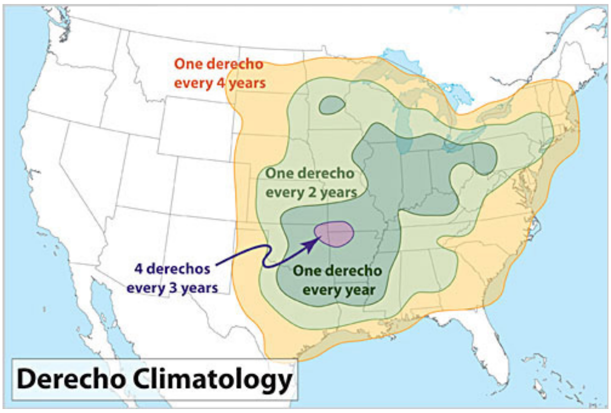
At this boundary, denser, colder air moves in, making the less dense, warm air rise. This displaced warm air cools as it rises because air pressure decreases with increasing height in the atmosphere. As the air cools, it becomes saturated with water vapor, and condensation (the shift from a vapor gas state to a liquid state) begins to occur. This phase shift takes place because the cooler air contains less thermal energy than warmer air does, and this reduction in energy allows the water molecules to “link” together faster than they are torn apart. At frontal boundaries, warm air quickly rises and condenses, and clouds form. Because liquid water droplets in the clouds must be very small to remain suspended in the air, when there is a significant amount of condensation, the small water droplets come together, eventually becoming too large to remain suspended. This process leads to dramatic rainstorms.

Air pressure plays a key role in the formation and severity of these storms. Warm air has a lower pressure relative to cold air, and the movement of air from areas of high pressure to areas of low pressure generates wind. Therefore, when a cold front moves into an area that is very warm, the significant difference in air pressure will generate strong winds. The greater the temperature difference, the greater the air pressure difference and, consequently, the greater the speed at which the air will move. Wind is very common in the Midwest, and the topography of the area plays an important role in wind formation, allowing for warm air to heat up over large expanses of flat cropland without hills or mountains to influence the direction of air movement. Therefore, the Midwest has the perfect ingredients for severe weather: flat topography and large temperature differences on a day-to-day basis.

While severe thunderstorms are often a weekly occurrence in much of the Midwest, two less common storm hazards have the potential to cause serious property damage and endanger lives: derechos and tornados. Both storm events are associated with wind shear, which occurs when the wind speed or direction changes with increasing height in the atmosphere. Wind shear can happen when a cold front moves rapidly into an area with very warm air. There, the condensing water droplets mix with the cooler, drier air in the upper atmosphere to cause a downdraft.

When these downdrafts are very powerful, they can cause a derecho, or a set of powerful straight-line winds that exceed 94 kilometers per hour (kph) (58 miles per hour mph) and can often approach 160 kph (100 mph). These powerful windstorms can travel over 400 kilometers (250 miles) and cause substantial wind damage, knocking down trees and causing widespread power outages. The lightning associated with these intense storms can cause both forest fires and house fires. Approximately one derecho every year or two will occur in much of the Midwest. They are less frequent in the upper Midwest states, which remain cooler throughout the summers.

The differences between tornadoes and derechos are indicated in their names: the word derecho is the Spanish word for straight ahead, while the word tornado has its roots in the Spanish word tonar, which means to turn. Both types of storm events can be associated with the same major cold front boundary because they require similar ingredients to get started. However, tornado formation is a more complicated process. At the frontal boundary, warm, moist air rapidly rises as cooler, dry air descends. In the meantime, the pressure differences between the warm and cold air masses cause strong winds. As conditions in the atmosphere develop to cause a tornado, clouds with a visible horizontal rotation can appear. The clouds seem to roll like waves crashing on the shore of a beach. This horizontal motion can tilt, lifting the rotating cloud vertically, and the rolling cloud will form a tornado. Most tornados will last a few seconds to several minutes. During that time, many tornado-prone areas will use tornado sirens to alert residents of the danger. A smaller tornado might generate flying debris that can cause injury or damage to buildings, while larger tornados can cause buildings and houses to be completely broken apart. Tornados are classified by their ranking on the Enhanced Fujita scale, or EF scale. The classifications are estimates of the wind speeds based on the type of damage that is observed following the storm.



Derecho frequency in the continental US.

Although specific tornado paths are not predictable, the conditions that produce them are used to alert people so that they will seek shelter. The National Weather Service issues a watch, if the conditions are right for a type of storm event, or a warning, if the conditions are occurring or imminent for the storm event. The National Weather Service is part of the National Oceanographic and Atmospheric Administration, which maintains a US map of all current watches and warnings. Since the atmospheric conditions can change very quickly, an important factor in preventing loss of human life is getting the public to act upon the severe weather alerts. One way in which severe weather expert Dr. Greg Forbes has sought to improve public response to warnings is through a tornado alert index that helps people evaluate the risk of a local tornado. The Tor:Con index used by the Weather Channel provides a number from 1 to 10 that represents the probability of a tornado occurring. Meteorologists evaluate the atmospheric conditions associated with a storm and assign a score. For example, a 4 on the Tor:Con index would indicate a 40%, or moderate, chance of a tornado forming in a particular area. The hope is that by representing risk as a number from 1 to 10, people will be more likely to heed warnings and seek shelter.

Other severe weather events are more loosely associated with seasonal weather. Hurricanes occur when a warm and moist tropical low-pressure air mass forms over portions of the Atlantic Ocean south and east of Florida. These storms gather strength because the warm summer ocean water evaporates, causing very humid, low-pressure air. The air rises and condenses into water droplets that form clouds and release latent heat. The latent heat provides energy for even greater evaporation of warm ocean water, and thus the cycle continues until the low-pressure center moves over land. These storms are considered tropical depressions when wind speeds are below 63 kph (39 mph). As the storm develops a more organized structure, however, with more concentrated rising warm air in the center and bands of rain, it will officially become a tropical storm when its wind speeds reach the 63 to 117 kph (39 to 73 mph) range. Once winds have reached 119 kph (74 mph), the storm is classified as a hurricane.

Hurricanes are not common in the Midwest. However, if a hurricane is particularly strong, it can move far enough northward and inland to cause a significant rain event for areas in the Midwest. The impact on the Midwest is usually less serious than the property damage experienced along the southern and eastern seaboards of the United States. Natural hazards experienced during a hurricane are similar to those experienced during a severe thunderstorm that is accompanied by flooding.

Weather Hazards

Frost

Frost occurs when the air temperature near the ground surface falls below 0 °C. Low temperatures generally retard the growth of the crop plants. Cold advection is more injurious during winter season because it creates a typical hazard when the field crops are in their seedling stage.

However, wheat crop can withstand freezing temperature but the plants are killed, if the roots are disturbed by frost heave. Frost occurrence is more common in middle and high latitudes. It occurs rarely in the tropical regions. However, it may occur on the high mountains in the tropical regions. The quality of the mature crops can be reduced by sub- freezing temperatures.

Frost is very injurious to the vegetable crops. Therefore, every year potato and tomato crops are damaged worth crores of rupees due to low temperature injuries.

These crops are susceptible to frost injury right up to the maturity. The flowering stage is a critical period for most of the field crops and young fruit plants suffer serious damage due to low temperature injuries.

To protect the plants from the frost, there are many techniques in which the temperature is not allowed to fall below frost level:

i) The temperature of the plant is increased by increasing the soil temperature. The soil temperature can be increased by giving irrigation to the crop.

ii) By covering the plants with glass or plastic covers. In this way, the temperature of the plants rises.

iii) Sprinkling irrigation also increases the temperature of the air.

High Temperature

High temperatures are experienced during summer season in many parts of the tropical and sub-tropical regions. Prolonged high temperature conditions can lead to heat wave conditions. Generally heat wave conditions can occur during the months of April, May and even June.

If the maximum temperature remains above normal by 6-7 °C, moderate heat wave conditions are said to occur. If the maximum temperature remains above normal by 8 °C or more, then it may be termed as severe heat wave.

Heat waves often develop over Rajasthan, Haryana and Punjab areas, which are far away from the coastal areas. At the same time, hot and strong north-westerly winds may cause heat waves over the coastal areas of Orissa and Andhra Pradesh. However, heat wave incidence is rare over the peninsula south of the latitude 13° north because of maritime influence and fairly humid conditions.

Generally, heat wave conditions may persist for 4-5 days. But sometimes they persist for another one week. The intensity of heat wave is found to be maximum during the months of May and June.

Hot winds are experienced by many areas in the world. Generally, these winds are generated in those areas which are located under the influence of anticyclonic circulation. Their severity is further enhanced by the advection of hot air from other hot areas.

These hot winds are also caused when the air mass descends down the slopes. Foehn is one of the hot winds, which is generated by adiabatic heating when the air mass descends on the leeward side of the mountains.

These hot winds are generally experienced on the northern side of the Alps Mountain in Switzerland. These winds are comparatively warmer and drier than the prevailing air mass of that area. These warm and dry winds can melt the snow rapidly.

As a result, sufficient water becomes available to the crops which are grown under rainfed conditions. On the other hand, the arrival of these hot and dry winds can increase the air temperature suddenly, resulting adverse effect on the standing crops.

Similarly, hot and dry winds are also called Chinook winds. These winds prevail on the eastern slopes of the Rocky Mountains. Under favourable conditions, these winds can develop over any mountain range. These winds carry huge thermal energy which can melt the snow very quickly. These winds are also called snow eater.

Under the influence of these winds, the air temperature can increase by about 22 °C within 24 hours. On 27th January 1940, a rise in temperature of 14 °C was recorded in two hours at Danver, Colorada. These warm and dry winds can reduce the severity of the winter in the western parts of the Great Plains in North America.

High temperatures are generally found over the land in the tropical areas. During summer season, if the maximum and minimum temperature remains above normal for a few days, then excessive thermal energy accumulates which decreases the relative humidity drastically. Under such conditions, the water requirements of the crop plants increase manifold resulting adverse impact on the growth of the plants.

Under high temperature conditions, the growth of the plants is retarded. The vegetable crops are more sensitive to high temperature conditions. The plants can be protected by giving frequent irrigations. Shelterbelts can be raised to decrease the effect of high temperature.

Drought

Drought occurs in those areas of the world, where the soil moisture is not sufficient to meet the demands of the potential evapotranspiration. Low relative humidity, wind and high temperatures are the contributory factors, which can create drought conditions by increasing the evapotranspiration.

It is a common phenomenon in the desert areas, where evapotranspiration exceeds the rainfall. Under such conditions, agriculture is not possible without irrigation.

Drought is one of the worst disastrous of various natural hazards. Drought is generally considered to be a period of moisture deficiency. Drought occurs whenever the supply of moisture from rainfall or stored in the soil becomes insufficient to fulfil the optimum water needs of the plants.

Drought is such a phenomena, whose effect is felt after it has happened. Under prolonged drought conditions, it is not possible to raise agricultural crops. Therefore, drought conditions impose a great threat to the agricultural production.

The water requirements of the plants vary from season to season and from place to place. The water requirement of a crop depends upon the weather conditions prevailing during different stages of the crop.

At the same time, the stage of the crop is very important; therefore the water requirement increases from early stage to the reproductive stage of the crop. Inadequate soil moisture availability during reproductive stage has detrimental effects on the yield.

Drought creates adverse impact on the agriculture. There may be failure of crops under severe drought conditions. Thus, the prolonged drought conditions can shatter the economy of a region.

Drought can be divided into four types:

- Permanent Droughts: Permanent droughts are found in the desert area, where rainfall is not equal to the water needs of the plants. In such cases, evaporation always exceeds total rainfall during the life cycle of the crops. Agriculture is not possible without irrigation.
- Seasonal Droughts: Seasonal droughts occur in those areas, where there are well-defined rainy and dry seasons. These droughts are expected every year. Agriculture is possible during the rainy season and it is possible only with the use of irrigation in dry season.
- Contingent Droughts: Contingent droughts occur when rainfall is erratic and variable. These droughts are found in sub-humid and humid areas. These droughts can occur in any season but these are more severe during the periods of greatest water need. They are serious because they cannot be predicted. The crops stand wilt under the influence of these three droughts.
- Invisible Droughts: These droughts cannot be recognised very easily. Invisible drought can occur at any time. It may occur even during rainy season when the daily supply of moisture fails to meet the daily water requirements of the plants. Invisible droughts are very harmful for the crops. Yield of the crop is adversely affected under these conditions. High yield can be obtained by supplying irrigation to the crop.

Floods

Floods are the major weather hazards, which are caused by heavy rainfall over a given area in a short period of time. In some of the areas, flood producing storms follow seasonal pattern, whereas in other areas flood producing storms occur irregularly. These floods cause heavy damage to the crops and agricultural buildings.

There are three types of floods:

- First type of flood is caused due to intense local rainfall. In such cases, a very large amount of water is precipitated over a small area within a short time. Under these circumstances, the rate of arrival of water at the surface of the earth is much greater than the infiltration rate into the saturated soil. In such cases, flash floods can occur.

  The flash floods are most common in those areas which experience heavy thunderstorms. Therefore, these may be regarded as a potential hazard whenever intense rainfall occurs. In the arid climates, the thunder showers resulting flash floods are erratic. These types of flash floods are common during monsoon season in the hilly areas.

- Second type of flood occurs, when snow begins to melt rapidly. This happens only when the rise of temperature is associated with rain. Warm rain melts snow more quickly than hot sunshine, most of which is reflected by the white surface. In mountainous areas of mid and high latitudes, snow melts results flooding with the onset of the warm season. Such floods have severe agricultural effects.
- Third type can be called autumn or winter flood, which is caused by rainfall lasting for many days. Although the rate of rainfall may be quite less but the total precipitation over a period of one or more days may be considerable. The fast moving water droplets can damage the delicate crop plants and seriously affect their growth and hence yield is reduced.

Storms

Tropical Storms/Thunder Storms

Tropical storms/Thunder storms are the most destructive weather phenomenon. Many parts of the earth experience these storms. Several thousand thunder storms occur every day mainly in the tropics. Their number is smaller over the oceans than over the land, owing to lack of intense convection above water surface. Thunder storms rarely occur in the polar areas.

These are always associated with unstable air and strong vertical motions that produce cumulonimbus clouds. They derive their energy from the release of latent heat of condensation in the rising humid air.

The tropical storms develop in those areas of the oceans, where temperature at the sea surface exceeds 26 °C. High temperature conditions lead to the formation of a low pressure area. As a result, the winds get organised in the form of cyclonic circulation. A low pressure area gets intensified into a depression due to the availability of abundant water vapours.

Later on, pressure decreases rapidly and depression changes into a cyclone. The tropical storms occur in Bay of Bengal and Arabian Sea. They cause lot of damage to the agricultural crops and in some cases the tropical storms bring needed rains to the drought affected agricultural area.

Conditions favourable for the development of thunder storms are given below:

- Strong convection due to intense heating of the land surface.
- Passage of cold, moist air mass over the warm water surface.
- Forced ascent of conditionally unstable air along the convergence zone or along the slope of the mountains.
- Radiational cooling at upper levels.
- Cold advection aloft and warm advection at the surface.

Generally thunder storms caused by the surface heating over land are most common during summer afternoon and early evening. But thunderstorms occur over the ocean during night time because water surface is warmer than the air aloft.

Hail Storms

Hailstorms are the worst weather hazards. Generally hail storms develop in the cumulonimbus clouds. Large hails are always associated with thunderstorms. Hails are generally confined to a small area of the storm. Large hailstones cause a great damage to the life and agricultural crops.

Their intensity increases during the months of March and April when the wheat crop reaches the harvesting stage. Thus crops worth crores of rupees are damaged every year.

Dust Storms

Dust storms generally occur during summer season when the atmospheric pressure decreases suddenly. The wind speed can reach up to 100 km/hr and in some cases the speed may even exceed 100 km/hr. Trees are severely affected by the dust storms and the electric poles are uprooted.

Normally dust storms do not cause rainfall because sufficient water vapours are not available for the formation of the clouds. However, if the amount of water vapours increases and becomes sufficient for the formation of the clouds, thunder showers may occur.

Tornadoes and Water Spouts

The tornado is generally associated with cumulonimbus clouds. It extends downward from the base of the cloud in the form of a chimney. This chimney has both translatory as well as rotatory motion. Therefore, it has the tendency to touch the land surface.

The pressure within the chimney falls rapidly and may be exceptionally low at the centre of the chimney as compared to the adjoining atmospheric air outside the chimney.

As a result, a tremendous force is generated within the chimney. Wherever it touches the ground, the force within the chimney can suck or lift the big objects above the ground surface causing great damage to the objects coming on its way.

The diameters of the chimney vary from 10 meter to 100 meter or even 1km to 2km. The damage caused by the tornado is further enhanced by the strong surface winds associated with the storm.

Tornadoes occur in many areas of the world. Maximum number of tornadoes is found in U.S.A. The word tornado refers to the most violent storm in which the speed of the surface wind can exceed 400 km/hr over a small area. The maximum wind speed in a tornado has never been measured. The vertical velocity can exceed 250 km/hr. These tornadoes cause lot of damage to life and property and agricultural buildings.

There has been no universal theory of the tornado formation. Generally collision of two different air masses may lead to the development of a tornado. Instability occurs, when a dry, cold (heavy) polar air mass pushes the warm, humid (light) air mass upwards. The rising warm, humid air mass loses temperature at the dry adiabatic lapse rate.

The air mass becomes cold and saturated, which leads to condensation. Huge amount of latent heat released during condensation keeps the rising air mass warm. These causes the air currents reach greater heights inducing very low pressure in the center of the air column, which becomes a site of strong winds.

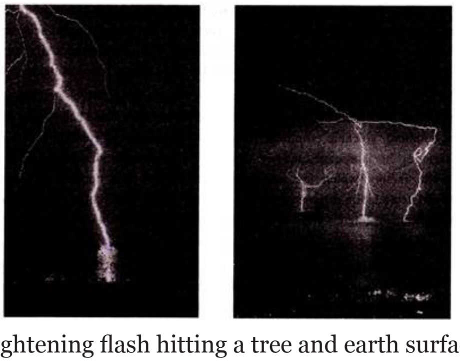
As a result, cyclonic circulation along with strong updraft leads to the formation of a funnel shaped storm. As a result, cyclonic circulation along with strong updraft leads to the formation of a funnel shaped storm cloud associated with extremely loud roaring noise and unusually intense lightening.

Water Spouts

When a tornado occurs on the water surface / surface of the ocean, it is called water spout. Whenever the chimney of the tornado touches the water surface, it sucks water upwards and sometimes it may lift small vessels in the oceans. But the damage caused by the water spout is less as compared to the tornado over the land.

Lightening

Lightening is also a natural calamity and it is always associated with a cumulonimbus cloud. The vertical extent of this cloud may extend up to 10-16 km height above the ground surface. Such clouds consist of positive charge or even potential difference is created between the cloud and the earth.



A lightening flash hitting a tree and earth surface.

As a result, a giant sparkle of lightening is generated. Sometimes a lightening flash may hit any object like a tree or a building on the ground.

In the United States, lightening accounts for more deaths than any other weather hazard. The lightening casualties generally occur in the afternoon. Lightening can strike the aircraft causing heavy damage. It also causes a substantial amount of property damage. Forest fire generally occurs because of lightening under dry conditions.

Blizzards

Blizzards are another weather hazard which cause heavy damage to the life and property. The combination of very low temperatures and very strong winds and snow storm is called blizzard. These are generally found in high latitudes where extra tropical cyclones are prevalent during winter season.

Earthquakes and Tsunami Waves

Of all the natural calamities, earth quakes and tsunami waves are the worst calamities of the world, which cause great damage and devastation in those areas where they occur.

Thunderstorms

Thunderstorm is a violent short-lived weather disturbance that is almost always associated with lightning, thunder, dense clouds, heavy rain or hail, and strong, gusty winds. Thunderstorms arise when layers of warm, moist air rise in a large, swift updraft to cooler regions of the atmosphere. There the moisture contained in the updraft condenses to form towering cumulonimbus clouds and, eventually, precipitation. Columns of cooled air then sink earthward, striking the ground with strong downdrafts and horizontal winds. At the same time, electrical charges accumulate on cloud particles (water droplets and ice). Lightning discharges occur when the accumulated electric charge becomes sufficiently large. Lightning heats the air it passes through so intensely and quickly that shock waves are produced; these shock waves are heard as claps and rolls of thunder. On occasion, severe thunderstorms are accompanied by swirling vortices of air that become concentrated and powerful enough to form tornadoes.

Thunderstorms are known to occur in almost every region of the world, though they are rare in Polar Regions and infrequent at latitudes higher than 50° N and 50° S. The temperate and tropical regions of the world, therefore, are the most prone to thunderstorms. In the United States the areas of maximum thunderstorm activity are the Florida peninsula (more than 90 thunderstorm days per year), the Gulf Coast (70–80 days per year), and the mountains of New Mexico (50–60 days per year). Central Europe and Asia average 20 to 60 thunderstorm days per year. It has been estimated that at any one moment there are approximately 1,800 thunderstorms in progress throughout the world.

Lightning Damage

Most lightning strikes cause damage through the large current flowing in the return stroke or through the heat that is generated by this and the continuing current. The precise mechanisms whereby lightning currents cause damage are not completely understood, however. If lightning strikes a person, the stroke current can damage the central nervous system, heart, lungs, and other vital organs.

When a building or power line is struck by lightning or is exposed to the intense electromagnetic fields from a nearby flash, the currents and voltages that appear on the structure are determined both by the currents and fields in the discharge and by the electrical response of the object and its grounding system. For instance, if a lightning surge enters an unprotected residence by way of an electric power line, the voltages may be large enough to cause sparks in the house wiring or appliances. When such flashovers occur, they may short-circuit the alternating current power system, and the resulting power arc may start a fire. In such instances, the lightning does not start the fire directly, but it does cause a power fault (short circuit), and then the power currents do the damage. In the case of metals, large currents heat the surface at the air-arc interface and the interior by electron collisions with the metal lattice. If this heat is also great enough, the metal will melt or evaporate.

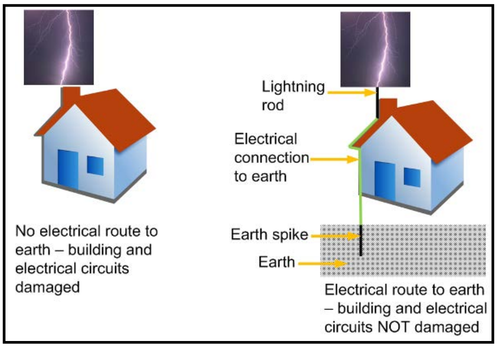
At least three properties of the return-stroke current can cause damage; these are the peak current, the maximum rate of change of the initial current, and the total amount of charge transferred. For objects that have a resistive impedance, such as a ground rod or a long power line, the peak voltage during a strike is proportional to the peak current produced of the lightning stroke and the resistivity of the struck object. For example, if a 100,000 ampere peak current flows into a 10-ohm grounding system, 1 million volts will be produced. A common hazard associated with the large voltages produced by lightning strikes is the re-direction of some of the energy (that is, a flashover) from the original target to an adjacent object. Such secondary discharges, or side-flashes, often cause damage comparable to that of a direct strike, and they are one of the main hazards of standing under or near an isolated tree (or any other tall object) during a thunderstorm. Such large voltages frequently cause secondary discharges or side-flashes to radiate outward from the object that is struck to another object nearby. One form of a side-flash can even occur in the ground near the point of lightning attachment.

For objects that have an inductive electrical impedance, such as the wires in a home electrical system, the peak voltage will be proportional to the maximum rate of change of the lightning current and the inductance of the object. For example, one metre of straight copper wire has a self-inductance on the order of one microhenry. The peak rate of change in the lightning current in a return stroke is on the order of 100,000 amperes per microsecond; therefore, about 100,000 volts will appear across this length of conductor for the duration of the change, typically 100 nanoseconds (billionths of a second).

The heating and subsequent burn-through of metal sheets, as on a metal roof or tank, are to a first approximation proportional to the total charge injected into the metal at the air-arc interface. Generally, large charge transfers are produced by long-duration continuing currents that are in the range of 100 to 1,000 amperes, rather than by the peak currents, which have a relatively short duration. The heat produced by long continuing currents is frequently the cause of forest fires. A typical cloud-to-ground flash transfers 20 to 30 coulombs of charge to the ground, and extreme flashes transfer hundreds and occasionally thousands of coulombs.

Lightning Protection

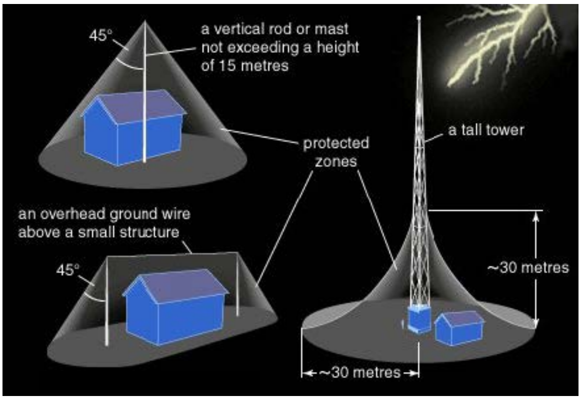
The best personal protection against lightning is to be alert to the presence of a hazard and then to take common-sense precautions, such as staying inside a house or building or inside an automobile, where one is surrounded by (but not in contact with) metal. People are advised to stay away from outside doors and windows and not to be in contact with any electrical appliances, such as a telephone, or anything connected to the plumbing system. If caught outdoors, people are advised to avoid isolated trees or other objects that are preferred targets and to keep low so as to minimize both height and contact with the ground (that is, crouch but do not lie down). Swimming pools are not safe during a lightning storm because water is a good conductor of electricity, and hence being in the pool effectively greatly multiplies the area of one's "ground" contact.



Lightning rod protection system for a residential building: The flow of electricity from a lightning strike is channeled harmlessly around the outside of the building and into the ground.

The frequency with which lightning will directly strike a building in a particular region can be estimated from the building's size and the average number of strikes that occur in the region. If a building is struck whenever a stepped leader comes within 10 metres (33 feet) of the exterior of the building, then a building that is 12 metres (39 feet) wide and 16 metres (52 feet) long (an area of 192 square metres, or about 2,000 square feet) will have an effective strike zone of 32 metres by 36 metres (an area of 1,152 square metres, or 12,400 square feet). In a region where an average of three cloud-to-ground lightning strikes occur per square kilometre annually, such a building will experience an average of 0.0035 direct strike per year, or one strike about every 290 years (1,152 square metres × 3 flashes per square kilometre × 10^{-6} metres per square kilometre). In a region where there is an annual average of five strikes per square kilometre, the same building will experience an average of 0.0058 direct strikes per year, or one strike about every 174 years. These calculations indicate that, for the second example, an average of one of every 174 buildings of similar size will be directly struck by lightning in that region each year.

Structures may be protected from lightning by either channeling the current along the outside of the building and into the ground or by shielding the building against damage from transient currents and voltages caused by a strike. Many buildings constrain the path of lightning currents and voltages through use of lightning rods, or air terminals, and conductors that route the current down into a grounding system. When a lightning leader comes near the building, the lightning rod initiates a discharge that travels upward and connects with it, thus controlling the point of attachment of lightning to the building. A lightning rod functions only when a lightning strike in the immediate vicinity is already immanent and so does not attract significantly more lighting to the building. The down conductors and grounding system function to guide the current into the ground while minimizing damage to the structure. To minimize side-flashes, the grounding resistance should be kept as low as possible, and the geometry should be arranged so as to minimize surface breakdown. Overhead wires and grounded vertical cones may also be used to provide a cone-shaped area of lightning protection. Such systems are most efficient when their height is 30 metres (98 feet) or less.



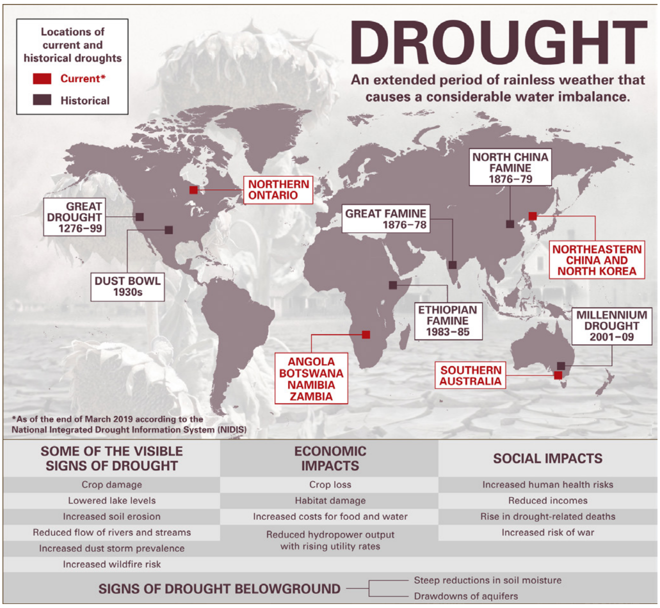
Lightning rod types

Figure shows, (Left top) Vertical rods or masts up to 15 metres in height create lightning protection zones that extend in a 45° cone from the rod's tip. (Left bottom) Connecting two rods with a wire extends the zone of protection. (Right) Towers taller than 30 metres provide protection for an area 30 metres high and 60 metres wide. The protected zone is in the shape of an inverted funnel with inward-curving sides. Towers between 15 and 30 metres high create protected zones of similar shape but with height and width equal to tower height.

Protection of the contents of a structure can be enhanced by using lightning arresters to reduce any transient currents and voltages that might be caused by the discharge and that might propagate into the structure as traveling waves on any electric power or telephone wires exposed to the outside environment. The most effective protection for complex structures is provided by topological shielding. This form of protection reduces amounts of voltage and power at each level of a system of successive nested shields. The partial metallic shields are isolated, and the inside surface of each is grounded to the outside surface of the next. Power surges along wires coming into the structure are deflected by arrestors, or transient protectors, to the outside surface of each shield as they travel through the series, and are thus incrementally attenuated.

Drought

Drought is also spelled drouth, lack or insufficiency of rain for an extended period that causes a considerable hydrologic (water) imbalance and, consequently, water shortages, crop damage, streamflow reduction, and depletion of groundwater and soil moisture. It occurs when evaporation and transpiration (the movement of water in the soil through plants into the air) exceed precipitation for a considerable period. Drought is the most serious physical hazard to agriculture in nearly every part of the world. Efforts have been made to control it by seeding clouds to induce rainfall, but these experiments have had only limited success.



SOME OF THE VISIBLE SIGNS OF DROUGHT	ECONOMIC IMPACTS	SOCIAL IMPACTS
Crop damage	Crop loss	Increased human health risks
Lowered lake levels	Habitat damage	Reduced incomes
Increased soil erosion	Increased costs for food and water	Rise in drought-related deaths
Reduced flow of rivers and streams	Reduced hydropower output with rising utility rates	Increased risk of war
Increased dust storm prevalence		
Increased wildfire risk		

SIGNS OF DROUGHT BELOWGROUND — Steep reductions in soil moisture; Drawdowns of aquifers

locations of major historical droughts and significant 2015–16 droughts: Infographic depicting the locations of significant droughts of 2015–16 and some major drought episodes throughout history.

There are four basic kinds of drought:

1. Permanent drought characterizes the driest climates. The sparse vegetation is adapted to aridity, and agriculture is impossible without continuous irrigation.

2. Seasonal drought occurs in climates that have well-defined annual rainy and dry seasons. For successful agriculture, planting must be adjusted so that the crops develop during the rainy season.
3. Unpredictable drought involves an abnormal rainfall failure. It may occur almost anywhere but is most characteristic of humid and sub humid climates. Usually brief and irregular, it often affects only a relatively small area. However, on-going large-scale droughts of this kind are possible, especially in drier regions with several subsequent years of inadequate rainfall or snowpack.
4. Invisible drought can also be recognized: in summer, when high temperatures induce high rates of evaporation and transpiration, even frequent showers may not supply enough water to restore the amount lost; the result is a borderline water deficiency that diminishes crop yields.

Dust Storms

Climate change and improper land use practices are increasing the frequency of dust and sand storms which is having a negative impact on the health, environment, and economy of affected areas.

A meteorological phenomenon, dust storms are common across semi-arid and arid regions of the world. When strong winds, also known as gust fronts, blow loose dirt and sand from the dry land surface, it results in a dust storm.

Where are Dust Storms Common?

Dry lands around the Arabian Peninsula and North Africa as well as the arid regions of Iran, Pakistan, and India are all susceptible to dust storms. The arid and semi-arid areas in China also experience such storms. In the Sahara Desert, where sand covers the land, sandstorms are the more preferred term since here the wind blows up huge volumes of sand from the desert surface. Sand is coarser than the finer dust particles, which means sandstorms are more devastating in nature than dust storms.

What Causes a Dust Storm?

Dust storms are facilitated by the processes of saltation and suspension, processes that move soil from one place and deposit it in another. As a strong wind moves over a dry and dusty or sandy terrain, the larger dust or sand particles will first vibrate. Then, the particles will saltate (leap) from the ground and fall back repeatedly. This process will break down the salt or dust particles to smaller particles. Soon, the particles will be small enough to remain in suspension and thus blow with the wind to faraway places.

Gusts that transform into dust storms may be produced when air cooled by rain after an intense thunderstorm begins to flow or a dry cold front moves into a dry air mass and flow over hotter terrains. In arid lands like deserts, dust storms are caused primarily due to thunderstorm outflows or due to the creation of strong pressure gradients leading to high velocity winds flowing over a large area. The weight of the suspended particulates and the atmospheric stability determines the vertical extent of the dust or sand that is raised. In some instances, particulates may be raised as high as 20,000 feet above the ground.

Poor Farming Practices and Dust Storms

Poor farming and grazing practices can trigger dust storms in an area. Dryland farming is one of the farming techniques that might expose dust and sand to the air. Intensive tillage, a dryland farming technique where land remains bare for a certain period of time when no cover crops are there to protect the land, often creates the perfect land conditions for dust storms. Thus, soil conservation practices need to be adopted to protect the top soil against wind erosion.

Effects of Dust Storms on the Environment

Dust and sand storms have increased over the years largely due to the adverse effects of climate change and improper land-use practices. Sand storms in the desert can be extremely treacherous and stall traffic through desert roads for days. The reduced visibility during such storms often disturbs life in the desert and people have to wait to get out of their homes in search of water and food resources. Such storms also damage the landscape, cause the shifting of sand dunes, and catalyze the desertification process. Today, dust storms are more frequent in nature. In Mauritania, there were only about 2 dust storms annually during the 1960s. Now, the number has increased to 8. Even within the span of a single year, levels of dust blowing from the African east coast increased 5 times between 2006 and 2007.

Effect of Dust Storms on Human Health

Long-term exposure to dust storms can severely impact the health of individuals. It increases the chances of lung infection. People with asthma have worsening symptoms. It also leads to increased morbidity and mortality in people due to asphyxiation. Long-term exposure to dust particles might lead to silicosis and lung cancer. The danger of keratoconjunctivitis sicca or (“dry eyes”) might lead to permanent blindness.

Effect of Dust Storms on the Economy

Dust storms have a negative impact on agriculture in the affected areas. The abrasive action of such storms might adversely affect young crop plants. Also, the top layer of soil containing nutrient-rich light particles and organic matter are removed during such storms. Road and aircraft transportation are affected during such dust storms due to reduced visibility.

Beneficial Effects of Dust Storms

Not all effects of dust storms are bad. The dust blown in from the Sahara by wind blowing over the ocean reaches Central and South America and is the source of nutrients for the rainforests growing in these regions. Plantain growth in Hawaii is facilitated by dust accumulating on land during such storms. Ancient dust storm deposits called loess acts as highly fertile top soil for crops grown in China and the mid-western US.

Dust Storms Outside Earth

Dust storms are known to occur on Mars where the storms have a much wider extent than on our planet and often encircle the entire planet. Wind speeds can be as high as 60 miles per hour. However, winds cannot attain the speed of hurricane-force winds of Earth due to the much lower atmospheric pressure on the red planet.

Heat Waves

Heat wave is also called heatwave period of prolonged abnormally high surface temperatures relative to those normally expected. Heat waves may span several days to several weeks and are significant causes of weather-related mortality, affecting developed and developing countries alike. Globally, the increasing frequency and intensity of heat waves observed since the 1950s has been associated with climate change. Such weather phenomena may be characterized by low humidity, which may exacerbate drought, or high humidity, which may exacerbate the health effects of heat-related stress, which include heat exhaustion, dehydration, and heatstroke.

No formal, standardized definition of a heat wave exists. The World Meteorological Organization defines it as five or more consecutive days during which the daily maximum temperature surpasses the average maximum temperature by 5 °C (9 °F) or more. Some countries have adopted their own standards. For example, the India Meteorological Department requires that temperatures increase 5–6 °C (9–10.8 °F) or more above the normal temperature, whereas the U.S. National Weather Service defines a heat wave as a spell of “abnormally and uncomfortably hot and unusually humid weather” spanning two days or more.

Oppressively hot and humid air masses lingering over populated areas can produce many deaths, especially in the middle latitudes, where many people—including the very young, the very old, and those with health problems—may be more susceptible to heat stress. Notable modern episodes include the Russian heat wave of 2010 (which covered 1,036,000 square km [400,000 square miles] and killed 55,000 people), the

European heat wave of 2003 (in which more than 30,000 people died), the U.S. heat wave and drought of 1988 (which killed more than 4,000 people), and the Indian heat wave of 2015 (which killed more than 2,500 people).

Wildfires

Though they are classified by the Environmental Protection Agency as natural disasters, only ten to 15 percent of wildfires occur on their own in nature. The other 85 to 90 percent result from human causes, including unattended camp and debris fires, discarded cigarettes, and arson.

Naturally occurring wildfires can spark during dry weather and droughts. In these conditions, normally green vegetation can convert into bone-dry, flammable fuel; strong winds spread fire quickly; and warm temperatures encourage combustion. With these ingredients, the only thing missing is a spark—in the form of lightning, arson, a downed power line, or a burning campfire or cigarette—to wreak havoc.

Firefighters battle the Woolsey Fire as it burns through Malibu, California on Monday.

Natural or man-made, three conditions must be present for a wildfire to burn: fuel, oxygen, and a heat source. Firefighters call these three elements the fire triangle.

- Fuel is any flammable material surrounding a fire, including trees, grasses, brush, even homes. The greater an area's fuel load, the more intense the fire is likely to be. The most wildfire-prone state is California, which lost 1,823,153 acres of land to 8,054 wildfires in 2018.
- Air supplies the oxygen a fire needs to burn. California wildfires are often made worse by the hot, dry Santa Ana winds, which can carry a spark for miles.
- Heat sources help spark the wildfire and bring fuel to temperatures hot enough to ignite. Lightning, burning campfires or cigarettes, and even the sun can all provide sufficient heat to spark a wildfire.

Violent infernos are most common in the U.S. West, where heat, drought, and frequent thunderstorms create ripe conditions. Montana, Idaho, Wyoming, Washington, Colorado, Oregon, and California experience some of the worst conflagration. Wildfires also occur around the world and in most of the 50 states.

How they are Stopped?

Firefighters battle blazes by depriving them of one or more of the fire triangle fundamentals. Traditional methods include:

- Water dousing and spraying fire retardants to extinguish existing fires.
- Working in teams, often called hotshots, to clear vegetation to contain and eventually starve the fire of its fuel. The results are called firebreaks.
- Controlled burning, or creating backfires, is another process firefighters may employ to stop a wildfire. Literally, this method involves fighting fire with fire. These prescribed—and controlled—fires remove undergrowth, brush, and litter from a forest, depriving an otherwise raging wildfire of fuel.

Benefits of Wildfires

Although they are feared, naturally occurring wildfires play an integral role in nature. By burning dead or decaying matter, they can return otherwise trapped nutrients to the soil. They also act as a disinfectant, removing disease-ridden plants and harmful insects from an ecosystem.

High winds and hot temperatures fanned a 1996 wildfire in the foothills around Boise, Idaho, into an inferno that burned for seven days. When it was finally extinguished, the outbreak—dubbed the Eighth Street Fire—had scorched some 15,000 acres (6,000 hectares) and stripped bare two of the region’s major watersheds.

Wildfires thin forest canopies and undergrowth, allowing sunlight to reach the forest floor and a new generation of seedlings to grow. In fact, some species of trees, like sequoias, rely on fire for their seeds to even open.

What to do in a Wildfire?

Before:

- If you know a wildfire is traveling towards your area, the best thing to do is leave. Immediately.
- If you live in a fire-prone area, its best to prepare for that course of action ahead of time. Have an evacuation plan in mind and a “go bag” with emergency supplies already packed during fire season.
- Keep brush, weeds, and other potential fuels trimmed back on your property, especially around your home.
- Put away grills, propane tanks, or other flammable materials that may be in your yard.
- Close all doors and windows and fill sinks, tubs, and other containers with water to discourage fire.
- Shut off natural gas, propane, or fuel oil supplies.
- When you purchase a home in a wildfire-prone area, try to avoid neighborhoods on steep slopes or barren of vegetation, suggests the California Chaparral Institute. Although some people fear that houses near shrubs are more likely to burn, that’s not necessarily the case, the institute says. Rather, a landscape without vegetation can be the perfect runway for winds to bring embers, which are one of the biggest threats to homes during a wildfire.
- Wetting your roof may help reduce the risk of airborne embers catching, says the California Chaparral Institute. In fact, some people in fire-prone areas even install rooftop sprinklers for that purpose.
- If you cannot leave as a fire approaches, dial 911. Then don a face mask, or better, an N95 respirator to help reduce smoke and particle inhalation.

During:

- If you can still leave, leave.
- Listen for emergency alerts.
- If you cannot leave, stay inside. Go to the safest building or room, with the lowest smoke levels. Crouch low for the best air. If you don’t have masks breathe through a wet cloth.
- If you are caught outside, try to find a body of water to crouch in. If you can’t, find a depression with the least vegetation and lie low, covering yourself with wet blankets, clothes, or soil if possible.

After:

- Do not return until instructed to do so.
- Listen to authorities before drinking water from the area.
- Avoid items that are hot, smoky, or charred.
- Text friends and family, but don’t call. Lines may be busy.
- Wear a dust mask and document property damage.
- Beware of the risk of flooding, since trees and protective vegetation might have been removed, exposing loose soil.

Tropical Cyclones

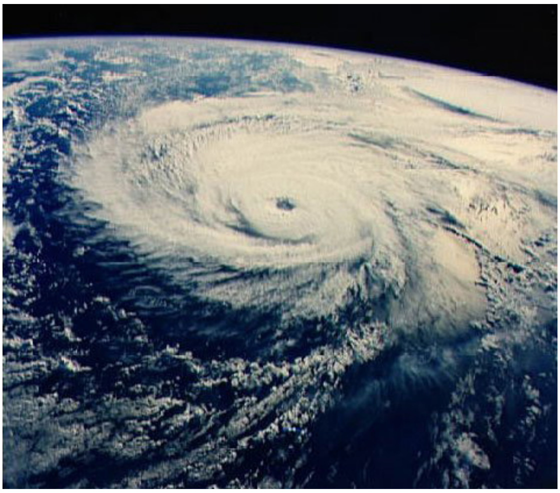
Wrecked houseboats and bent palm trees in Key West, Florida, show the effects of Hurricane Georges.

Tropical cyclone is also called typhoon or hurricane, an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain. Drawing energy from the sea surface and maintaining its strength as long as it remains over warm water, a tropical cyclone generates winds that exceed 119 km (74 miles) per hour. In extreme cases winds may exceed 240 km (150 miles) per hour, and gusts may surpass 320 km (200 miles) per hour. Accompanying these strong winds are torrential rains and a devastating phenomenon known as the storm surge, an elevation of the sea surface that can reach 6 metres (20 feet) above normal levels. Such a combination of high winds and water makes cyclones a serious hazard for coastal areas in tropical and subtropical areas of the world. Every year during the late summer months (July–September in the Northern Hemisphere and January–March in the Southern Hemisphere), cyclones strike regions as far apart as the Gulf Coast of North America, northwestern Australia, and eastern India and Bangladesh.

Tropical cyclones are known by various names in different parts of the world. In the North Atlantic Ocean and the eastern North Pacific they are called hurricanes, and in the western North Pacific around the Philippines, Japan, and China the storms are referred to as typhoons. In the western South Pacific and Indian Ocean they are variously referred to as severe tropical cyclones, tropical cyclones, or simply cyclones. All these different names refer to the same type of storm.

Anatomy of a Cyclone

Tropical cyclones are compact, circular storms, generally some 320 km (200 miles) in diameter, whose winds swirl around a central region of low atmospheric pressure. The winds are driven by this low-pressure core and by the rotation of Earth, which deflects the path of the wind through a phenomenon known as the Coriolis force. As a result, tropical cyclones rotate in a counterclockwise (or cyclonic) direction in the Northern Hemisphere and in a clockwise (or anticyclonic) direction in the Southern Hemisphere.



Typhoon Odessa in the western North Pacific Ocean.

The wind field of a tropical cyclone may be divided into three regions. First is a ring-shaped outer region, typically having an outer radius of about 160 km (100 miles) and an inner radius of about 30 to 50 km (20 to 30 miles). In this region the winds increase uniformly in speed toward the centre. Wind speeds attain their maximum value at the second region, the eyewall, which is typically 15 to 30 km (10 to 20 miles) from the centre of the storm. The eyewall in turn surrounds the interior region, called the eye, where wind speeds decrease rapidly and the air is often calm. These main structural regions.

The Eye

A characteristic feature of tropical cyclones is the eye, a central region of clear skies, warm temperatures, and low atmospheric pressure. Typically, atmospheric pressure at the surface of Earth is about 1,000 millibars. At the centre of a tropical cyclone, however, it is typically around 960 millibars, and in a very intense “super typhoon” of the western Pacific it may be as low as 880 millibars. In addition to low pressure at the centre, there is also a rapid variation of pressure across the storm, with most of the variation occurring near the centre. This rapid variation results in a large pressure gradient force, which is responsible for the strong winds present in the eyewall.

Horizontal winds within the eye, on the other hand, are light. In addition, there is a weak sinking motion, or subsidence, as air is pulled into the eyewall at the surface. As the air subsides, it compresses slightly and warms, so that temperatures at the centre of a tropical cyclone are some 5.5 °C (10 °F) higher than in other regions of the storm. Because warmer air can hold more moisture before condensation occurs, the eye of the cyclone is generally free of clouds. Reports of the air inside the eye being “oppressive” or “sultry” are most likely a psychological response to the rapid change from high winds and rain in the eyewall to calm conditions in the eye.

The Eyewall

The most dangerous and destructive part of a tropical cyclone is the eyewall. Here winds are strongest, rainfall is heaviest, and deep convective clouds rise from close to Earth’s surface to a height of 15,000 metres (49,000 feet). The high winds are driven by rapid changes in atmospheric pressure near the eye, which creates a large pressure gradient force. Winds actually reach their greatest speed at an altitude of about 300 metres (1,000 feet) above the surface. Closer to the surface they are slowed by friction, and higher than 300 metres they are weakened by a slackening of the horizontal pressure gradient force. This slackening is related to the temperature structure of the storm. Air is warmer in the core of a tropical cyclone, and this higher temperature causes atmospheric pressure in the centre to decrease at a slower rate with height than occurs in the surrounding atmosphere. The lessened contrast in atmospheric pressure with altitude causes the horizontal pressure gradient to weaken with height, which in turn results in a decrease in wind speed.

Friction at the surface, in addition to lowering wind speeds, causes the wind to turn inward toward the area of lowest pressure. Air flowing into the low-pressure eye cools by expansion and in turn extracts heat and water vapour from the sea surface. Areas of maximum heating have the strongest updrafts, and the eyewall exhibits the greatest vertical wind speeds in the storm—up to 5 to 10 metres (16.5 to 33 feet) per second, or 18 to 36 km (11 to 22 miles) per hour. While such velocities are much less than those of the horizontal winds, updrafts are vital to the existence of the towering convective clouds embedded in the eyewall. Much of the heavy rainfall associated with tropical cyclones comes from these clouds.

The upward movement of air in the eyewall also causes the eye to be wider aloft than at the surface. As the air spirals upward it conserves its angular momentum, which depends on the distance from the centre of the cyclone and on the wind speed around the centre. Since the wind speed decreases with height, the air must move farther from the centre of the storm as it rises.

When updrafts reach the stable tropopause (the upper boundary of the troposphere, some 16 km [10 miles] above the surface), the air flows outward. The Coriolis force deflects this outward flow, creating a broad anticyclonic circulation aloft. Therefore, horizontal circulation in the upper levels of a tropical cyclone is opposite to that near the surface.

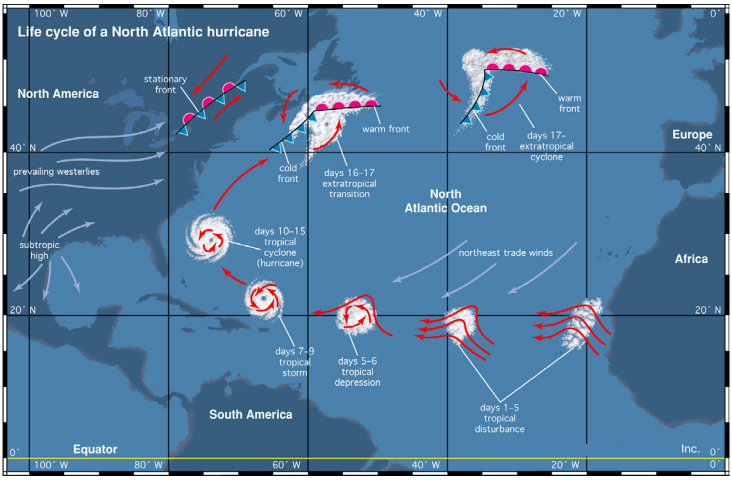
Rainbands

In addition to deep convective cells (compact regions of vertical air movement) surrounding the eye, there are often secondary cells arranged in bands around the centre. These bands, commonly called rainbands, spiral into the centre of the storm. In some cases the rainbands are stationary relative to the centre of the moving storm, and in other cases they seem to rotate around the centre. The rotating cloud bands often are associated with an apparent wobbling of the storm track. If this happens as the tropical cyclone approaches a coastline, there may be large differences between the forecast landfall positions and actual landfall.

As a tropical cyclone makes landfall, surface friction increases, which in turn increases the convergence of airflow into the eyewall and the vertical motion of air occurring there. The increased convergence and rising of moisture-laden air is responsible for the torrential rains associated with tropical cyclones, which may be in excess of 250 mm (10 inches) in a 24-hour period. At times a storm may stall, allowing heavy rains to persist over an area for several days. In extreme cases, rainfall totals of 760 mm (30 inches) in a five-day period have been reported.

Life of a Cyclone

A circulation system goes through a sequence of stages as it intensifies into a mature tropical cyclone. The storm begins as a tropical disturbance, which typically occurs when loosely organized cumulonimbus clouds in an easterly wave begin to show signs of a weak circulation. Once the wind speed increases to 36 km (23 miles) per hour, the storm is classified as a tropical depression. If the circulation continues to intensify and the wind speeds exceed 63 km (39 miles) per hour, then the system is called a tropical storm. Once the maximum wind speed exceeds 119 km (74 miles) per hour, the storm is classified as a tropical cyclone.



There are six conditions favourable for this process to take place. The conditions are listed first below, and then their dynamics are described in greater detail:

1. The temperature of the surface layer of ocean water must be 26.5 °C (80 °F) or warmer, and this warm layer must be at least 50 metres (150 feet) deep.
2. A preexisting atmospheric circulation must be located near the surface warm layer.
3. The atmosphere must cool quickly enough with height to support the formation of deep convective clouds.
4. The middle atmosphere must be relatively humid at a height of about 5,000 metres (16,000 feet) above the surface.
5. The developing system must be at least 500 km (300 miles) away from the Equator.
6. The wind speed must change slowly with height through the troposphere—no more than 10 metres (33 feet) per second between the surface and an altitude of about 10,000 metres (33,000 feet).

Formation

The fuel for a tropical cyclone is provided by a transfer of water vapour and heat from the warm ocean to the overlying air, primarily by evaporation from the sea surface. As the warm, moist air rises, it expands and cools, quickly becoming saturated and releasing latent heat through the condensation of water vapour. The column of air in the core of the developing disturbance is warmed and moistened by this process. The temperature difference between the warm, rising air and the cooler environment causes the rising air to become buoyant, further enhancing its upward movement.

If the sea surface is too cool, there will not be enough heat available, and the evaporation rates will be too low to provide the tropical cyclone enough fuel. Energy supplies will also be cut off if the warm surface water layer is not deep enough, because the developing tropical system will modify the underlying ocean. Rain falling from the deep convective clouds will cool the sea surface, and the strong winds in the centre of the storm will create turbulence. If the resulting mixing brings cool water from below the surface layer to the surface, the fuel supply for the tropical system will be removed.

The vertical motion of warm air is by itself inadequate to initiate the formation of a tropical system. However, if the warm, moist air flows into a preexisting atmospheric disturbance, further development will occur. As the rising air warms the core of the disturbance by both release of latent heat and direct heat transfer from the sea surface, the atmospheric pressure in the centre of the disturbance becomes lower. The decreasing pressure causes the surface winds to increase, which in turn increases the vapour and heat transfer and contributes to further rising of air. The warming of the core and the increased surface winds thus reinforce each other in a positive feedback mechanism.

Intensification

The dynamics of a tropical cyclone rely on the exterior of a storm being cooler than its core, so it is necessary that the temperature of the atmosphere drop sufficiently rapidly with height. The warm, saturated air rising in the centre of the circulation tends to keep rising as long as the surrounding air is cooler and heavier. This vertical movement allows deep convective clouds to develop. The rising air in the core also draws in some air from the surrounding atmosphere at altitudes of around 5,000 metres (16,000 feet). If this external air is relatively humid, the circulation will continue to intensify. If it is sufficiently dry, then it may evaporate some of the water drops in the rising column, causing the air to become cooler than the surrounding air. This cooling will result in the formation of strong downdrafts that will disrupt the rising motion and inhibit development.

For the development of the rapid rotation characteristic of tropical cyclones, the low-pressure centre must be located at least 500 km (300 miles) away from the Equator. If the initial disturbance is too close to the Equator, then the effect of the Coriolis force will be too small to provide the necessary spin. The Coriolis force deflects the air that is being drawn into the surface low-pressure centre, setting up a cyclonic rotation. In the Northern Hemisphere the direction of the resulting circulation around the low is counterclockwise, and in the Southern Hemisphere it is clockwise.

A final requirement for the intensification of tropical cyclones is that there must be little change in the wind speed with height above the surface. If the winds increase too much with altitude, the core of the system will no longer be vertically aligned over the warm surface that provides its energy. The area being warmed and the surface low-pressure centre will move apart, and the positive feedback mechanism will be suppressed. Conditions in the tropics that encourage the development of tropical cyclones include a typically minor north-to-south variation in temperature. This relative lack of a temperature gradient causes wind speed to remain relatively constant with height.

Dissipation

Tropical cyclones dissipate when they can no longer extract sufficient energy from warm ocean water. As mentioned above, a tropical cyclone can contribute to its own demise by stirring up deeper, cooler ocean waters. In addition, a storm that moves over land will abruptly lose its fuel source and quickly lose intensity.

A tropical cyclone that remains over the ocean and moves into higher latitudes will change its structure and become extratropical as it encounters cooler water. The transformation from a tropical to an extratropical cyclone is marked by an increase in the storm's diameter and by a change in shape from circular to comma- or v-shaped as its rainbands reorganize. An extratropical cyclone typically has a higher central pressure and consequently has lower wind speeds. Extratropical cyclones, which are fueled by a north-to-south variation of temperature, weaken and dissipate in a few days.

Tropical Cyclone Damage

Horizontal Wind

Hurricane Dennis: Strong winds from Hurricane Dennis.

High winds cause some of the most dramatic and damaging effects associated with tropical cyclones. In the most intense tropical cyclones, sustained winds may be as high as 240 km (150 miles) per hour, and gusts can exceed 320 km (200 miles) per hour. The length of time that a given location is exposed to extreme winds depends on the size of the storm and the speed at which it is moving. During a direct hit from a tropical cyclone, an area may endure high winds for several hours. In that time even the most solidly constructed buildings may begin to suffer damage. The force of the wind increases rapidly with its speed. Sustained winds of 100 km (62 miles) per hour exert a pressure of 718 pascals (15 pounds per square foot), while an approximate doubling of wind speed to 200 km (124 miles) per hour increases the pressure almost fivefold to 3,734 pascals. A building with a large surface area facing the wind may be subjected to immense forces. Some of the local variability in damage that is often observed during tropical cyclones is due to the direction that buildings face relative to the prevailing wind.

Horizontal winds associated with a tropical cyclone vary in strength depending on the area of the storm in which they occur. The strongest winds are located in the right-forward quadrant of the storm, as measured along the line that the storm is moving. The intensification of winds in this quadrant is due to the additive effect of winds from the atmospheric flow in which the storm is embedded. For example, in a hurricane approaching the East Coast of the United States, the highest and most damaging winds are located to the northeast of the storm centre.

Tornadoes

The intense sustained winds present near the centre of tropical cyclones are responsible for inflicting heavy damage, but there is another wind hazard associated with these storms—tornadoes. Most tropical disturbances that reach storm intensity have tornadoes associated with them when they make landfall, though the tornadoes tend to be weaker than those observed in the Midwestern United States. The number of tornadoes varies, but about 75 percent of tropical cyclones generate fewer than 10. The largest number of tornadoes associated with a tropical cyclone was 141, reported in 1967 as Hurricane Beulah struck the Texas Gulf Coast in the United States.

Tornadoes can occur in any location near the centre of the storm. At distances greater than 50 km (30 miles) from the centre, they are confined to the northeast quadrant of Northern Hemisphere storms and to the southwest quadrant of Southern Hemisphere storms. How the tornadoes are generated is not clear, but surface friction probably plays a role by causing the wind to slow as the tropical cyclone makes landfall. Wind speeds near the surface decrease while those at higher levels are less affected, setting up a low-level horizontal rotation that becomes tilted into the vertical by updrafts, thus providing the concentrated spin required for a tornado.

Gusts, Downbursts and Swirls

In addition to tornadoes, tropical cyclones generate other localized damaging winds. When a tropical cyclone makes landfall, surface friction decreases wind speed but increases turbulence; this allows fast-moving air aloft to be transported down to the surface, thereby increasing the strength of wind gusts. There is also evidence of tropical cyclone downbursts, driven by evaporative cooling of air. These downbursts are similar to microbursts that may occur during severe thunderstorms. The winds associated with them typically flow in a different direction than those of the cyclone, allowing them to be identified. Other small-scale wind features associated with tropical cyclones are swirls. These are very small, intense, and short-lived vortices that occur under convective towers embedded in the eyewall. They are not classified as tornadoes because their peak winds last only a few seconds. Swirls may rotate in either a counterclockwise or a clockwise direction, and their peak winds are estimated to approach 320 km (200 miles) per hour.

The Storm Surge

In coastal regions an elevation of sea level—the storm surge—is often the deadliest phenomenon associated with tropical cyclones. A storm surge accompanying an intense tropical cyclone can be as high as 6 metres (20 feet). Most of the surge is caused by friction between the strong winds in the storm's eyewall and the ocean surface, which piles water up in the direction that the wind is blowing. For tropical cyclones in the Northern Hemisphere this effect is largest in the right-forward quadrant of the storm because the winds are strongest there. In the Southern Hemisphere the left-forward quadrant has the largest storm surge.

A fertilizer plant at the port of Paradip, India, inundated by a storm surge after the Orissa cyclone.

A small part of the total storm surge is due to the change in atmospheric pressure across the tropical cyclone. The higher atmospheric pressure at the edges of the storm causes the ocean surface to bulge under the eye, where the pressure is lowest. However, the magnitude of this pressure-induced surge is minimal because the density of water is large compared with that of air. A pressure drop of 100 millibars across the diameter of the storm causes the sea surface under the eye to rise about 1 metre (3 feet).

Flooding caused by the storm surge is responsible for most of the deaths associated with tropical cyclone landfalls. Extreme examples of storm surge fatalities include 6,000 deaths in Galveston, Texas, in 1900 and the loss of more than 300,000 lives in East Pakistan (now Bangladesh) in 1970 from a storm surge that was estimated to be 9 metres (30 feet) high. Improvements in forecasting the expected height of storm surges and the issuing of warnings are necessary as the population of coastal areas continues to increase.

Rainfall

Tropical cyclones typically bring large amounts of water into the areas they affect. Much of the water is due to rainfall associated with the deep convective clouds of the eyewall and with the rainbands of the outer edges of the storm. Rainfall rates are typically on the order of several centimetres per hour with shorter bursts of much higher rates. It is not uncommon for totals of 500 to 1,000 mm (20 to 40 inches) of rain to be reported over some regions. Rainfall rates such as these may overwhelm the capacity of storm drains, resulting in local flooding. Flooding may be particularly severe in low-lying regions such as in Bangladesh and the Gulf Coast of the United States. It is also a problem in areas where mountains and canyons concentrate the rainfall, as occurred in 1998 when floods caused by rains from Hurricane Mitch washed away entire towns in Honduras.

Another source of high precipitation may be provided by the migration of moist air from the clouds of the mature tropical cyclone. When this moisture moves into areas of low pressure at higher latitudes, significant precipitation may result. An example of this occurred in 1983, when the remnants of the eastern Pacific Hurricane Octave moved into a Pacific cold front that had stalled over the southwestern United States, drenching the Arizona desert with 200 mm (8 inches) of rain in a three-day period. On average, that region receives 280 mm (11 inches) of rain in an entire year.

Ranking and Naming a Cyclone

Intensity Scales

A wide range of wind speeds is possible between tropical cyclones of minimal strength and the most intense ones on record, and tropical cyclones can cause damage ranging from the breaking of tree limbs to the destruction of mobile homes and small buildings. To aid in issuing warnings to areas that may be affected by a storm, and to indicate the severity of the potential threat, numerical rating systems have been developed based on a storm's maximum wind speed and potential storm surge. For tropical systems in the Atlantic and eastern Pacific, the Saffir-Simpson hurricane scale is used. This scale ranks storms that already have reached hurricane strength. A similar scale used to categorize storms near Australia includes both tropical storms and tropical cyclones. Though these two scales have different starting points, the most intense rating in each—category 5—is similar. Numerical ranking scales are not utilized in any of the other ocean basins.

Australian scale of cyclone intensity

Category	Wind speed		Damage
	Km/hr	Mph	
1	63–90	39–56	Some damage to crops, trees, caravans (mobile homes); gusts to 125 km/hr (78 mph).

2	91–125	57–78	Heavy damage to crops, significant damage to caravans; gusts of 125–170 km/hr (78–105 mph).
3	126–165	79–102	Some caravans destroyed; some roofs and structures damaged; gusts of 170–225 km/hr (105–140 mph).
4	166–226	103–140	Significant damage to roofs and structures; caravans destroyed; gusts of 225–280 km/hr (140–174 mph).
5	>226	>140	Widespread destruction; gusts greater than 280 km/hr (174 mph).

Saffir-Simpson hurricane wind scale			
Category	Wind speed		Damage
	Mph	Km/hr	
1	74–95	119–153	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96–110	154–177	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111–129	178–208	Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	130–156	209–251	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	>157	>252	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Naming Systems

It is not uncommon for more than one tropical cyclonic system to be present in a given ocean basin at any given time. To aid forecasters in identifying the systems and issuing warnings, tropical disturbances are given numbers. When a system intensifies to tropical storm strength, it is given a name.

In the United States, names given to hurricanes during World War II corresponded to radio code names for the letters of the alphabet (such as Able, Baker, and Charlie). In 1953 the U.S. National Weather Service began to identify hurricanes by female names, and in 1978 a series of alternating male and female names came into use. The lists of names are recycled every six years—that is, the 2003 list is used again in 2009, the 2004 list in 2010, and so on—as is shown in the table of tropical cyclone names for the North Atlantic and the table of names for the eastern North Pacific. Names of very intense, damaging, or otherwise newsworthy storms are retired. Names that will not be used again include Gilbert, a 1988 category 5 hurricane that had the lowest central atmospheric pressure (888 millibars) ever recorded in the Atlantic. Also retired is Mitch, the name of a category 5 hurricane that stalled off the coast of Honduras for two days in 1998 before slowly moving inland, inundating Central America with heavy rain and causing mudslides and floods that took nearly 10,000 lives. Another notable storm whose name has been retired was Hurricane Ivan, which reached category 5 on three separate occasions during its long life cycle in September 2004. Ivan almost completely destroyed all agricultural infrastructures in Grenada, wrecked much of that year's crops in Jamaica, leveled 1.1 million hectares (2.7 million acres) of timber in Alabama, and caused almost 100 deaths along its path.

Hurricane names for tropical cyclones in the eastern North Pacific Ocean					
2018	2019	2020	2021	2022	2023
Aletta	Alvin	Amanda	Andres	Agatha	Adrian
Bud	Barbara	Boris	Blanca	Blas	Beatriz
Carlotta	Cosme	Cristina	Carlos	Celia	Calvin
Daniel	Dalila	Douglas	Dolores	Darby	Dora
Emilia	Erick	Elida	Enrique	Estelle	Eugene
Fabio	Flossie	Fausto	Felicia	Frank	Fernanda
Gilma	Gil	Genevieve	Guillermo	Georgette	Greg
Hector	Henriette	Hernan	Hilda	Howard	Hilary
Ileana	Ivo	Iselle	Ignacio	Ivette	Irwin
John	Juliette	Julio	Jimena	Javier	Jova
Kristy	Kiko	Karina	Kevin	Kay	Kenneth
Lane	Lorena	Lowell	Linda	Lester	Lidia
Miriam	Mario	Marie	Marty	Madeline	Max
Norman	Narda	Norbert	Nora	Newton	Norma
Olivia	Octave	Odalys	Olaf	Orlene	Otis
Paul	Priscilla	Polo	Pamela	Paine	Pilar
Rosa	Raymond	Rachel	Rick	Roslyn	Ramon
Sergio	Sonia	Simon	Sandra	Seymour	Selma
Tara	Tico	Trudy	Terry	Tina	Todd
Vicente	Velma	Vance	Vivian	Virgil	Veronica

Willa	Wallis	Winnie	Waldo	Winifred	Wiley
Xavier	Xina	Xavier	Xina	Xavier	Xina
Yolanda	York	Yolanda	York	Yolanda	York
Zeke	Zelda	Zeke	Zelda	Zeke	Zelda
Alberto	Andrea	Arthur	Ana	Alex	Arlene
Beryl	Barry	Bertha	Bill	Bonnie	Bret
Chris	Chantal	Cristobal	Claudette	Colin	Cindy
Debby	Dorian	Dolly	Danny	Danielle	Don
Ernesto	Erin	Edouard	Elsa	Earl	Emily
Florence	Fernand	Fay	Fred	Fiona	Franklin
Gordon	Gabrielle	Gonzalo	Grace	Gaston	Gert
Helene	Humberto	Hanna	Henri	Hermine	Harold
Isaac	Imelda	Isaias	Ida	Ian	Idalia
Joyce	Jerry	Josephine	Julian	Julia	Jose
Kirk	Karen	Kyle	Kate	Karl	Katia
Leslie	Lorenzo	Laura	Larry	Lisa	Lee
Michael	Melissa	Marco	Mindy	Martin	Margot
Nadine	Nestor	Nana	Nicholas	Nicole	Nigel
Oscar	Olga	Omar	Odette	Owen	Ophelia
Patty	Pablo	Paulette	Peter	Paula	Philippe
Rafael	Rebekah	Rene	Rose	Richard	Rina
Sara	Sebastien	Sally	Sam	Shary	Sean
Tony	Tanya	Teddy	Teresa	Tobias	Tammy
Valerie	Van	Vicky	Victor	Virginie	Vince
William	Wendy	Wilfred	Wanda	Walter	Whitney

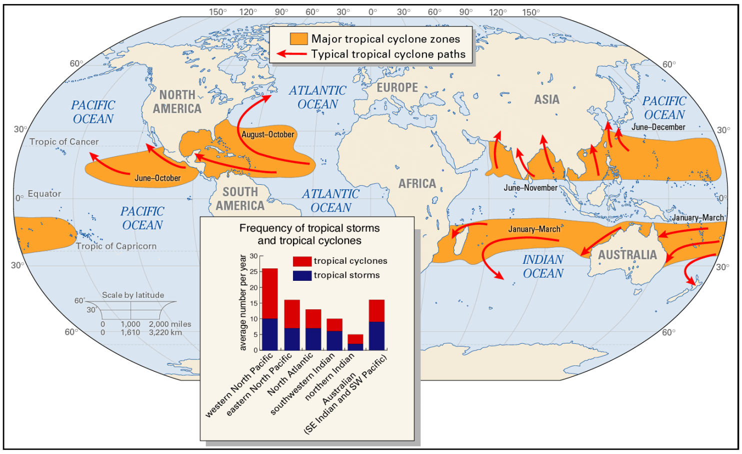
Pacific and Indian basin storms are named according to systems established by regional committees under the auspices of the World Meteorological Organization. Each region maintains its own list of names, and changes to the list (such as retiring a name) are ratified at formal meetings. Two or more lists of names are alternated each year for several regions, including the central North Pacific (i.e., the Hawaii region), the western North Pacific and South China Sea, the southern Indian Ocean west of 90 °E, the western South Pacific Ocean, and Australia's eastern, central, and northern ocean regions. In some areas, such as the northern Indian Ocean, tropical cyclones are given numbers instead of names.

Location and Patterns of Tropical Cyclones

Ocean Basins and Peak Seasons

Tropical oceans spawn approximately 80 tropical storms annually, and about two-thirds are severe (category 1 or higher on the Saffir-Simpson scale of intensity). Almost

90 percent of these storms form within 20° north or south of the Equator. Poleward of those latitudes, sea surface temperatures are too cool to allow tropical cyclones to form, and mature storms moving that far north or south will begin to dissipate. Only two tropical ocean basins do not support tropical cyclones, because they lack waters that are sufficiently warm. The Peru Current in the eastern South Pacific and the Benguela Current in the South Atlantic carry cool water Equatorward from higher latitudes and so deter tropical cyclone development. The Pacific Ocean generates the greatest number of tropical storms and cyclones. The most powerful storms, sometimes called super typhoons, occur in the western Pacific. The Indian Ocean is second in the total number of storms, and the Atlantic Ocean ranks third.



Major tracks and frequency of tropical cyclones (hurricanes and typhoons) and tropical storms.

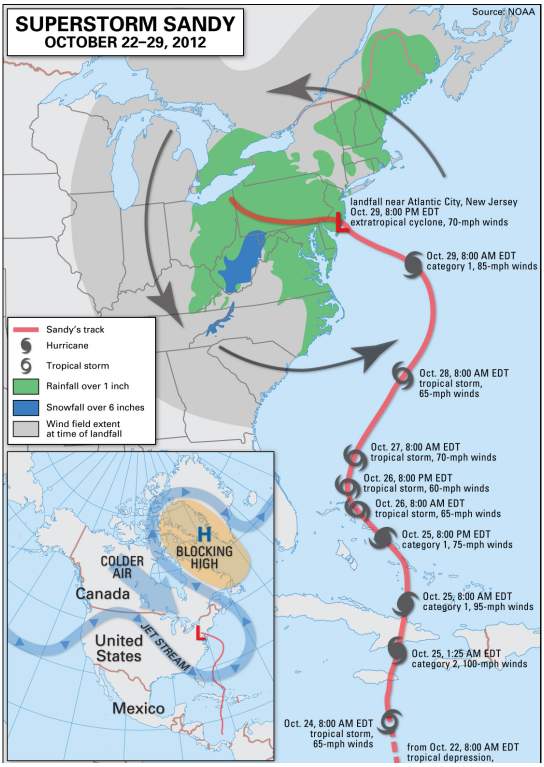
Tropical cyclones are warm season phenomena. The peak frequency of these storms occurs after the maximum in solar radiation is received for the year, which occurs on June 22 in the Northern Hemisphere and December 22 in the Southern Hemisphere. The ocean surface reaches its maximum temperature several weeks after the solar radiation maximum, so most tropical cyclones occur during the late summer to early fall—that is, from July to September in the Northern Hemisphere and from January to March in the Southern Hemisphere.

Favourable Wind Systems

The lower latitudes are favourable for the generation of tropical cyclones not only because of their warm ocean waters but also because of the general atmospheric circulation of the region. Tropical cyclones originate from loosely organized, large-scale circulation systems such as those associated with the strong, low-level easterly jet over Africa. This jet generates easterly waves—regions of low atmospheric pressure that have a maximum intensity at an altitude of about 3,600 metres (12,000 feet) and a horizontal extent of about 2,400 km (1,500 miles). Most of the tropical cyclones in the Atlantic and eastern North Pacific begin as easterly waves. Given favourable conditions, an easterly wave may intensify and contract horizontally, ultimately resulting in the characteristic circulation of a tropical cyclone. In the western Pacific, large areas of upper-level low pressure help pull air from the centre of the developing disturbances and thus contribute to a drop in surface atmospheric pressure. It is these features, known as tropical upper tropospheric troughs, or TUTTs, that are responsible for the large number of tropical cyclones in the western Pacific.

In some cases, external geographic factors aid in development of tropical cyclones. The mountains of Mexico and Central America modify easterly waves that move through the Caribbean and into the eastern Pacific. This often results in closed circulations at low levels over the eastern Pacific Ocean, many of which develop into tropical cyclones.

Tropical Cyclone Tracks



Superstorm Sandy: The evolution of Superstorm Sandy, from its origin as a tropical depression in the Caribbean Sea and its transformation into a hurricane.

Tropical cyclones in both the Northern and Southern Hemispheres tend to move westward and drift slowly poleward. Their motion is due in large part to the general circulation of Earth's atmosphere. Surface winds in the tropics, known as the trade winds, blow from east to west, and they are responsible for the general westward motion of tropical cyclones. For the poleward movement, two other factors are responsible. One is the presence of large-scale regions of subsiding air, known as subtropical highs, over the oceans poleward of the trade winds. These regions of high atmospheric pressure have anticyclonic circulations (that is, clockwise circulation in the Northern

Hemisphere and counterclockwise in the Southern), so that winds on the western edges of these large-scale circulations move toward the poles. The second factor is the Coriolis force, which becomes progressively stronger at higher latitudes. The diameter of a tropical cyclone is large enough for the Coriolis force to influence its poleward side more strongly, and hence the tropical cyclone is deflected toward the pole. Once a tropical cyclone moves poleward of the subtropical high, it begins to move eastward under the influence of the middle-latitude westerlies (which blow toward the east). When the motion of a tropical cyclone changes from westward to eastward, the tropical cyclone is said to recurve.

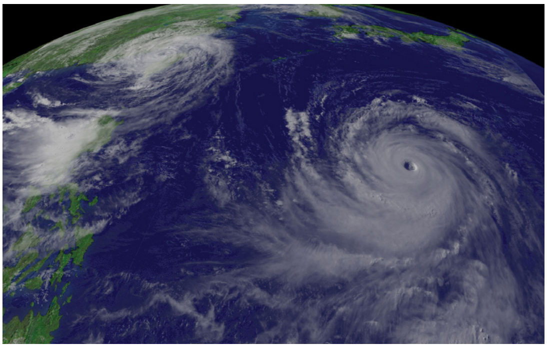
Tropical cyclones in the Northern Hemisphere can travel to higher latitudes than in the Southern Hemisphere because of the presence of warm clockwise oceanic currents such as the Kuroshio and the Gulf Stream. In the North Atlantic the warm waters of the Gulf Stream supply energy to hurricanes as they move along the east coast of the United States, allowing them to survive for a longer time. It is not uncommon for very intense tropical systems to make landfall as far north as Boston (42 °N). On the other hand, hurricanes do not make landfall on the west coast of the United States even though prevailing winds over the North Pacific Ocean move eastward toward land. Instead, they tend to weaken rapidly as they recurve because they are moving over cooler ocean waters.

Tracking and Forecasting

In the first half of the 20th century the identification of tropical cyclones was based on changes in weather conditions, the state of the sea surface, and reports from areas that had already been affected by the storm. This method left little time for advance warning and contributed to high death tolls. Observation networks and techniques improved with time; with the advent of weather satellites in the 1960s, the early detection and tracking of tropical cyclones was greatly improved.

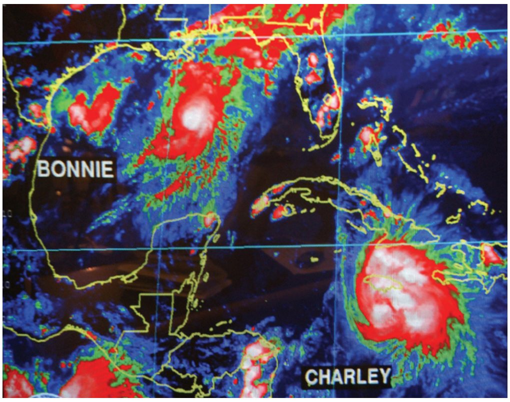
Earth's Western Hemisphere: A view of Earth's Western Hemisphere from space showing Hurricane inda approaching Baja California.

Use of Satellites and Aircraft



“Supertyphoon” Chaba (right) approaching Japan and Typhoon Aere (left) hitting Taiwan, as photographed by the GOES-9 satellite.

An array of geostationary satellites (those that remain over a fixed position on Earth) is operated by a number of countries. Each of these satellites provides continuous displays of Earth’s surface in visible light and in infrared wavelengths. It is the latter that are most important in tracking the stages of tropical cyclone development. Infrared images show the temperatures of cloud tops, thus allowing the loosely organized convection associated with easterly waves to be detected by the presence of cold, high clouds. They also show the deep, organized convection characteristic of a tropical cyclone. Satellite images not only show a storm’s location but also can be used to estimate its intensity because certain cloud patterns are characteristic of particular wind speeds.



A screen at the U.S. National Hurricane Center, Miami, Florida, shows an infrared satellite image of Tropical Storm Bonnie (left) and Hurricane Charley (right).

Although satellite images provide general information on the location and intensity of tropical cyclones, detailed information on a storm’s strength and structure must be obtained directly, using aircraft. This information is essential in providing the most accurate warnings possible. Operational reconnaissance is done only by the United States for storms that may affect its continental landmass. No other country does this type of reconnaissance. Tropical cyclones in other ocean basins occur over a larger region, and most countries do not have the financial resources to maintain research aircraft. When evidence of a developing circulation is detected in the Atlantic or Caribbean, a U.S. Air Force C-130 aircraft is dispatched to determine if a closed circulation is present. The centre of circulation is noted, and an instrument called a dropsonde is released through the bottom of the aircraft to measure the temperature, humidity, atmospheric pressure, and wind speed. In many cases, the naming of a tropical storm, or its upgrade from tropical storm to tropical cyclone, is based on aircraft observations.

Landfall Forecasts

Tropical storms developing in the world's ocean basins are tracked by various national weather services that have been designated Regional Specialized Meteorological Centres (RSMCs) by the World Meteorological Organization (WMO). The RSMCs are located at Miami, Florida, and Honolulu, Hawaii, U.S.; Tokyo, Japan; Nadi, Fiji; Darwin, Northern Territory, Australia; New Delhi, India; and Saint-Denis, Réunion. Warnings are also issued for more limited regions by Tropical Cyclone Warning Centres in a number of locations, including Port Moresby, Papua New Guinea; Wellington, New Zealand; and Perth, Western Australia, and Brisbane, Queensland, Australia. In addition, the Joint Typhoon Warning Centers in Hawaii are responsible for U.S. military forecasts in the western Pacific and Indian Oceans, which overlap a number of WMO regions of responsibility.

Forecasting hurricane landfall and providing warnings for storms that will affect the United States is done by the National Hurricane Center in Miami. Forecasters use a variety of observational information from satellites and aircraft to determine the current location and intensity of the storm. This information is used along with computer forecast models to predict the future path and intensity of the storm. There are three basic types of computer models. The simplest ones use statistical relations based on the typical paths of hurricanes in a region, along with the assumption that the current observed motion of the storm will persist. A second type of model, called a statistical-dynamical model, forecasts the large-scale circulation by solving equations that describe changes in atmospheric pressure, wind, and moisture. Statistical relations that predict the track of the storm based on the large-scale conditions are then used to forecast the storm's future position. A third type of model is a purely dynamic forecast model. In this model, equations are solved that describe changes in both the large-scale circulation and the tropical cyclone itself. Dynamic forecast models show the interaction of the tropical cyclone with its environment, but they require the use of large and powerful computers as well as very complete descriptions of the structure of the tropical cyclone and that of the surrounding environment. Computer models currently do well in forecasting the path of tropical cyclones, but they are not as reliable in forecasting changes in intensity more than 24 hours in advance.

Once forecasters have determined that a tropical cyclone is likely to make landfall, warnings are issued for the areas that may be affected. The forecasters provide a "best-track" forecast, which is an estimate of the track and maximum wind speed over a period of 72 hours based on all available observations and computer model results. Strike probability forecasts are issued that indicate probabilities (in percentages) that the tropical cyclone will affect a given area over a given time interval. These forecasts allow local authorities to begin warning and evacuation plans. As the storm approaches, a tropical cyclone watch is issued for areas that may be threatened. In especially vulnerable areas, evacuation may be initiated based on the watch. If tropical cyclone conditions are expected in an area within 24 hours, a tropical cyclone warning is issued. Once a warning is issued, evacuation is recommended for areas prone to storm surges and areas that may be isolated by high water.

Long-term Forecasts

Forecasts of expected numbers of Atlantic tropical cyclones are now being made well in advance of the start of each year's tropical cyclone season. The forecast model takes into account seasonal trends in factors related to tropical cyclone formation such as the presence of El Niño or La Niña oceanic conditions, amount of rainfall over Africa, winds in the lower stratosphere, and atmospheric pressure and wind tendencies over the Caribbean. Based on these factors, forecasts are issued concerning the expected numbers of tropical storms, tropical cyclones, and intense tropical cyclones for the Atlantic. These forecasts are issued in December, and they are revised in June and again in August of each year for the current Atlantic tropical cyclone season. The forecast model has displayed reasonable skill in predicting the total number of storms each season.

Climatic Variations and Tropical Cyclone Frequency

The number of tropical cyclones generated during a given a year has been observed to vary with certain climatic conditions that modify the general circulation of the atmosphere. One of these conditions is the intermittent occurrence of El Niño, an oceanic phenomenon characterized by the presence every few years of unusually warm water over the equatorial eastern Pacific. The presence of unusually cool surface waters in the region is known as La Niña. While the factors connecting El Niño and La Niña to tropical cyclones are complicated, there are a few general relationships. During years when El Niño conditions are present, upper-level winds over the Atlantic tend to be stronger than normal, which increases the vertical shear and decreases tropical cyclone activity. La Niña conditions result in weaker shear and enhanced tropical cyclone activity. The variation of sea surface temperature associated with El Niño and La Niña also changes the strength and location of the jet stream, which in turn alters the tracks of tropical cyclones. There are indications that El Niño and La Niña modulate tropical cyclone activity in other parts of the world as well. More tropical cyclones seem to occur in the eastern portion of the South Pacific during El Niño years, and fewer occur during La Niña years.

The possibility is being examined that changes in Earth's climate might alter the numbers, intensity, or paths of tropical cyclones worldwide. Increasing the amount of carbon dioxide and other greenhouse gases in the atmosphere through the burning of fossil fuels and other human activities may increase the global average temperature and the temperature of the sea surface. These potential changes would influence the maximum intensity reached by a tropical cyclone, which depends on both the sea surface temperature and the temperature of the upper troposphere. An increase in global temperature, however, could actually decrease the number of tropical cyclones, because any change in temperature would be accompanied by changes in Earth's general circulation. If tropical atmospheric circulation were to change in such a way as to increase the winds at upper levels, then there could be a decrease in tropical cyclone activity. An assessment by the World Meteorological Organization of the effect of climate change on tropical cyclones concluded that there is no evidence to suggest that an enhanced greenhouse effect will cause any major changes in the global location of tropical cyclone genesis or the total area of Earth's surface over which tropical cyclones form. Furthermore, while the maximum potential intensity of tropical cyclones may increase by 10 to 20 percent with a doubling of the concentration of carbon dioxide in the atmosphere, factors such as increased cooling due to ocean spray and changes in the vertical temperature variation may offset these effects.

Blizzard

While snowstorms are a common occurrence in many areas during the winter months, blizzards are a rarer occurrence. In order for a snowstorm to be classified as a blizzard it must meet the following criteria: a large amount of snowfall, winds greater than 56 km/h (35 mph), and less than ¼ of a mile visibility. These conditions must last for over three hours for a blizzard to occur. In short, a blizzard is a severe snowstorm with strong and powerful winds in excess of 35 mph for more than 3 hours and visibility of less than a 1/4 mile. During a blizzard, the temperature is often below 0 degrees, because of this frostbite and hypothermia is common. In the United States, blizzards occur most frequently in the Plain States, the Northeast, and on mountain tops, although they can occur almost anywhere that gets snowfall.

Facts of Blizzards

1. A blizzard is a severe snowstorm characterized by strong sustained winds of at least 56 km/h (35 mph) and lasting for more than 3 hours.
2. Two legendary blizzards occurred in 1888. The first is known as the schoolhouse blizzard. It occurred across the Great Plains and was so named because of the school children stranded in their schoolhouses. About 235 people lost their lives. A large portion of the number of deaths was of school children who had attempted to walk home. The second of the blizzards is known as the Great Blizzard of 1888. New Jersey, New York, Massachusetts, and Connecticut were battered with nearly 50 inches of snow. The area came to a complete stand still and people were trapped in their homes for a week. Over 30 people were killed.
3. The first blizzard announced as a Federal Emergency was in 1977. It occurred in the southern region of Ohio and New York. It lasted for 5 days and the snow was 12 inches thick.
4. A huge blizzard in 1993 effected huge portion of the United States and Canada. It resulted in over 10 million power outages as well as the death of over 300 people.
5. The snowiest place in the United States is Rochester in New York. It often receives more than 8 feet of snowfall in a year.
6. When watching the weather forecast, a “Winter Storm Watch” may be issued in advance which means that there is a possibility of winter storm affecting your area although not definitely on the way. A “Winter Storm Warning” indicates the need to be ready for a blizzard that is on its way or already taking place.
7. It is not suggested to go outside during a blizzard as it increases the chance of hypothermia, accident and death.
8. Blizzards that occur on the East Coast are commonly known as Nor’Easters. Because of the presence of the Atlantic Ocean, the storm blows over the ocean and can last for up to 24 hours and dumps huge amounts of snow over the area.
9. If you need to travel by car in an emergency during a blizzard, you must have an emergency aid kit which should contain water, jumper cables, road flares, tow rope, non-perishable snacks that should help in case you get stuck on snow or your car breaks down.
10. If you live in an area in which blizzards can occur, you should always be prepared. You should make sure you have enough food and supplies. The supplies you should have include a radio with spare batteries, candles, a charged cell phone and lots of blankets to keep warm. Often children who are caught outside their homes when a blizzard begins have gotten lost as a result of the blinding snow.

11. In order to adapt to living in blizzard prone areas, the people of central Canada and mid-western USA build their homes with sloped roofs in order to avoid accumulation as the snow instead falls off.

How do Blizzards Form?

A blizzard is a long lasting and intense snowstorm with very strong winds. Generally, blizzards form when cold polar air meets warm, moist air from lower latitudes.

Three things are needed for a blizzard to occur, cold air at the surface, lots of moisture, and lift:

1. Cold air (below freezing): In order for there to be snowfall, the air temperature both up in the clouds and down at ground level must be cold. If the air temperature is warm near the ground, the snow will melt before the reaches the ground causing rain instead.
2. Moisture: This is known as water vapor. An excellent source of water vapor is when the air must blow across a large body of water, such as the ocean. As the airs blows over the water, some water is evaporated into the air. This is water vapor.
3. Warm, rising air: Warm air must rise over cold air in order for a blizzard to form. This can happen in two ways. The wind can pull warm air from the equator towards the poles, and cold air from the poles towards the equator. When warm and cold air meet, a front is formed which results in participation. If warm air rises up a mountaintop it can cool as it rises, forming clouds and blizzard snows.

Effects of Blizzards

1. A blizzard has the ability to put a city into standby, sometimes even for days. It can make driving conditions impossible and results in kids not being able to get to school as well as adults not being able to get to work. This in turn means school and businesses close and people are housebound.

2. Low air pressure during a blizzard can make breathing difficult for some people.
3. Electrical wires can be damaged resulting in a loss of electricity to homes. People are left without the use of computers, TV’s, appliances, and lights.
4. Anyone caught outside in a blizzard is at risk of getting frostbite or hypothermia.
5. A blizzard can cause damage to property, including roof cave-ins and broken windows. Falling trees can also damage cars.
6. Blizzards can cause car accidents and people can also get stuck on highways in their cars if they happen to be on the road when the blizzard hits.
7. Blizzards are life threatening and people have lost their lives because of them.
8. Blizzards hurt the economy as businesses lose money when people can’t get to work.
9. When transport routes and shops close during a blizzard there is a chance of food and water scarcity if the blizzard lasts for an extended period of time.
10. Even after the blizzard has passed it can take days for a city or town to get back to normal. Normal travel is particularly impacted because of the difficulty with plowing the large accumulations of snow.
11. Because of freezing temperatures, trees, plants, and crops can be destroyed in a blizzard. Forceful winds combined with a temperature that is around freezing can have the same effect as temperatures of more than 30 degrees below freezing on crops. In order to adapt to this, people living in areas prone to blizzards often plant wheat crops in the winter months.
12. Trees often lose their limbs due to the extreme winds, as well as damaging the tree; this can also damage property as well as injure people.
13. There is a high risk of flooding following a blizzard. When the temperature starts to rise and melt the snow, it can melt at a faster pace than the ability of the land to absorb it.
14. As well as being life threatening to humans, blizzards are also life threatening to animals. They can die if exposed to extreme cold temperatures. They can also die if they are stranded somewhere without food and water. Pets should be brought inside during a blizzard.

Hailstorm

A hailstorm is an unusual weather phenomenon in which balls of ice, called hail, fall from the sky. The ice balls are nothing more than solid precipitation that will form under certain conditions.

Fast Facts about Hail

- Hail is formed at high altitudes within massive clouds when supercooled water droplets adhere to each other and form layers of ice.
- The average velocity of a falling hailstone is approximately 106 miles per hour (mph).

What Causes a Hailstorm to Occur?

Several conditions are required in the atmosphere in order for hailstorms to occur. Highly developed Cumulonimbus clouds need to be present. These are the massive anvil or mushroom shaped clouds that are seen during thunderstorms which can reach heights up to 65,000 feet. There must also be strong currents of air ascending through these clouds. These currents are commonly known as updrafts. The updrafts contain ice particles, as a large number of water droplets become solid ice at the low temperatures found at high altitudes within the massive clouds. The last remaining condition is that the clouds will need to contain high concentrations of supercooled liquid water.

How does Hail Form?

A hailstone begins as a water droplet that is swept up by an updraft inside of a thundercloud. Inside the cloud, there are a large number of other supercooled water droplets already present. These supercooled particles will adhere to the water droplet's surface, forming layers of ice around it. As the water droplet reaches higher elevations within the cloud it comes into contact with more and more supercooled particles. This is because it is at the highest parts of the cloud, where the temperature is too low (at least 32 degrees Fahrenheit) for water molecules to remain in either a liquid or gaseous state. The hail embryo will grow larger and larger as it reaches higher altitudes in the updraft.

The hailstone will reach a size and weight where gravity will begin to act on it and pull it down. However, this is not necessarily the end of its formation, as it could be pulled into another strong updraft and remains in the upper part of the cloud. A stone the size of a golf ball would need an updraft flowing at 60 miles per hour (mph) to keep it elevated in the cloud. The size the hailstone reaches depends on the amount of time it spends surrounded by supercooled water droplets, but eventually gravity causes the stone to fall to the Earth.

During this process hailstones can become considerably large. In 2010, the largest hailstone found in the United States (Vivian, South Dakota) was 8 inches in diameter, 18.5 inches in circumference, and weighed approximately two pounds. As gravity takes over, they will fall to Earth at approximately 106 miles per hour. The exact velocity each stone falls at will vary depending on several conditions, such as weight, air friction and collisions with other suspended objects.

Hurricanes

A hurricane is a type of tropical cyclone or severe tropical storm. A typical cyclone is accompanied by thunderstorms, and a counterclockwise circulation of winds near the earth's surface. A hurricane has maximum sustained winds of 74 mph or higher. A tropical storm has sustained winds of 39-73 mph.

Hurricanes can cause catastrophic damage to coastlines and several hundred miles inland. Hurricanes can produce winds exceeding 155 miles per hour as well as tornadoes and microbursts. Moving or airborne debris can break windows and doors and allow high winds and rain inside a home or business. In some hurricanes, wind alone can cause extensive damage such as downed trees and power lines, collapsing weak areas of homes, businesses or other buildings. Additionally, hurricanes can create storm surges along the coast and cause extensive damage from heavy rainfall. Floods and flying debris from the excessive winds are often the deadly and destructive results of these weather events. Slow moving hurricanes traveling into mountainous regions tend to produce especially heavy rain. Excessive rain can trigger landslides or mudslides and flash flooding.

Each hurricane usually lasts for over a week, moving 10-20 miles per hour over the open ocean. Hurricanes gather heat and energy through contact with warm ocean waters. Evaporation from the seawater increases their power. Hurricanes rotate in a counter-clockwise direction around an "eye" in the Northern Hemisphere and clockwise direction in the Southern Hemisphere. The center of the storm or "eye" is the calmest part.

All Atlantic coastal areas, including New Hampshire, are subject to hurricanes or tropical storms. The Atlantic Hurricane Season begins on June 1st and ends on November 30th each year. Historically, the most active time for hurricane development is mid-August through mid-October.

Classification

Hurricanes are classified into five categories according to the Saffir-Simpson Hurricane Wind Scale, based on wind speed and potential to cause damage.

Category One – Winds 74-95 mph

- Very dangerous winds will produce some damage.
  - Minor damage to exterior of homes.
  - Toppled tree branches, uprooting of smaller trees.
  - Extensive damage to power lines, power outages.

Category Two – Winds 96-110 mph

- Extremely dangerous winds will cause extensive damage.
  - Major damage to exterior of homes.
  - Uprooting of small trees and many roads blocked.
  - Guaranteed power outages for long periods of time – days to weeks.

Category Three – Winds 111-129 mph

- Devastating damage will occur.
  - Extensive damage to exterior of homes.
  - Many trees uprooted and many roads blocked.
  - Extremely limited availability of water and electricity.

Category Four – Winds 130-156 mph

- Catastrophic damage will occur.
  - Loss of roof structure and/or some exterior walls.
  - Most trees uprooted and most power lines down.
  - Isolated residential areas due to debris pile up.
  - Power outages lasting for weeks to months.

Category Five – Winds greater than 157 mph

- Catastrophic damage will occur.
  - A high percentage of homes will be destroyed.
  - Fallen trees and power lines isolate residential areas.
  - Power outages lasting for weeks to months.
  - Most areas will be uninhabitable.

Familiarize yourself with the terms to the right to help identify hazards associated with hurricanes. Watches and warnings can be issued, not only for hurricanes, but for tropical storms that pose a risk to an area as well.

Take Action before a Hurricane

Consider taking preventative actions before hurricane season begins and/or before a hurricane arrives. During a hurricane or tropical storm watch (threat of hurricane or tropical storm conditions within 48 hours), monitor local radio or television stations for official emergency information and instructions.

Steps to be Ready

1. Complete the Family Emergency Plan and discuss it as a family. This is a simple way of keeping each member of the family informed on critical information: where to reconnect should you become separated, who to call, and what you will do should an earthquake occur.
2. Complete the Emergency Contacts Card and place one in your Emergency Kit.
3. Prepare an Emergency Kit. The Emergency Kit should be easily accessible should you and your family be forced to shelter in place (stay at home) for a period of time.

Take Action in your Home

If a hurricane is likely going to impact your area, you should:

- Listen to the radio or TV for information.
- Turn off utilities if instructed to do so. Otherwise, turn the refrigerator thermostat to its coldest setting and keep its doors closed.
- Keep rain gutters and downspouts clear of debris.
- Close and lock all windows. If possible, cover all of your home’s windows. Permanent storm shutters offer the best protection for windows. A second option is to board up windows with 5/8” exterior grade or marine plywood, cut to fit and ready to install. Tape does not prevent windows from breaking.
- Install straps or additional clips to securely fasten your roof to the frame structure. This will reduce roof damage.
- Reinforce your garage doors; if wind enters a garage it can cause dangerous and expensive structural damage.
- If time or circumstance allows, secure first floor doorways with sandbags, duct tape or heavy plastic to protect interior from possible flooding.

- Install a generator for emergencies.
- If in a high-rise building, when high winds are present, be prepared to take shelter on a lower floor because wind conditions increase with height. When flooding may be occurring, be prepared to take shelter on a floor safely above the flooding and wave effects.
- Learn community hurricane evacuation routes and how to find higher ground. Determine where you would go and how you would get there if you needed to evacuate. If instructed to evacuate, do so following first responder instructions.
- Learn the elevation level of your property and whether the land is flood-prone. This will help you know how your property will be affected when storm surge or tidal flooding are forecasted.
- Ensure you have a supply of water for sanitary purposes such as cleaning and flushing toilets. Fill the bathtub and other large containers with water.
- Avoid using the phone, except for serious emergencies.
- Tie down or bring indoors any objects that might be blown around by hurricane winds (outdoor furniture, decorations, garbage cans, display racks, signs and any other loose objects that are normally left outside).
- If you own a boat, determine how and where to moor and secure it.
- Ensure that all vehicles are serviced and fuelled in case you may need to evacuate. Determine where they can be stored during the storm if you do not evacuate.
- Be sure trees and shrubs around your home are well trimmed so they are more wind resistant.
- If you are advised to evacuate, lock the doors when you leave.

Insurance

Hurricanes cause heavy rains that can cause extensive flood damage in coastal and inland areas. Everyone is at risk and should consider flood insurance protection. Flood insurance is the only way to financially protect your property or business from flood damage.

Be Safe during a Hurricane

If you are under a hurricane or tropical storm warning, it means that it is expected to affect your area within 36 hours. It is important to be aware and knowledgeable on what’s happening, listen to news reports, secure important items to higher ground and get ready to make the decision on whether you need to evacuate.

If you are advised to evacuate, do so immediately. Evacuation is simple and safer before the hurricane arrives. Don't forget your emergency kit, which should include your Emergency Contacts Card and your Family Emergency Plan which includes your evacuation location options. Have your evacuation plan ready, and follow recommended routes. Know that flash flooding can occur. If there is any possibility of a flash flood, move to higher ground right away. Do not wait for instructions to move.

You should evacuate under the following conditions:

- If you are directed by local authorities to do so. Be sure to follow their instructions.
- If you live in a mobile home or temporary structure; such structures are particularly hazardous during hurricanes no matter how well fastened to the ground.
- If you live in a high-rise building—hurricane winds are stronger at higher elevations.
- If you live on the coast, on a floodplain, near a river, or on an inland waterway.
- If you feel you are in danger.

If you are unable to evacuate, go to your safe room. If you do not have one, follow these guidelines:

- Stay indoors during the hurricane and away from windows and glass doors, even if they are covered.
- Close all interior doors – secure and brace external doors. Closed doors will help prevent damaging hurricane winds from entering rooms.
- Keep curtains and blinds closed. Do not be fooled if there is a lull; it could be the eye of the storm – winds will pick up again.
- Take refuge in a small interior room, closet, or hallway on the lowest level.
- Lie on the floor under a table or another sturdy object.

Take Action after a Hurricane

After the impact of a hurricane or tropical storm, stay alert for extended rainfall and flooding, even after the hurricane or tropical storm has weakened.

Avoid Injuries when Returning to your Home

- Continue listening to a NOAA Weather Radio or the local news for the latest updates.
- Stay alert for extended rainfall and subsequent flooding even after the hurricane or tropical storm has ended.

- If you evacuated, return home only when officials say it is safe.
- Drive only if necessary and avoid flooded roads and washed-out bridges. Stay off the streets. If you must go out, watch for fallen objects, downed electrical wires, and weakened walls, bridges, roads, and sidewalks.
- Stay away from loose, dangling, or downed power lines and report them immediately to the power company.
- Inspect your home for damage. Take pictures of damage, both of the building and its contents, for insurance purposes. If you have any doubts about safety, have your residence inspected by a qualified building inspector or structural engineer before entering.
- If you smell gas or hear a blowing or hissing noise, open a window and get everyone outside quickly. Turn off the gas, using the outside main valve if you can, and call the gas company. If you turn off the gas for any reason, it must be turned back on by a professional.
- Check for sewer and water pipe damage. If you suspect sewage lines are damaged, avoid using the toilets and call a plumber. If water pipes are damaged, contact the water company and avoid using water from the tap.
- Use battery-powered flashlights in the dark and when examining buildings. Do NOT use candles.
- Watch your pets closely and keep them under your direct control.
- Use extreme caution when encountering debris.
- Wear protective clothing and be cautious when cleaning up to avoid injury.
- Use the telephone only for emergency calls.
- Never use a generator inside homes, garages, crawlspaces, sheds, or similar areas, even when using fans or opening doors and windows for ventilation. Deadly levels of carbon monoxide can quickly build up in these areas and can linger for hours, even after the generator has shut off.

Ice Storms

When warm and cold air meets, the resulting weather phenomena can be an ice storm. Ice storms can be particularly dangerous because the freezing rain makes an icy glaze on roads and other outdoor surfaces. Very heavy amounts of ice brutally damage trees and weigh down power lines. In fact, the weight of the ice can be increased by 30 times! The weight of the ice is made worse if the wind speed is high. The areas with the highest frequency of freezing rain occasions are the Midwest and Northeast.

The accumulations of ice are classified according to the impact they have. They are classified as nuisance, disruptive, and crippling. During a nuisance ice storm event, less than ¼ of an inch of ice accumulates. Travel, especially on roads with bridges, can be difficult. Disruptive ice storms are typically an ice accumulation of ¼ of an inch to ½ of an inch. During these storms, there can be power outages and sagging or breaking tree limbs. The most dangerous ice storm is the crippling variety. This category of storm causes widespread ice accumulations of over ½ inch, and may reach accumulations of one inch. Due to severe damage to trees and power lines, power may be interrupted for many days. This is especially dangerous for those who do not have back-up power solutions and go for prolonged periods with no heat.

Tornadoes

Tornado is a small-diameter column of violently rotating air developed within a convective cloud and in contact with the ground. Tornadoes occur most often in association with thunderstorms during the spring and summer in the mid-latitudes of both the Northern and Southern Hemispheres. These whirling atmospheric vortices can generate the strongest winds known on Earth: wind speeds in the range of 500 km (300 miles) per hour have been measured in extreme events. When winds of this magnitude strike a populated area, they can cause fantastic destruction and great loss of life, mainly through injuries from flying debris and collapsing structures. Most tornadoes, however, are comparatively weak events that occur in sparsely populated areas and cause minor damage.

This describes tornado occurrence and formation as products of instability within the Earth's air masses and wind systems. Wind speeds and destructiveness are discussed with special reference to the Enhanced Fujita Scale of tornado intensity. For short, descriptive entries on closely related phenomena.

The Enhanced Fujita (EF) Scale of tornado intensity

	wind speed range			
EF number	metres per second	kilometres per hour	feet per second	miles per hour
0	29–38	105–137	95–125	65–85
1	38–49	138–177	126–161	86–110
2	50–60	179–217	163–198	111–135
3	61–74	219–266	199–242	136–165
4	74–89	267–322	243–293	166–200
5	89+	322+	293+	over 200

Tornado Occurrence and Distribution

Global Occurrence

Tornadoes have been reported on all continents except Antarctica. They are most common on continents in the mid-latitudes (between 20° and 60 °N and S), where they are frequently associated with thunderstorms that develop in regions where cold polar air meets warm tropical air.

Calculating which country has the most tornadoes per year depends on how this measurement is defined. The United Kingdom has the most tornadoes per land size, most of them weak. On average, about 33 tornadoes are reported annually there. In absolute numbers, the United States has the most tornadoes by far (more than 1,000 per year have been reported every year since 1990). It also has the most violent tornadoes (about 10 to 20 per year). Tornadoes of this intensity are very infrequent outside of the United States. Canada reports the second largest number of tornadoes (about 80 to 100 annually). Russia may have many tornadoes, but reports are not available to quantify their occurrence. About 20 tornadoes are reported in Australia each year, though the actual number is likely much higher. Many storms occur in uninhabited areas, and so any tornadoes that they produce are undocumented.

Records of tornado occurrences are fragmentary for many areas, making estimates of global tornado frequency difficult. Insurance records show that tornadoes have caused significant losses in Europe, India, Japan, South Africa, and Australia. Rare but deadly tornadoes have occurred in many other countries, including Bangladesh, China, and Argentina. There are few tornado reports from either the Arctic or the equatorial tropics.

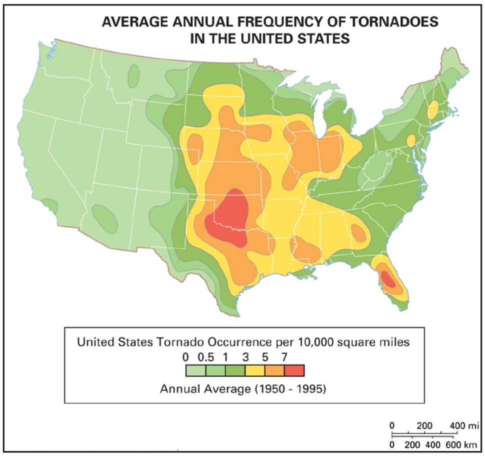
In the United Kingdom almost all reported tornadoes are associated with vigorous convection occurring in advance of and along a cold frontal boundary. Large temperature differences are associated with early winter cold fronts that move rapidly across the country from the north and west, at times spawning widespread outbreaks of small tornadoes. For example, the passage of a very strong frontal boundary across the United Kingdom on November 23, 1981, produced 105 documented tornadoes. Similar phenomena occur in other European countries such as France and Belgium.

Most Southern Hemisphere tornadoes occur in Australia. Many reports come from New South Wales, where there were 173 reported tornadoes from 1901 to 1966. In addition, South Africa and Argentina both reported 191 tornadoes from 1930 to 1979. Because tornado formation is closely tied to the speed and directional shear of the wind with height, tornadoes in the Southern Hemisphere almost exclusively rotate clockwise, opposite to the rotation of their Northern Hemisphere counterparts.

Occurrence in the United States

Reported Events

Though tornadoes occur in every state, they are most frequent and attain the highest intensities in the central portion of the United States. Texas has the most reported tornadoes each year, about 125 on average for the years 1953–91; Florida, with almost 10 tornadoes per 10,000 square miles per year, has the most per area. However, most Florida tornadoes are very weak and affect extremely small areas.



Map of the average annual frequency of tornadoes in the United States, showing the range of "Tornado Alley" from Texas through Nebraska.

From 1916 through 1998, about 45,000 tornadoes were documented in the United States. From 1916 to 1953, approximately 158 tornadoes were reported per year. After 1953, the beginning of the "modern period" of tornado documentation, the number of reports rose to more than 800 per year. (The modern period is considered to have begun in 1953 because this was the first full year in which the U.S. Weather Bureau issued tornado watches—that is, bulletins reporting that a tornado might be imminent.) The increased number of tornadoes reported was due to improvements in observing and recording (largely because of the establishment of a network of volunteer tornado "spotters"), which allowed a greater number of weak events to be recognized. During the interval from 1953 to 1998, there was an average of 169 "tornado days" (days on which one or more tornadoes were reported) per year. However, the early years of the modern period, with their relatively fewer reports, bias these averages. If only the 15 years 1984 through 1998 were considered, the average number of tornadoes per year would be 1,025, occurring on 173 tornado days per year. These higher numbers are credited to additional improvements in tornado reporting.

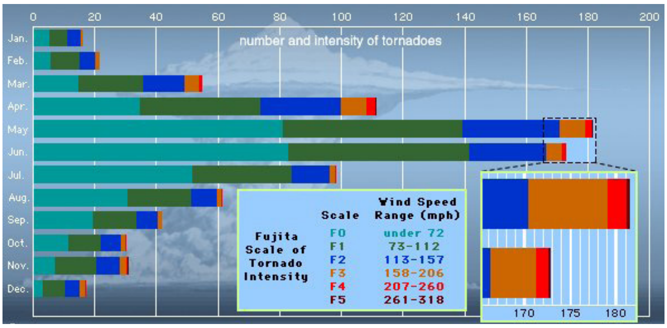
Geographic Distribution

When the number of tornado occurrences, their intensity, and the area they affect are considered, the centre of tornado activity is unquestionably seen to exist in the western portions of the southern Great Plains. The region of maximum tornado frequency, rightfully called Tornado Alley, extends from west Texas northeast through the western and central portions of Oklahoma and Kansas and across most of Nebraska.

Another area of frequent tornado occurrence is found across eastern Iowa, Illinois, Indiana, western Ohio, the southern portions of Wisconsin and Michigan, and the northern part of Kentucky. While this area experiences fewer tornadoes than does Tornado Alley, it has been struck by some of the strongest known tornadoes and has been the site of several large tornado outbreaks (that is, the occurrence of multiple tornadoes from the same weather system). The Gulf States (from east Texas to central Florida) have many weak tornadoes and have had outbreaks. The Gulf States also experience many tornadoes associated with hurricanes.

Seasonal Patterns

While most tornadoes develop in the spring and summer, tornadoes have occurred every day of the year. Several days have had many occurrences, reflecting large regional and national outbreaks. The distribution of reported tornadoes by month for the period 1916 through 1990 shows that about 74 percent of all tornadoes are reported from March through July. Peak months are April (14 percent), May (22 percent), and June (20 percent). December and January are the months of lowest activity.



Graph shows the number and intensity of tornadoes in the United States per month. Tornado wind speed is ranked according to the Fujita Scale of tornado intensity. The occurrence of high-intensity tornadoes, though rare, is most common from March through June. Tornadoes are less common during the winter because air-mass boundaries are not as likely to be characterized by the strong temperature and moisture contrasts required to fuel powerful thunderstorms.

The main concentration of tornado activity migrates across the central portion of the United States in a seasonal cycle. Toward the end of winter (late February), the centre of tornado activity lies over the central Gulf States. At this time, southward-moving cold air reaches the southern limit of its expansion and encroaches on the Gulf Coast. As spring progresses, the days grow longer and more solar energy is intercepted. Land temperatures rise, and warm, moist air from the Gulf of Mexico progressively drives back the cold air. The centre of activity then moves eastward to the southeastern Atlantic states, with tornado frequency peaking there in April.

As spring advances and gives way to summer, the centre of tornado activity gradually shifts westward and then northward. It moves across the southern Plains in May and June and then into the northern Plains and the Great Lakes states by early summer. Late summer through early fall is usually a relatively quiet time because the temperature and moisture contrasts across the boundary between the two air masses are weak. An extension of the Bermuda high (a centre of high atmospheric pressure that develops over the Atlantic Ocean) dominates the southeastern third of the United States, and, while thunderstorms occur frequently in the warm, moist air, they seldom become severe. In late fall the days grow shorter, the temperature and moisture contrast intensifies again, and the centre of tornado activity retreats south toward the Gulf, completing the annual cycle.

Superimposed on this general pattern are large year-to-year variations. These arise because almost all tornado-producing storms are embedded within episodic northward surges of warm, moist air. The distribution of tornadoes in any one year thus reflects the weather patterns—especially the tracks followed by the synoptic-scale low-pressure centres—prevailing in that year.

Regional factors must also be taken into account. Along the Gulf Coast, tornadoes can be produced by thunderstorms that come ashore as a hurricane makes landfall. In a few cases, many tornadoes will be produced. For example, on September 20, 1967, thunderstorms in Hurricane Beulah produced 115 tornadoes in south Texas.

Diurnal Patterns

Although tornadoes can occur at all times of the day, they are most frequent from mid-afternoon to early evening. In the central United States, where most tornadoes occur, tornado frequency is highest between 5:00 and 6:00 PM. Weak and strong tornadoes occur most frequently in this same hour. Violent tornado occurrences peak an hour later, between 6:00 and 7:00 PM. Tornado occurrences peak in the late afternoon to early evening because there must be sufficient time for the Sun strongly to heat the ground and the surface layer of the atmosphere, thus inducing and sustaining severe thunderstorms. Few reports (roughly 1 percent) are from between 5:00 and 6:00 AM, the period just around sunrise when the atmosphere is often very stable.

Tornado Outbreaks

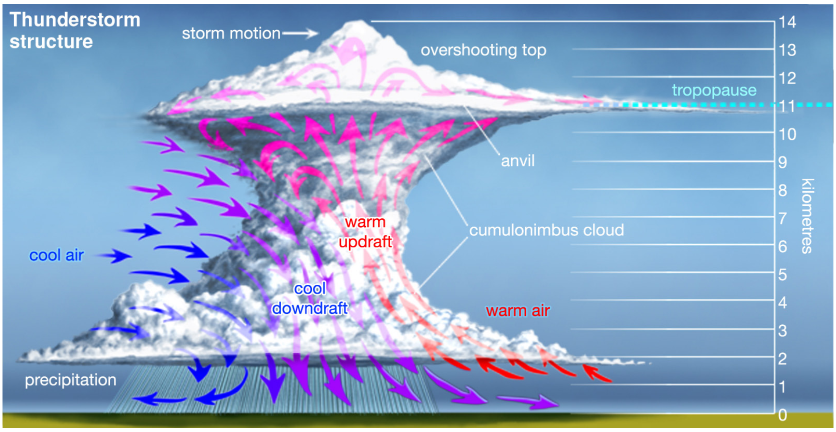
A tornado outbreak is the occurrence of several tornadoes over a region, usually due to thunderstorms embedded in the same synoptic-scale weather system. Outbreaks are classified according to the number of tornadoes reported: small (6 to 9 tornadoes), medium (10 to 19), and large (more than 20 tornadoes). Outbreaks are also classified according to the area affected: in local outbreaks, one or only a portion of one state is affected; in regional outbreaks, two or three states contain all or almost all the tornadoes; in national outbreaks, tornadoes are reported in many states.

On most tornado days, only a relatively small region has the essential conditions juxtaposed in just the right way to foster tornado development. This alignment usually lasts for only a small portion of an afternoon. As a consequence, only the two or three storms that form in this region are likely to produce tornadoes. Most of these vortices are weak, but one or more may be strong. Most occur in the space of one to two hours in the middle to late afternoon. Situations like this give rise to small local outbreaks several times per year.

Most dangerous are national outbreaks. Perhaps once every 10 to 15 years, the synoptic-scale weather pattern produces conditions favourable to the production of strong storms over a large portion of the central United States. The number of conditions required to align over this large an area usually limits the occurrence of such widespread outbreaks to March and April. Many of the tornadoes are likely to be strong or violent. The largest national tornado outbreak was the Super Outbreak of April 26–28, 2011, which spawned more than 300 tornadoes across the eastern United States. The second largest was the Super Outbreak of April 3–4, 1974, which was credited with producing 148 tornadoes in the central and southern United States (though 4 of these were later reclassified as downbursts by the meteorologist T. Theodore Fujita). The third largest was the April 11–12, 1965, Palm Sunday Outbreak.

Prediction and Detection of Tornadoes

The first step in predicting the likely occurrence of tornadoes involves identifying regions where conditions are favourable to the development of strong thunderstorms. Essential ingredients for the occurrence of such storms are cool, dry air at middle levels in the troposphere superimposed over a layer of moist, conditionally unstable air near the surface.



Structure of a thunderstorm.

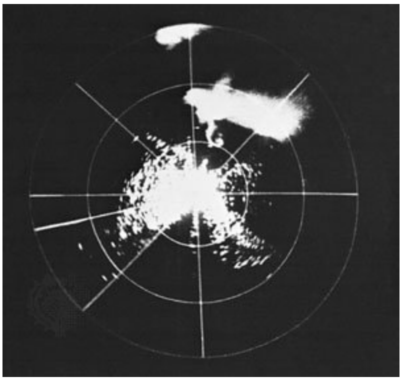
In figure, when the atmosphere becomes unstable enough to form large, powerful updrafts and downdrafts (as indicated by the red and blue arrows), a towering thundercloud is built up. At times the updrafts are strong enough to extend the top of the cloud into the tropopause, the boundary between the troposphere (or lowest layer of the atmosphere) and the stratosphere.

Conditions commonly leading to thunderstorm development occur along the warm side of the boundary line, or front that separates cold, dry air from warm, moist air. The degree of instability present in the atmosphere is approximated by the contrasts in temperature and moisture across the frontal boundary that divides the two air masses. For a storm to generate tornadoes, other factors must be present. The most important of these is a veering wind profile (that is, a progressive shifting of the wind, clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere, with increasing height) at low and middle levels, along with strong winds at high levels. Both of these wind actions are necessary to provide the required spin in the air that may eventually culminate in a tornado. A veering wind profile can be provided by the same strong temperature contrasts powering the thunderstorm, and high-altitude winds can be provided by the jet stream, the thin ribbon of high-speed air found in the upper half of the troposphere.

For the generation of a tornado, the diffuse spin must be concentrated into a small area as an evolving storm goes through several distinct stages of development. The first appearance of rotation in a storm is caused by the interaction of a strong, persistent updraft with the winds that blow through and around the storm. Rotation intensifies as the speed of the wind increases and as its direction veers from southeast to south and then around to west (in the Northern Hemisphere) with increasing height through the lower half of the troposphere.

Forecasters in the United States have learned to carefully monitor the wind profile in regions of instability and to estimate how temperatures and winds will evolve through the course of a day, while at the same time tracking the movement and intensity of the jet stream. With the aid of modern observing systems, such as vertically pointing radars (called wind profilers) and imaging systems on satellites that can measure the flow of water vapour through the Earth’s atmosphere, forecasters can usually identify where conditions will be favourable for tornado formation one to seven hours in advance. This information is transmitted to the public as a tornado watch. A tornado warning is issued when a tornado has been spotted either visually or on a weather radar.

Once strong thunderstorms begin to form, local offices of the National Weather Service monitor their development using imagery from satellite sensors and, most important, from radars. These allow forecasters to follow the evolution of the storms and to estimate their intensity. In the past, weather surveillance radars provided information only on the intensity of rainfall within the storms. Weather forecasters then had to infer the onset of rotation within a storm’s updraft from circumstantial evidence, such as when the precipitation began to curve around the updraft to produce a "hook echo," a hook-shaped region of precipitation that flows out of the main storm and wraps around the updraft. Such inferences were highly subjective and prone to false alarms or very short-notice warnings. Today, modern weather surveillance radars not only provide information on the intensity of a storm's rainfall but also utilize the Doppler principle to sense winds within thunderstorms. Wind speeds are determined from radio waves reflected by raindrops and other particles carried along by the wind.



Hook echo of a tornado in Champaign. This was the first occasion on which the hook echo, an important clue in the tornado warning system, was recorded.

Doppler radars can measure rotation in the updraft and allow forecasters to watch the formation of a mesocyclone (that is, a region of rotating air within a thunderstorm). On Doppler radar, the presence of a well-organized mesocyclone is indicated by a small region of concentrated shear in the wind. On one side of the mesocyclone the rotating winds flow toward the radar; and on the other, they move away. In some cases, the formation of the tornado core can be detected. The tornado core is a roughly cylindrical region of lower atmospheric pressure that is bounded by the maximum tangential winds (the fastest winds circulating around the centre of the tornado). The radar indication of intense concentrated rotation is called the tornado vortex signature, although this area does not always evolve into a tornado core. These improvements have allowed forecasters to increase warning times while reducing false alarms.

Tornado-tracking activities under way with a field command vehicle from the National Severe Storms Laboratory (NSSL) in Goshen county, Wyo., as part of the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2).

Death and Damage

In the period 1916 through 1998, tornadoes claimed 12,282 lives in the United States, an average of 150 deaths per year. For the period 1953 through 1998, tornadoes claimed 4,032 lives, an average of 88 deaths per year. The decrease in fatalities is due to improvements in safety awareness and severe-weather warnings. There have been wide variations in the number of deaths from one year to the next, the minimum being 15 deaths in 1986 and the maximum being 805 in 1925 (due largely to the Great Tri-State Tornado of March 18, 1925). Since the advent of improved warning systems, three years contributed disproportionately to the total number of deaths: 1953, 1965, and 1974. Of the 519 deaths in 1953, 323 were due to strong tornadoes striking three urban areas (Waco, Texas; Flint, Michigan; and Worcester, Massachusetts). The high death counts in 1965 and 1974 (301 and 366, respectively) were the result of large national tornado outbreaks—the April 11–12, 1965, Palm Sunday Outbreak and the April 3–4, 1974, Super Outbreak.

Most deaths and injuries in tornadoes result from individuals being struck by flying debris. People are sometimes injured or killed by being rolled across the ground by the high winds. Also, a few people appear to have been killed by being carried aloft and then dropped from a great height.

Almost all of the damage caused by tornadoes can be attributed to wind-induced forces tearing structures apart. High-speed air flowing over a building's roof and around its corners produces forces that pull upward and outward, respectively. Once windows or doors on the windward side of a building break, air rushes in; this pushes outward on the remaining walls and upward on the roof from the inside, adding to the forces induced by the outside airflow. Often a building is torn apart so quickly and dramatically by these forces that it appears to explode.

It used to be thought that many buildings "exploded" owing to the development of an extreme difference in pressure between their interiors and the outside air. The rate at which pressure changes at a point on the surface as a tornado approaches may be as great as 100 hectopascals per second (100 hectopascals are equivalent to about 10 percent of atmospheric pressure at sea level). While this is a significant drop, studies have shown that most structures are sufficiently open that, even with the high rate of pressure change associated with a rapidly moving tornado; interior pressure can adjust quickly enough to prevent an explosion. Indeed, since the area of greatly reduced pressure beneath a tornado is small compared with the area of damaging winds, it is likely that a building already will have suffered damage from the winds by the time it experiences a rapid drop in outside pressure.

Tornado Safety

Tornadoes produce extremely hazardous conditions. The main dangers are caused by extremely high winds and flying debris. Little can be done to prevent heavy damage to structures that are directly hit by a tornado, though good building practices (such as securely fastening the roof of the house to the walls and securing the walls to the foundation) can reduce damage to structures on the periphery of a tornado's circulation. Consequently, most hazard research has been focused on saving lives and reducing injuries.

Surviving a tornado requires an understanding of the hazards and some preparation. The most important step is taking shelter. People are advised not to waste time opening windows to reduce the pressure in a house. It is a myth that sudden pressure changes associated with tornadoes cause structures to explode, and flying debris is likely to break the windows before the tornado hits anyway. The best protection in the home can be found under a sturdy table or workbench in the basement. In homes without basements (or when time is extremely limited), the recommendation is to shelter in a small interior room such as a closet or bathroom, preferably one with thick walls and no windows. A mattress can be used as additional cover, and a heavy blanket can protect against dust. It is recommended that people also shield their head and neck with their arms. People are strongly advised to avoid windows in all cases, as flying glass can cause terrible wounds.

Many of the fatalities produced by tornadoes occur in mobile homes. Such homes are very lightly constructed and begin to come apart at relatively low wind speeds. In addition, they can easily be blown over and disintegrate, producing ample amounts of sharp-edged flying debris. Consequently, mobile homes—even ones with anchors or tie-downs—offer no shelter from even very weak tornadoes. At the first indication of possible tornadic activity, residents of mobile homes are advised to seek shelter in sturdy buildings. If no such building is available, it is better to shelter in a ditch or culvert than to remain in the home.

If caught in the open in tornadic conditions, it is recommended to stay low to the ground (preferably in a ditch or culvert) and to hold onto a sturdy object such as a tree stump. The main danger is from being tumbled along the ground by high winds, which can in effect beat a person to death.

It is advised that cars be abandoned as a tornado approaches and that shelter be sought in a ditch. Many tornado-related deaths have occurred in traffic jams, such as those associated with the April 10, 1979, tornado in Wichita Falls, Texas. Cars tend to be tumbled over and over by tornadoes and, in extreme cases, carried aloft and dropped from significant heights. Victims are often thrown from the tumbling car or blown out through the windows.

Tornado Intensity

Tornado intensity is not estimated directly from measured wind speeds, because tornadoes rarely pass near meteorological instruments. Rather, it is commonly estimated by analyzing damage to structures and then correlating that damage with the wind speeds required to produce such destruction. This method is essential to assigning tornadoes specific values on the Enhanced Fujita Scale, or EF-Scale, of tornado intensity. The notion of developing such a scale for use in comparing events and in research was proposed in 1971 by the Japanese American meteorologist T. Theodore Fujita.

Fujita’s scale was widely used in the United States and adapted for use in other parts of the world; however, almost from the beginning, the limitations of his approach were recognized. The primary criticisms were a lack of sufficient damage indicators for the many building types found in modern society, no recognition of regional variations in types and quality of construction of otherwise similar structures, and a lack of a definitive correlation between observed damage and wind speed. As a result, there were inconsistencies in the rating of tornado intensity in the historical records (which is shown as noise in statistical analyses). Also, tornado wind speeds, especially in very high wind events, were overestimated.

In 2004, after 33 years of experience with the original Fujita Scale, leading atmospheric researchers and tornado forecasters developed a plan to improve the estimation process and eliminate some of the limitations. The result, the Enhanced Fujita Scale, was adopted for use in 2007. It retains many of the features of the original scale but provides more precision at the higher intensity values. The scientists and forecasters also worked out ways to adjust the older records so that EF values would be available for the comparison.

To classify a tornado using the EF-Scale, the damage occurring along the tornado’s track is mapped. A tornado’s intensity varies along its path, with the most extreme damage usually being restricted to a small area, and the overall EF-Scale value assigned represents the tornado’s highest attained intensity. Once the degree of damage to structures and vegetation has been assessed and matched with the appropriate EF-Scale value, the maximum wind velocities within the range associated with the EF-Scale value are assigned. Even in its improved form, such a system is inevitably limited. For example, a powerful tornado that does not pass near buildings or trees, causing little or no damage, may be given an EF-Scale value less than its true intensity.

The Enhanced Fujita Scale recognizes tornadoes of six different intensities ranging in number from EF0 to EF5. For many purposes, these can be grouped into three broader categories—weak, strong, and violent—which are described in turn below, using Fujita’s original photographs to illustrate the type of damage associated with each category.

Weak (EF0 and EF1) Tornadoes

Though most tornadoes (60 to 70 percent) are in this category, they account for less than 5 percent of all deaths. A weak tornado usually has a single funnel cloud (that is, a column of water droplets) resembling an elongated, upward-opening cone with a smooth surface. The cone often does not touch the ground. In weak tornadoes, vertical wind speeds are thought to be greatest along the central axis of circulation. Many weak tornadoes appear not to extend upward far beyond the base of the parent storm.

Machine shed pushed from its foundation, the type of "moderate damage" associated with weak tornadoes (ranking F1 on the Fujita Scale of tornado intensity).

Strong (EF2 and EF3) Tornadoes

About 35 percent of all tornadoes are in the strong category, and they account for about 30 percent of all deaths. Typically, a strong tornado has a broad, columnar funnel cloud. The funnel surface usually has a rough, rapidly changing texture, reflecting small-scale turbulence. Available evidence suggests that in a strong tornado, most of the rising air surges upward in a cylindrical annulus around the central axis. Vertical speeds are lower along the axis itself. Sometimes "suction vortices" can be seen within the tornado core at its point of contact with the ground. This little-understood feature appears to contain the highest wind speeds in the tornado. Strong tornadoes extend well up into the generating thunderstorm because they generally form in or around a strongly rotating updraft that may persist through the storm's full height.

Multiunit building with its roof and many walls destroyed, the type of "severe damage" associated with strong tornadoes (ranking F3 on the Fujita Scale of tornado intensity).

Violent (EF4 and EF5) Tornadoes

Only a very few tornadoes (2 percent or so) reach intensities high enough to be categorized as violent; however, they account for about 65 percent of all deaths. In many cases, a violent tornado has a broad core with a diameter of 0.5 km (0.3 mile) or more. At the centre of the core, there is a relatively calm and clear eye. In the eye, nonswirling air flows down from upper levels of the thunderstorm due to low pressure in the base of the core. Upon reaching the ground, this descending inner flow turns outward and mixes with air rushing in from the inflow boundary layer (that is, the layer of air near ground level). The combined flow then spirals upward around the eye in an annulus.

Completely disintegrated residential subdivision, the type of "incredible damage" associated with the most violent tornadoes (ranking F5 on the Fujita Scale of tornado intensity).

In some violent tornadoes, secondary vortices may form in the annulus, giving rise to what is termed a multiple-vortex tornado. In these secondary vortices, air spins rapidly around the axes while the vortices themselves rotate around the periphery of the central eye. Small secondary vortices are also called suction vortices when they are most evident in the corner region, the area where the wind entering the base of the tornado abruptly "turns the corner" from primarily horizontal to vertical flow. A tornado with one or more suction vortices is distinguished from a multiple-vortex tornado in that a suction vortex is at most only several hundreds of metres high, while multiple vortices extend all the way up into the cloud base of the parent thunderstorm. The fastest known surface winds occur around the tips of secondary vortices.

Physical Characteristics of Tornadoes

Airflow Regions

Fully developed tornadoes contain distinct regions of airflow. As is shown in the figure, the central axis of circulation is within the core region, a roughly cylindrical area of lower atmospheric pressure that is bounded by the maximum tangential winds (the fastest winds circulating around the centre of the tornado). If a visible funnel cloud forms, it will occur within the core region. The funnel cloud consists of a column of water droplets, commonly called the condensation funnel. In very dry conditions there may be no condensation funnel associated with a tornado.

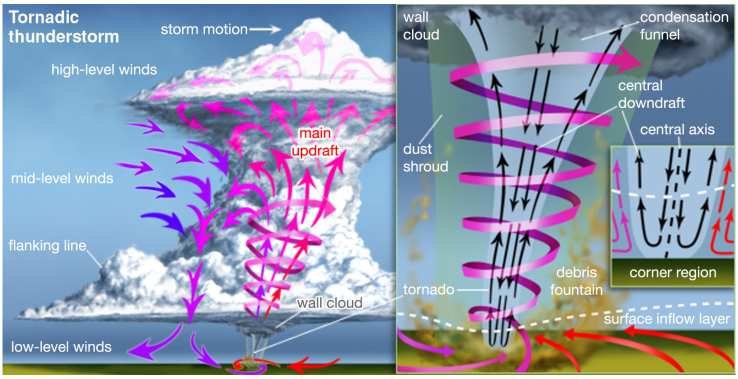


Figure indicates (Left) Tornadic thunderstorm: The rotating updraft that produces the tornado extends high into the main body of the cloud.(Right) Anatomy of a tornado: Air feeds into the base of a tornado and meets the tornado's central downflow. These flows mix and spiral upward around the central axis. The tornado's diameter can be much greater than that of the visible condensation funnel. At times the tornado may be hidden by a shroud of debris lifted from the ground.

Responding to the reduced pressure in the central core, air near the ground located in what is referred to as the inflow boundary layer converges from all directions into a tornado's "corner region." This region gets its name because the wind abruptly "turns the corner" from primarily horizontal to vertical flow as it enters the core region and begins its upward spiral. The corner region is very violent. It is often marked by a dust whirl or a debris fountain, where the erupting inflow carries aloft material ripped from the surface. The inflow boundary layer that feeds the corner region is usually a few tens of metres deep and has turbulent airflow. Above the boundary layer, the core is surrounded by a weakly swirling outer flow—the inflow to the storm's updraft—where radial motions (movements toward or away from the tornado's axis) is relatively small. Somewhere aloft (exactly where is not known), the core and the swirling outer flow merge with the updraft of the generating thunderstorm.

Winds in a tornado are almost always cyclonic; that is, they turn counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. This dominance of rotation direction is indirectly due to the Earth's rotation, which plays a role in controlling the structure of all large-scale weather systems. As is explained more fully in the section Tornado formation, most tornadoes are produced by thunderstorms, and a tornado's parent thunderstorm is in turn embedded within a larger weather system that determines the vertical shear in the winds (that is, their change in speed and direction with height across the troposphere). These systems rotate cyclonically, and a tornado's rotation comes from a concentration of the spin present in the sheared winds. However, not all tornadoes are cyclonic. About 5 percent of all observed tornadoes rotate anticyclonically—that is, they turn clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Wind Speeds and Air Pressures

Measurement of wind speeds can be obtained by photogrammetry (measurements from photographs) and through remote sensing techniques using the Doppler Effect. These two techniques are complementary. They provide information about tornado wind speeds by tracking objects in and around the core (the assumption being that the objects are moving with the speed of the air). Photogrammetry allows speeds across the image plane to be determined by analysis of motions of dust packets, pieces of vegetation, and building debris as recorded on film or videotape, but it cannot be used to determine wind speed toward or away from the camera. On the other hand, through processing of Doppler-shifted electromagnetic "echoes" received from raindrops and debris illuminated with pulses of radio waves (radar) or light (lidar), wind speed toward or away from the instrument can be determined.

Under some conditions, extreme wind speeds can occur in the corner region of a tornado. The few measurements of violent tornado winds that have been made using Doppler radar and photogrammetry suggest that the maximum possible tangential wind speeds generated by tornadoes are in the range of 125 to 160 metres per second, or 450 to 575 km per hour (about 410 to 525 feet per second, or 280 to 360 miles per hour). Most researchers believe the actual extreme value is near the lower end of this range. Consistent with this thinking was the measurement made using a mobile Doppler radar of the fastest wind speed ever measured, 318 miles per hour (about 512 km per hour), in a tornado that hit the suburbs of Oklahoma City, Oklahoma, on May 3, 1999.

Maximum tangential speeds occur in a ring-shaped region that surrounds the tip of the vortex core that is centred 30 to 50 metres (100 to 160 feet) above the ground. (Hence, they tend to be a bit higher than damage-causing winds at the surface.) The vertical speeds of air rising as a central jet through the hole in the ring may be as high as 80 metres per second, or 300 km per hour (about 250 feet per second, or 170 miles per hour). Radial speeds of air flowing from the inflow region to the corner region (which feeds the central jet) are estimated to reach 50 metres per second, or 180 km per hour (about 160 feet per second, or 110 miles per hour). Because the organization of the airflow varies considerably with tornado intensity, extremes in vertical and radial speeds may not occur at the same time as extremes in tangential speeds.

These extreme speeds are the strongest winds known to occur near the Earth's surface. In reality, they occur over a very small portion of the tornado core close to the ground. Their actual occurrence is rare, and, when they do occur, they usually last only a very short time.In almost all tornadoes (about 98 percent), the maximum attained wind speed is much less than these maximum possible speeds.

While there have not been any direct measurements of atmospheric pressure in tornadoes, a few measurements have been taken when tornadoes passed near weather stations with barographs (instruments that record atmospheric pressure over time). Data from such incidents, along with measurements made in laboratory vortices, provide for the construction of mathematical models describing the distribution of surface pressure beneath tornadoes. These models, combined with information on tornado winds, are used to extrapolate what was the most likely air pressure at the centre of any given tornado.

These extrapolations indicate that a region of low surface pressure is centred beneath the tornado core. The area of this region is relatively small compared with that of the annulus of high-speed winds that surrounds it. Even for violent tornadoes, the reduction in surface pressure in this area (relative to surface pressure in the surrounding atmosphere) is probably no more than 100 hectopascals (that is, about 10 percent of standard atmospheric pressure at sea level). In most tornadoes, the reduction in central surface pressure is not that great.

The lowest atmospheric pressure in a tornado is thought to be at the centre of the core a few tens to a few hundred metres above the surface, though the magnitude of the pressure reduction is unknown. In violent tornadoes this pressure difference appears to be sufficient to induce a central downflow.

Funnel Clouds

A tornado is often made visible by a distinctive funnel-shaped cloud. Commonly called the condensation funnel, the funnel cloud is a tapered column of water droplets that extends downward from the base of the parent cloud. It is commonly mixed with and perhaps enveloped by dust and debris lifted from the surface. The funnel cloud may be present but not visible due to heavy rain. Over a tornado's lifetime, the size and shape of the funnel cloud may change markedly, reflecting changes in the intensity of the winds, the moisture content of the inflowing air, properties of the ground, and other factors. Very frequently the condensation funnel extends from the parent cloud only partway to the ground, and in very dry conditions there may be no condensation funnel. Generally, the more moist the air and the more intense the tornado, the larger the funnel cloud.

The funnel cloud usually outlines only the innermost core. Typically, its diameter is at most one-tenth that of the overall tornado circulation. Indeed, a tornado can occur without a funnel cloud being present at all. The funnel cloud's length can range from tens of metres to several kilometres; its diameter can span a few metres to hundreds of metres. Funnel clouds of weak tornadoes are usually cone-shaped, while strong and violent tornadoes form short, broad, cylindrical pillars. Long, rope-like tubes that trail off horizontally are common in the waning phase of many tornadoes.

Duration

The lifetime of a tornado is directly related to its intensity, with more intense tornadoes tending to last longer. On average, a tornado is on the ground for about 15 minutes, but this value is misleading because the average is heavily weighted by the rare but long-lived violent tornadoes. Most tornadoes are weak, lasting only about two to three minutes on average. A typical lifetime for strong tornadoes is about 8 minutes, while for violent events it is about 25 minutes. In exceptional cases, violent events can last more than three hours.

Speed and Direction of Movement

The movement of a tornado is determined by the motion of the generating thunderstorm. The average tornado moves at a speed of about 12 to 13 metres per second, or 43 to 47 km per hour (about 39 to 43 feet per second, or 27 to 29 miles per hour), but some have remained nearly stationary while others have traveled faster than 25 metres per second, or 90 km per hour (80 feet per second, or 55 miles per hour). As an extreme example, speeds of up to 33 metres per second, or 120 km per hour (110 feet per second, or 75 miles per hour) were measured in a tornado that struck Guin, Alabama, on April 3, 1974.

Most tornado-producing thunderstorms occur in a warm air mass that is under the influence of an active synoptic-scale low-pressure system (such a system covers about one-half of the continent). The middle-level winds (3 to 10 km [2 to 6 miles] in altitude) that in large part determine the direction of storm motion tend to be from the west or southwest in the Northern Hemisphere. Hence, most tornadoes (around 80 percent) come from the west or southwest and move to the east or northeast. Tornadoes move from northwest to southeast about 5 percent of the time. Many hurricane-related tornadoes have traveled east to west, as have a few Great Plains and Midwest tornadoes. In the Southern Hemisphere, storms (and consequently tornadoes) tend to move from the west or northwest to the east or southeast.

Tornado Cyclones, Tornado Families and Long-track Tornadoes

About 90 percent of tornadoes are associated with thunderstorms, usually supercells; this association accounts for many weak and almost all strong and violent tornadoes. The other 10 percent of tornado occurrences are associated with rapidly growing cumulus clouds; these vortices are almost always weak and short-lived.

As a very rough estimate, about 100,000 thunderstorms occur in the United States each year. About 10 percent of these (or about 10,000 per year) will become severe thunderstorms, and only about 5 percent to 10 percent of these severe storms (or about 500 to 1,000 per year) will produce tornadoes.

The typical tornado-producing thunderstorm lasts for two to three hours and usually produces one or two relatively short-lived tornadoes. The period of storm maturity during which a tornado is most likely to form may last only a few tens of minutes. However, on rare occasions a storm may produce a tornado cyclone (a core of concentrated rotation within the storm from which tornadoes are spawned) that is stable and long-lived. The strength of the tornado cyclone usually pulsates, creating a sequence of tornadoes. This gives rise to what is known as a tornado family. Tornado families typically have two or three members, though they can be much larger. During the Super Outbreak of April 3–4, 1974, in the United States, a single storm traveling along the Ohio River produced a family with eight members spread over several hundred kilometres.

On very rare occasions, the strength of a tornado cyclone will remain nearly constant for several hours, forming a single, long-lasting tornado with a continuous damage path many times the average length. This is referred to as a long-track tornado. Long-track tornadoes can be difficult to distinguish from tornado families. For instance, the Great Tri-State Tornado of March 18, 1925, is credited with a path length of 352 km (219 miles), though it cannot be proved that this event, which affected Missouri, Illinois, and Indiana, was an individual tornado or a series in the same family. On the other hand, the Monticello, Indiana, tornado on April 3, 1974 (part of the Super Outbreak mentioned above), produced a continuous track of damage for over 160 km (99 miles). It was also the fifth and final member of a tornado family.

Tornado Formation

The Mesocyclone

Tornadoes may occur wherever conditions favour the development of strong thunderstorms. Essential conditions for such storms are the presence of cool, dry air at middle levels in the troposphere, overlying a layer of moist, conditionally unstable air near the surface of the Earth. Conditional instability occurs when a saturated air parcel (air at 100 percent relative humidity) continues to rise once set in motion, but an unsaturated air parcel resists being displaced vertically. The unsaturated air, if moved upward, will be cooler than the surrounding air and it will sink. On the other hand, when conditionally unstable air rises it becomes warmer owing to the condensation of water vapour. As the water condenses, heat is released, further warming the air and fueling its rise. This convective action (that is, the circulation of air as a result of heat transfer) produces the huge clouds commonly associated with thunderstorms and tornadoes. Convection can be initiated when the Sun heats a localized area of the ground, destabilizing the near-surface air.

Thunderstorms can also form along the boundary, or front, between air masses of different temperatures. In this case, the denser cool air displaces the warmer and forces it to rise. The greater the contrast in temperature and moisture across the frontal boundary, the greater the instability of the atmosphere and the greater the likelihood of a strong thunderstorm.

Most tornadoes are formed when a strong updraft such as those described above acts to concentrate atmospheric rotation, or spin, into a swirling column of air. Spin is a natural occurrence in air because horizontal winds almost always experience both an increase in speed and a veering in direction with increasing height above the surface. The increase of wind speed with height (called vertical speed shear) produces “crosswise spin,” that is, rotation about a horizontal axis crosswise to the direction of wind flow. When air containing crosswise spin flows into an updraft, the spin is drawn upward, producing rotation about a vertical axis. The veering of wind direction with height (vertical direction shear) is another source of horizontal spin, this time oriented in the same direction as the wind flow and known as “streamwise spin.” When air containing streamwise spin is drawn into an updraft, it too is tilted upward and rotates about a vertical axis. Although crosswise spin and streamwise spin are oriented at right angles to each other, both rotations exist in the horizontal plane, and both types have been revealed by Doppler radar observations to contribute to the evolution of a rotating updraft. Radar observations also have shown that updraft rotation makes its appearance in a thunderstorm at altitudes of 4 to 8 km (2.5 to 5 miles). At first, the tilting of crosswise spin into the vertical appears to be the principal mechanism of rotation; subsequently, as updraft rotation intensifies, the tilting of streamwise spin becomes more important. The resulting swirling column of rising air, perhaps 10 to 20 km (6 to 12 miles) in diameter and only weakly rotating, is called a mesocyclone.

The Dynamic Pipe

As spin-up of the mesocyclone continues, its rotating action begins to reorganize airflow in the updraft. The local pressure field and the strongly curved wind field move toward a dynamic equilibrium called cyclostrophic balance. In this state, the pressure-gradient force, which acts to move air inward in response to the lower pressure in the centre of the rotating column, is equaled by the outward-directed centrifugal force. When cyclostrophic balance is achieved, air readily flows in a circular path around the mesocyclone’s axis, while flow toward or away from its centre is strongly suppressed. This state, in which airflow is constrained by its own rotation, is known as the dynamic pipe effect.

The middle level of the storm is usually the first area where cyclostrophic balance is achieved, and it is this section of the mesocyclone that begins to act as a dynamic pipe. Almost all the air flowing along the mesocyclone’s axis is drawn in through the bottom of the pipe. This inflow further intensifies rotation at the pipe’s lower end, causing it to extend rapidly downward as the more quickly rotating region comes into cyclostrophic balance.

Strong convergence of inflowing air at the lower end of the pipe causes air parcels to be accelerated upward and vertically “stretched.” Vertical stretching normally causes the mesocyclone to contract to a diameter of about 2 to 6 km (1 to 4 miles). As this happens, the mesocyclone rotates more quickly, which in turn strengthens the convergence of inflowing winds at its base. In this manner the mesocyclone grows in strength in a positive-feedback, or self-amplifying, process.

Development of the dynamic pipe effect can produce a mesocyclone that extends the full depth of the thunderstorm, from about 1 km (0.6 mile) above the ground to near the storm's top at about 15 km (9 miles). Frequently, the maturation of the mesocyclone is heralded at the bottom of the cloud by a lowering of a portion of the thunderstorm's base in the area of the updraft. This approximately cylindrical extension is known as a wall cloud. Surface winds with speeds as high as 33 metres per second, or 120 km per hour (110 feet per second, or 75 miles per hour) can be present beneath this swirling cloud, often producing damage even when no tornado forms.

The Tornado Core and the Condensation Funnel

The extension of a concentrated swirling core to the surface—in other words, the actual formation of a tornado—can occur once the mesocyclone is established. Most mesocyclones do not generate tornadoes. In the ones that do, a small region of increased convergence and stretching that is typically no more than one kilometre in diameter develops in the mesocyclone for reasons that have so far eluded storm researchers. This usually occurs at the interface between the thunderstorm's updraft and downdraft. Enhanced spin begins several kilometres above the ground, and then quickly builds downward. Around such a small volume, rotation is strong enough for a smaller dynamic pipe to form and extend to within several tens of metres of the surface. This dynamic pipe is called the tornado core. Once it forms, the parent mesocyclone is reclassified as a tornado cyclone.

As the core approaches the ground, surface friction slows the rotational motion and prevents the establishment of cyclostrophic balance. Surface friction also limits the rate of airflow into the base of the core. This restriction prevents inflow from filling the tornado's low-pressure core from below. At the same time, the parent storm's strong updraft prevents sufficient air from filling the core from above.

With air pressure in the vortex core thus reduced in comparison to the pressure outside the core at the same elevation, a condensation funnel forms. This occurs because, at lower atmospheric pressure, air flowing upward in the core cools more quickly with increasing height than air rising at higher pressure just outside the core. Assuming that inflowing air has the same amount of moisture throughout, air rising in the core reaches its dew point at a lower height than air rising just outside the core; any further rise leads to condensation and a visible cloud. Because pressure is lowest at the axis of the vortex, air rising along this centre line reaches its dew point nearer the ground than air spiraling up just a short distance outward. These processes gives rise to the characteristic conical or funnel shape of the condensation cloud.

Location in the Parent Storm

Many weak tornadoes form between the surface and the lowest portion of the parent cloud. These tornadoes exist for only a short time (a few minutes). Such tornadoes most commonly form beneath the flanking line of cumulus congestus clouds that frequently develop above a strong thunderstorm’s gust front (the leading edge of the storm’s downdraft). Often called gustnadoes, these vortices are true tornadoes when they are attached to the updraft of a rapidly growing congestus cloud. Gustnadoes draw their spin from the wind shear across the gust front. Their transient nature, relatively small diameters, and lack of a rotating region within the generating cloud cause them to be difficult to observe with radar. As a result, small tornadoes are not well documented, and in many respects they are less understood than stronger events.

In contrast to gustnadoes, almost all strong and violent tornadoes (and some weak ones as well) are closely connected with a rotating updraft that extends through much of the height of the parent storm. Such tornadoes tend to form near the interface between a storm’s updraft and downdraft. To an observer on the ground, they are generally perceived as being beneath the right-rear quadrant of the main body of the storm in the Northern Hemisphere as viewed along the storm path. Because of the connection of these tornadoes to large-diameter circulations within the thunderstorm, many of the events leading to their formation have been fairly well documented both visually and by radar.

Cloud Burst

Cloud bursting is an application deployment model in which an application runs in a private cloud or data center and bursts into a public cloud when the demand for computing capacity spikes. The advantage of such a hybrid cloud deployment is that an organization only pays for extra compute resources when they are needed.

Experts recommend cloud bursting for high performance, non-critical applications that handle non-sensitive information. An application can be deployed locally and then burst to the cloud to meet peak demands, or the application can be moved to the public cloud to free up local resources for business-critical applications. Cloud bursting works best for applications that don’t depend on a complex application delivery infrastructure or integration with other applications, components and systems internal to the data center.

When considering cloud bursting, an organization must consider security and regulatory compliance requirements. For example, cloud bursting is often cited as a viable option for retailers that experience peaks in demand during the holiday shopping season. However, cloud computing service providers do not necessarily offer a PCI DSS-compliant environment and retailers could be putting sensitive data at risk by bursting it to the public cloud.

Other issues related to cloud bursting arise from the potential for incompatibility between the different environments and the limited availability of management tools. Cloud computing service providers and virtualization vendors have developed tools to send workloads to the cloud and manage hybrid environments, but they often require all environments to be based on the same platform.

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5

Hydrologic Disasters

The disasters which are caused due to a severe amendment either in quality of earth's water, or in distribution or movement of water, are called hydrological disasters. The different types of hydrological disasters are coastal floods, urban floods, flash floods and tsunamis. This chapter discusses in detail the diverse aspects of these hydrological disasters.

Flood

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 on-going 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.

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 also represent a health hazard, 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 is also 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.

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

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 cannot 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

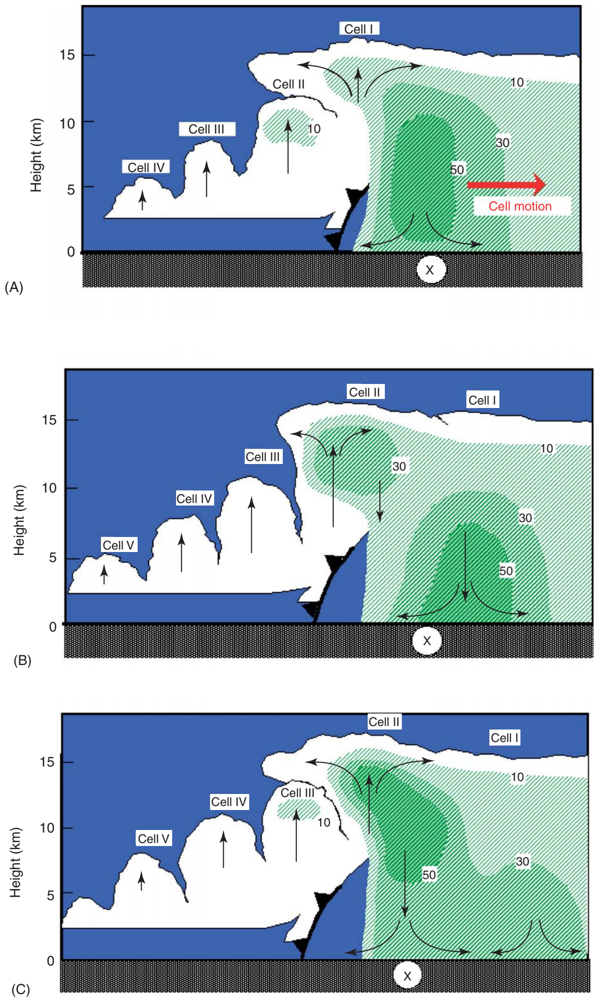
Flash floods are defined as those flood events where the rise in water is either during or within a few hours of the rainfall that produces the rise. Therefore, flash floods occur within small catchments, where the response time of the drainage basin is short. Many hydrological factors have relevance 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, 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 north-western Pennsylvania moved south-eastward, 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 are not 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 USA or in the European Alps is often of this type; that is, not involving thunderstorms.

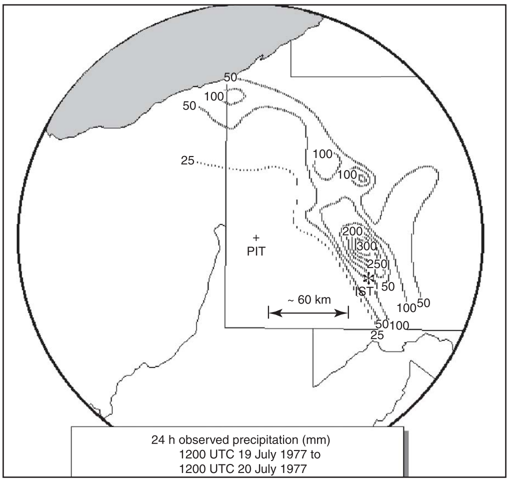
A characteristic of flash floods is the localized nature of the heaviest rainfall. As shown in figure, the most intense rainfall is typically confined to a relatively small area. When large amounts of this localized precipitation fall within a small drainage basin, flash floods can occur. Sometimes, 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 USA is well known for its heavy thunderstorm-produced rains during night time hours. Worldwide, thunderstorms are most common during the day, but on the central plains of the USA (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 night time hours, often forming clusters of thunderstorms known as mesoscale convective systems.

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.



Schematic of the 'training' effect.

In figure, (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 standard units of dBZ, which is related to the rainfall rate. (B) About 15 min 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. Cell IV and V are still immature.



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.

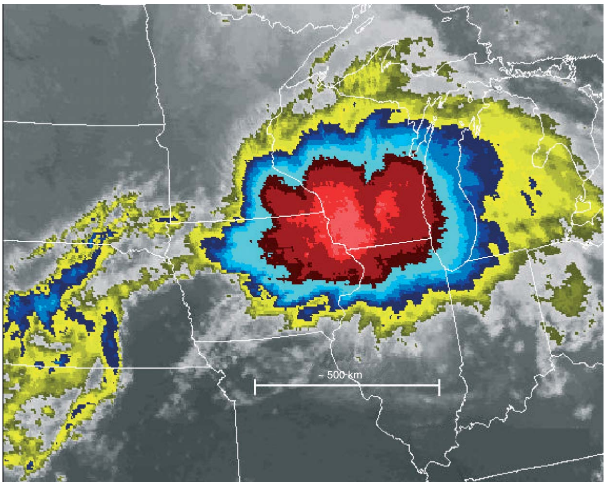
Because urbanized areas promote runoff of rainfall, rather than permitting most of the rain to be absorbed into the ground, flash flooding is more likely in cities than in rural areas surrounding a city. It takes much less rainfall in a city to create a flash flood situation than in a rural area of comparable 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 of 1998, Hurricane Mitch caused more than 9000 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 twentieth 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 snow melt and other factors besides rainfall.

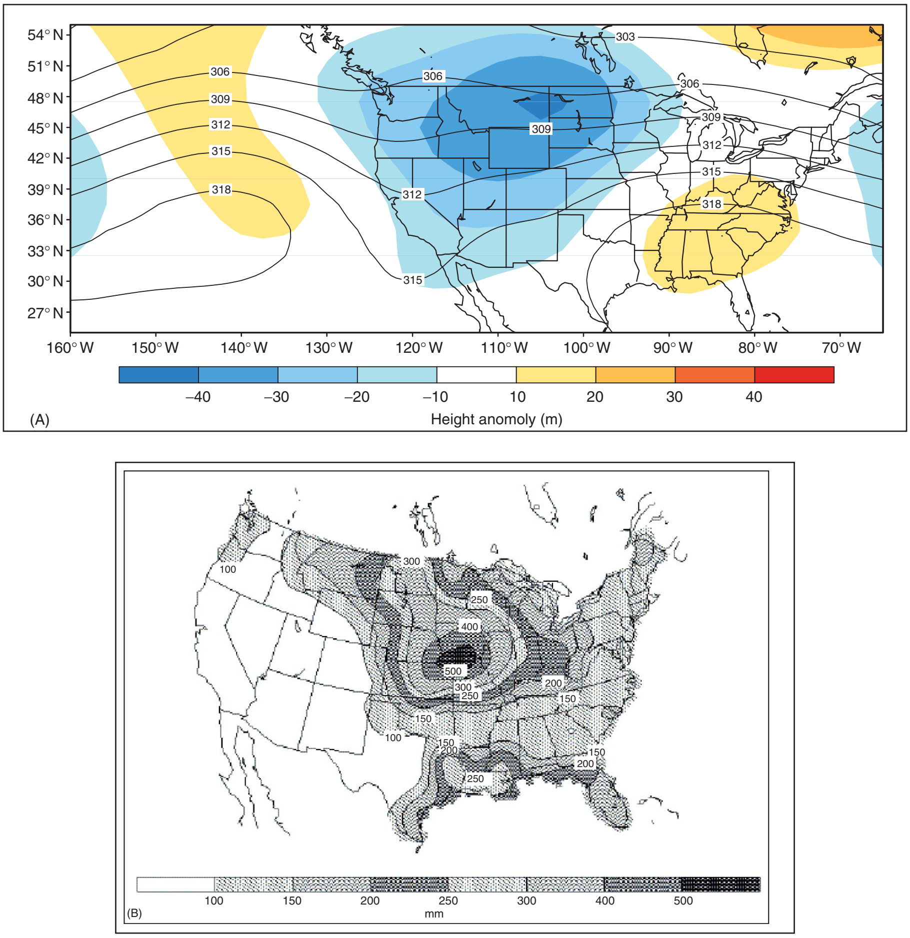


False-color enhanced infrared satellite image of a mesoscale convective system, with the light red colors indicating the coldest (therefore the highest) clouds.

The major flooding event during June and July of 1993 was the result of a weather pattern that produced a storm track across the upper Midwestern USA. 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 nearly the same areas, resulting in widespread significant rainfalls 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.



(A) Map of the 700 hPa heights (thin lines, in dam) and height anomalies (shading, in m) and (B) observed precipitation for the same period (shading, in mm).

Floods Arising from Nonprecipitation Events

Apart from floods resulting directly from rainfall, there are many ways in which 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 can also 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 snow melt. 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 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 13 November 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 USA. In many parts of the world, flood fatalities are associated with the most significant weather-related disasters. Flood damage cost in the USA is now on the order of several billion dollars annually, and this figure continues to rise.

Many people now live and play in flood-prone areas: for example, within floodplains of rivers and their tributaries, as well as along coastlines that are vulnerable to storm-caused flooding from tsunamis, tropical cyclones, and nontropical 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 floodplains, 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 snowmelt 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 protection from 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 moving 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 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 is certainly 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 those 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 dramatically increases the fraction of the rainfall that runs off, regardless of antecedent rainfall. Human-caused fires can also 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.

Types of Floods

Ponding (Or Pluvial Floods)

Ponding is a type of flooding that can happen in relatively flat areas. Rain water falling in an area is normally stored in the ground, in canals or lakes, or is drained away, or pumped out. When more rainwater enters a water system than can be stored, or can leave the system, flooding occurs. In this case, rain is the source of the flood: not water coming from a river, but water on its way to the river. That's why it is also called "pluvial flood".

Puddles and ponds develop on the land, canals are filled to brim and spill over; gradually a layer of water covers the land. It is like urban flooding, but without the sewage systems and in more rural areas.

Because of the gradual character people have time to go indoors or leave the area. The layer of water is no more than centimeters or perhaps decimeters high and causes no immediate threat to people's lifes. Depending on the economic activity and size of the area that is covered it may cause immense economic damage.

Coastal Flood

Coastal flooding occurs when normally dry, low-lying land is flooded by seawater. The extent of coastal flooding is a function of the elevation inland flood waters penetrate which is controlled by the topography of the coastal land exposed to flooding. The seawater can flood the land via from several different paths:

- Direct flooding: Where the sea height exceeds the elevation of the land, often where waves have not built up a natural barrier such as a dune system
- Overtopping of a barrier: The barrier may be natural or human engineered and overtopping occurs due to swell conditions during storm or high tides often on open stretches of the coast. The height of the waves exceeds the height of the barrier and water flows over the top of the barrier to flood the land behind it. Overtopping can result in high velocity flows that can erode significant amounts of the land surface which can undermine defense structures.
- Breaching of a barrier: Again the barrier may be natural (sand dune) or human engineered (sea wall), and breaching occurs on open coasts exposed to large waves. Breaching is where the barrier is broken down or destroyed by waves allowing the seawater to extend inland and flood the areas.

Coastal flooding is largely a natural event; however human influence on the coastal environment can exacerbate coastal flooding. Extraction of water from groundwater reservoirs in the coastal zone can enhance subsidence of the land increasing the risk of flooding. Engineered protection structures along the coast such as sea walls alter the natural processes of the beach, often leading to erosion on adjacent stretches of the coast which also increases the risk of flooding.

Causes

Coastal flooding can result from a variety of different causes including storm surges created by storms like hurricanes and tropical cyclones, rising sea levels due to climate change and by tsunamis.

Storms and Storm Surges

Storms, including hurricanes and tropical cyclones, can cause flooding through storm surges which are waves significantly larger than normal. If a storm event coincides with the high astronomical tide, extensive flooding can occur. Storm surges involve three processes:

1. Wind setup
2. Barometric setup
3. wave setup

Winds blowing in an onshore direction (from the sea towards the land) can cause the water to 'pile up' against the coast; this is known as wind setup. Low atmospheric pressure is associated with storm systems and this tends to increase the surface sea level; this is barometric setup. Finally increased wave breaking height results in a higher water level in the surf zone, which is wave setup. These three processes interact to create waves that can overtop natural and engineered coastal protection structures thus penetrating seawater further inland than normal.

Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC) estimate global mean sea-level rise from 1990 to 2100 to be between nine and eighty eight centimetres. It is also predicted that with climate change there will be an increase in the intensity and frequency of storm events such as hurricanes. This suggests that coastal flooding from storm surges will become more frequent with sea level rise. A rise in sea level alone threatens increased levels of flooding and permanent inundation of low-lying land as sea level simply may exceed the land elevation. This therefore indicates that coastal flooding associated with sea level rise will become a significant issue into the next 100 years especially as human populations continue to grow and occupy the coastal zone.

Tsunami

Coastal areas can be significantly flooded as the result of tsunami waves which propagate through the ocean as the result of the displacement of a significant body of water through earthquakes, landslides, volcanic eruptions and glacier calvings. There is also evidence to suggest that significant tsunami have been caused in the past by meteor impact into the ocean. Tsunami waves are so destructive due to the velocity of the approaching waves, the height of the waves when they reach land and the debris the water entrains as it flows over land can cause further damage.

Mitigation

It has been said that one way to prevent significant flooding of coastal areas now and into the future is by reducing global sea level rise. This could be minimised by further reducing greenhouse gas emissions. However, even if significant emission decreases are achieved, there is already a substantial commitment to sea level rise into the future. International climate change policies like the Kyoto Protocol are seeking to mitigate the future effects of climate change, including sea level rise.

In addition, more immediate measures of engineered and natural defences are put in place to prevent coastal flooding.

Engineered Defences

Groynes are engineered structures that aim to prevent erosion of the beach front.

There are a variety of ways in which humans are trying to prevent the flooding of coastal environments, typically through so-called hard engineering structures such as seawalls and levees. That armouring of the coast is typical to protect towns and cities which have developed right up to the beachfront. Enhancing depositional processes along the coast can also help prevent coastal flooding. Structures such as groynes, breakwaters and artificial headlands promote the deposition of sediment on the beach thus helping to buffer against storm waves and surges as the wave energy is spent on moving the sediments in the beach than on moving water inland.

Natural Defences

The coast does provide natural protective structures to guard against coastal flooding. These include physical features like gravel bars and sand dune systems, but also ecosystems such as salt marshes and mangrove forests have a buffering function. Mangroves and wetlands are often considered to provide significant protection against storm waves, tsunamis and shoreline erosion through their ability to attenuate wave energy. To protect the coastal zone from flooding, the natural defenses should, therefore, be protected and maintained.

Mangroves are one of the coasts natural defense systems against storm surges and flooding. Their high biomass both above and below the water can help dissipate wave energy.

Responses

As coastal flooding is typically a natural process, it is inherently difficult to prevent flood occurrence. If human systems are affected by flooding, an adaption to how that system operates on the coast through behavioral and institutional changes is required; these changes are the so-called *non-structural* mechanisms of coastal flooding response. Building regulations, coastal hazard zoning, urban development planning, spreading the risk through insurance and enhancing public awareness are some ways of achieving this. Adapting to the risk of flood occurrence, can be the best option if the cost of building defense structures outweighs any benefits or if the natural processes in that stretch of coastline add to its natural character and attractiveness. A more extreme and often difficult to accept response to coastal flooding is abandoning the area (also known as managed retreat) prone to flooding. This however raises issues for where the people and infrastructure affected would go and what sort of compensation should/could be paid.

Social and Economic Impacts

The coastal zone (the area both within 100 kilometres distance of the coast and 100 metres elevation of sea level) is home to a large and growing proportion of the global population. Over 50 percent of the global population and 65 percent of cities with populations over five million people are in the coastal zone. In addition to the significant number of people at risk of coastal flooding, these coastal urban centres are producing a considerable amount of the global Gross Domestic Product (GDP). People's lives, homes, businesses and city infrastructure like roads, railways and industrial plants are all at risk of coastal flooding with massive potential social and economic costs. The recent earthquakes and tsunami in Indonesia in 2004 and in Japan in March 2011 clearly illustrate the devastation coastal flooding can produce. Indirect economic costs can be incurred if economically important sandy beaches are eroded away resulting in a loss of tourism in areas dependent on the attractiveness of those beaches.

Environmental Impacts

Coastal flooding can result in a wide variety of environmental impacts on different spatial and temporal scales. Flooding can destroy coastal habitats such as coastal wetlands and estuaries and can erode dune systems. These places are characterised by their high biological diversity therefore coastal flooding can cause significant biodiversity loss and potentially species extinctions. In addition to this, these coastal features are the coasts natural buffering system against storm waves; consistent coastal flooding and sea level rise can cause this natural protection to be reduced allowing waves to penetrate greater distances inland exacerbating erosion and furthering coastal flooding. Prolonged inundation of seawater after flooding can also cause salination of agriculturally productive soils thus resulting in a loss of productivity for long periods of time. Food crops and forests can be completely killed off by salination of soils or wiped out by the movement of flood waters. Coastal freshwater bodies including lakes, lagoons and coastal freshwater aquifers can also be affected by saltwater intrusion. This can destroy these water bodies as habitats for freshwater organisms and sources of drinking water for towns and cities. Examples of existing coastal flooding issues include:

The Thames Barrier provides flood control for London, U.K.

London and the Thames Barrier

The Thames Barrier is one of the world's largest flood barriers and serves to protect London from flooding during exceptionally high tides and storm surges. The Barrier can be lifted at high tide to prevent sea waters flooding London and can be lowered to release stormwater runoff from the Thames catchment.

Significant flooding in New Orleans as a result of Hurricane Katrina and the failure of the city's flood protection systems.

South Canterbury Plains in New Zealand

Flooding of this low-lying coastal zone can result in prolonged inundation, which can affect the productivity of the affected pastoral agriculture for several years.

Hurricane Katrina in New Orleans

A village near the coast of Sumatra lies in ruin after the devastating tsunami that struck.

Hurricane Katrina made landfall as a category 3 cyclone on the Saffir–Simpson hurricane wind scale, indicating that it had become an only moderate level storm. However the catastrophic damage caused by the extensive flooding was the result of the highest recorded storm surges in North America. For several days prior to landfall of Katrina, wave set up was generated by the persistent winds of the cyclonic rotation of the system. This prolonged wave set up coupled with the very low central pressure level meant massive storm surges were generated. Storm surges overtopped and breached the levees and flood walls intended to protect the city from inundation. Unfortunately New Orleans is inherently prone to coastal flooding for a number of factors. Firstly, much of New Orleans is below sea level and is bordered by the Mississippi River therefore protection against flooding from both the sea and the river has become dependent on engineered structures. Land use change and modification to natural systems in the Mississippi River have rendered the natural defenses for the city less effective. Wetland loss has been calculated to be around 1,900 square miles (4,920 square kilometres) since 1930. This is a significant amount as four miles of wetland are estimated to reduce the height of a storm surge by one foot (30 centimeters).

Indonesia and Japan Post-earthquake and Tsunamis

An earthquake of approximately magnitude 9.0 struck off the coast of Sumatra, Indonesia causing the propagation of a massive tsunami throughout the Indian Ocean. This tsunami caused significant loss of human life, an estimate of 280,000 – 300,000 people has been reported and caused extensive damage to villages, towns, and cities and to the physical environment. The natural structures and habitats destroyed or damaged included coral reefs, mangroves, beaches, and seagrass beds. The more recent earthquake and tsunami in Japan in March 2012 also clearly illustrates the destructive power of tsunamis and the turmoil of coastal flooding.

Urban Flood

Urban flooding is significantly different from rural flooding as urbanization leads to developed catchments, which increases the flood peaks from 1.8 to 8 times and flood volumes by up to 6 times. Consequently, flooding occurs very quickly due to faster flow times (in a matter of minutes). Urban areas are densely populated and people living in vulnerable areas suffer due to flooding, sometimes resulting in loss of life. It is not only the event of flooding but the secondary effect of exposure to infection also has its toll in terms of human suffering, loss of livelihood and, in extreme cases, loss of life.

Urban areas are also centres of economic activities with vital infrastructure which needs to be protected 24x7. In most of the cities, damage to vital infrastructure has a bearing not only for the state and the country but it could even have global implications. Major cities in India have witnessed loss of life and property, disruption in transport and power and incidence of epidemics. Therefore, management of urban flooding has to be accorded top priority.

Increasing trend of urban flooding is a universal phenomenon and poses a great challenge to urban planners the world over. Problems associated with urban floods range from relatively localized incidents to major incidents, resulting in cities being inundated from hours to several days. Therefore, the impact can also be widespread, including temporary relocation of people, damage to civic amenities, deterioration of water quality and risk of epidemics.

Do’s and Dont’s

Before Floods

- Do not litter waste, plastic bags, plastic bottles in drains.
- Try to be at home if high tide and heavy rains occur simultaneously.
- Listen to weather forecast at All India Radio, Doordarshan. Also, messages by Municipal bodies from time to time and act accordingly.
- Evacuate low line areas and shift to safer places.
- Make sure that each person has lantern, torch, some edibles, drinking water, dry clothes and necessary documents while evacuating or shifting.
- Make sure that each family member has identity card.
- Put all valuables at a higher place in the house.

In the Flood Situation

- Obey orders by government and shift to a safer place.
- Be at safe place and they try to collect correct information.
- Switch of electrical supply and don’t touch open wires.
- Don’t get carried away by rumors and don not spread rumors.

DO’s

- Switch off electrical and gas appliances, and turn off services off at the mains.
- Carry your emergency kit and let your friends and family know where you are going.
- Avoid contact with flood water it may be contaminated with sewage, oil, chemicals or other substances.
- If you have to walk in standing water, use a pole or stick to ensure that you do not step into deep water, open manholes or ditches.
- Stay away from power lines electrical current can travel through water, Report power lines that are down to the power company.
- Look before you step-after a flood, the ground and floors are covered with debris, which may include broken bottles, sharp objects, nails etc. Floors and stairs covered with mud and debris can be slippery.

- Listen to the radio or television for updates and information.
- If the ceiling is wet shut off electricity. Place a bucket underneath the spot and poke a small hole into the ceiling to relieve the pressure.
- Use buckets, clean towels and mops to remove as much of the water from the afflicted rooms as possible.
- Place sheets of aluminium foil between furniture wet carpets.

Don’t

- Don’t walk through flowing water - currents can be deceptive, and shallow, fast moving water can knock you off your feet.
- Don’t swim through fast flowing water - you may get swept away or stuck by an object in the water.
- Don’t drive through a flooded area - You may not be able to see abrupt drop - offs and only half a meter of flood water can carry a car away. Driving through flood water can also cause additional damage to nearby property.
- Don’t eat any food that has come into contact with flood water.
- Don’t reconnect your power supply until a qualified engineer has checked it. Be alert for gas leaks - do not smoke or use candles, lanterns, or open flames.
- Don’t scrub or brush mud and other deposits from materials, This may cause further damage.
- Never turn on ceiling fixtures if ceiling is wet. Stay away from ceilings those are sagging.
- Never use TVs, VCRS, CRT terminals or other electrical equipment while standing on wet floors, especially concrete.
- Don’t attempt to remove standing water using your vacuum cleaner.
- Don’t remove standing water in a basement too fast. If the pressure is relieved too quickly it may put undue stress on the walls.

Recover and Build

After Floods

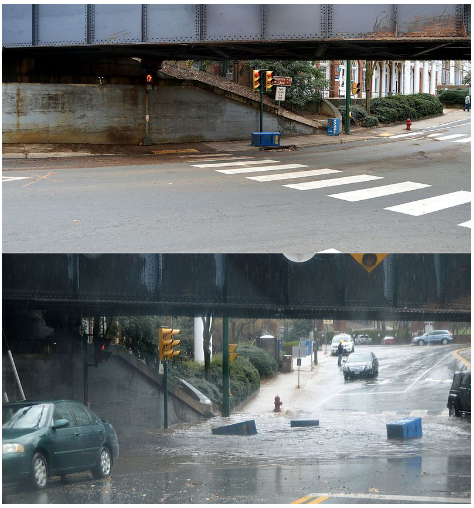
- Drink chlorinated or boiled water.
- Take clean and safe food

- Sprinkle insecticides in the water ponds/stagnant water.
- Please cooperate with disaster survey team by giving correct information.

Flash Flood

A flash flood after a thunderstorm in the Gobi, Mongolia.

A flash flood is a rapid flooding of low-lying areas: washes, rivers, dry lakes and depressions. It may be caused by heavy rain associated with a severe thunderstorm, hurricane, tropical storm, or meltwater from ice or snow flowing over ice sheets or snowfields. Flash floods may occur after the collapse of a natural ice or debris dam, or a human structure such as a man-made dam, as occurred before the Johnstown Flood of 1889. Flash floods are distinguished from regular floods by having a timescale of fewer than six hours between rainfall and the onset of flooding. The water that is temporarily available is often used by plants with rapid germination and short growth cycles and by specially adapted animal life.



An urban underpass during normal conditions (upper) and after fifteen minutes of heavy rain (lower).

Driving through a flash-flooded road.

Causes

Flash floods can occur under several types of conditions. Flash flooding occurs when it rains rapidly on saturated soil or dry soil that has poor absorption ability. The runoff collects in gullies and streams and, as they join to form larger volumes, often forms a fast flowing front of water and debris.

Flash floods most often occur in normally dry areas that have recently received precipitation, but they may be seen anywhere downstream from the source of the precipitation, even many miles from the source. In areas on or near volcanoes, flash floods have also occurred after eruptions, when glaciers have been melted by the intense heat. Flash floods are known to occur in the highest mountain ranges of the United States and are also common in the arid plains of the Southwestern United States. Flash flooding can also be caused by extensive rainfall released by hurricanes and other tropical storms, as well as the sudden thawing effect of ice dams. Human activities can also cause flash floods to occur. When dams fail, a large quantity of water can be released and destroy everything in its path.

Hazards

A flash flood greatly inundates a small ditch, flooding barns and ripping out newly installed drain pipes.

The United States National Weather Service gives the advice “Turn Around, Don’t Drown” for flash floods; that is, it recommends that people get out of the area of a flash flood, rather than trying to cross it. Many people tend to underestimate the dangers of flash floods. What makes flash floods most dangerous is their sudden nature and fast-moving water. A vehicle provides little to no protection against being swept away; it may make people overconfident and less likely to avoid the flash flood. More than half of the fatalities attributed to flash floods are people swept away in vehicles when trying to cross flooded intersections. As little as 2 feet (0.61 m) of water is enough to carry away most SUV-sized vehicles. The U.S. National Weather Service reported in 2005 that, using a national 30-year average, more people die yearly in floods, 127 on average, than by lightning (73), tornadoes (65), or hurricanes (16).

In deserts, flash floods can be particularly deadly for several reasons. First, storms in arid regions are infrequent, but they can deliver an enormous amount of water in a very short time. Second, these rains often fall on poorly absorbent and often clay-like soil, which greatly increases the amount of runoff that rivers and other water channels have to handle. These regions tend not to have the infrastructure that wetter regions have to divert water from structures and roads, such as storm drains, culverts, and retention basins, either because of sparse population or poverty, or because residents believe the risk of flash floods is not high enough to justify the expense. In fact, in some areas, desert roads frequently cross a dry river and creek beds without bridges. From the driver's perspective, there may be clear weather, when a river unexpectedly forms ahead of or around the vehicle in a matter of seconds. Finally, the lack of regular rain to clear water channels may cause flash floods in deserts to be headed by large amounts of debris, such as rocks, branches, and logs.

Deep slot canyons can be especially dangerous to hikers as they may be flooded by a storm that occurs on a mesa miles away. The flood sweeps through the canyon; the canyon makes it difficult to climb up and out of the way to avoid the flood.

River Flood

Rainfall over an extended period and an extended area can cause major rivers to overflow their banks. The water can cover enormous areas. Downstream areas may be affected, even when they didn't receive much rain themselves.

With large rivers the process is relatively slow. The rain water enters the river in many ways. Some rain will fall into the river directly, but that alone doesn't make the river rise high. A lot of rain water will run off the surface when the soil is saturated or hard. It will flow to small rivers that flow to larger rivers and these rivers flow into even larger rivers. In this way all the rain that fell in a large area (catchment area) comes together in this one very large river. When there is a lot of rain over a long period, you see the river rise gradually as it is fed with water form smaller rivers. It takes time for all the rainwater to reach the river, but once it is in the river it has to flow downstream to sea.

While the water level slowly rises, officials can decide to evacuate people before the river overflows. The area that is flooded can be huge. Villages surrounded by large stretches of water were cattle would normally graze. Whole communities can become isolated from the rest of the world as roads are blocked and communications are down. Here you see a simulation of the water level over time after a river dike breach in a low lying part of the Netherlands.

When a dike or a dam breaks and a lot of water is released suddenly, the speed of the water at the breach can be compared with the speed of a flash flood. As a larger area gets covered the speed will be reduced. The water spreads out as much as possible flowing to the lower lying areas before slowly rising. A breach is very dangerous for the people living close to it. The strength of the water may carry cars, trees and even houses away and cause loss of live.

Tsunami

Tsunami is also called seismic sea wave or tidal wave, catastrophic ocean wave, usually caused by a submarine earthquake, an underwater or coastal landslide, or a volcanic eruption. The term tidal wave is frequently used for such a wave, but it is a misnomer, for the wave has no connection with the tides.

Notable Tsunamis

One of the most destructive tsunamis in antiquity took place in the eastern Mediterranean Sea on July 21, 365 CE. A fault slip in the subduction zone beneath the island of Crete produced an earthquake with an estimated magnitude of 8.0–8.5, which was powerful enough to raise parts of the western third of the island up to 10 metres (33 feet). The earthquake spawned a tsunami that claimed tens of thousands of lives and caused widespread damage throughout the Mediterranean, from islands in the Aegean Sea westward to the coast of present-day Spain. Tsunami waves pushed ships over harbour walls and onto the roofs of houses in Alexandria, Egypt, while also ruining nearby croplands by inundating them with salt water.

Illapel, Chile, earthquake and tsunami.

Figure shows a magnitude-8.3 earthquake centred out to sea some 46 km (28.5 miles) west of Illapel, Chile, struck on September 16, 2015, producing widespread damage from shaking and tsunami waves measuring at least 4 metres (13 feet) high that lashed port towns such as Coquimbo.

Perhaps the most destructive tsunami in recorded history took place on December 26, 2004, after an earthquake of magnitude 9.1 displaced the ocean floor off the Indonesian island of Sumatra. Two hours later, waves as high as 9 metres (30 feet) struck the eastern coasts of India and Sri Lanka, some 1,200 km (750 miles) away. Within seven hours of the quake, waves washed ashore on the Horn of Africa, more than 3,000 km (1,800 miles) away on the other side of the Indian Ocean. More than 200,000 people were killed, most of them on Sumatra but thousands of others in Thailand, India, and Sri Lanka and smaller numbers in Malaysia, Myanmar, Bangladesh, Maldives, Somalia, and other locations.

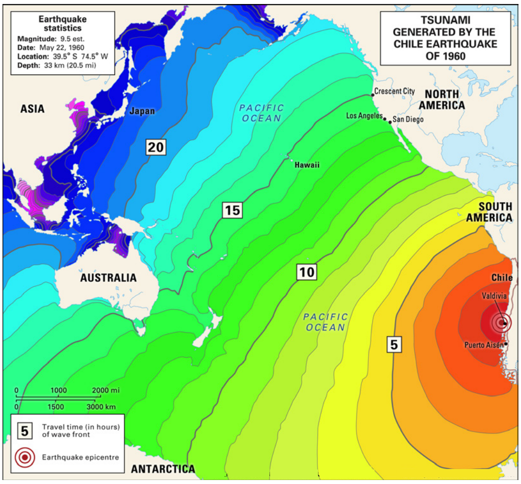
Banda Aceh, Indonesia, before and after the 2004 tsunami.

Figure shows photos taken before and after the arrival of a massive tsunami highlight the destruction of Banda Aceh, Indonesia, on December 26, 2004. The tsunami was generated by a magnitude-9.1 earthquake that occurred only 30 metres (98 feet) beneath the floor of the Indian Ocean.

On March 11, 2011, seafloor displacement resulting from a magnitude-9.0 earthquake in the Japan Trench of the Pacific Ocean created a large tsunami that devastated much of the eastern coast of Japan's main island of Honshu. Waves measuring as much as 10 metres (33 feet) high struck the city of Sendai and other low-lying coastal regions of Miyagi prefecture as well as coastal areas in the prefectures of Iwate, Fukushima, Ibaraki, and Chiba. The tsunami also instigated a major nuclear accident at the Fukushima Daiichi power station along the coast.

A massive tsunami, generated by a powerful undersea earthquake, engulfing a residential area in Natori, Miyagi prefecture, northeastern Honshu, Japan.

Other tsunamis of note include those that followed the spectacular explosive eruption of the Krakatoa (Krakatau) volcano on August 26 and 27, 1883, and the Chile earthquake of 1960. A series of blasts from Krakatoa submerged the island of Rakata between Sumatra and Java, creating waves as high as 35 metres (115 feet) in many East Indies localities, and killed more than 36,000 people. The largest earthquake ever recorded (magnitude 9.5) took place in 1960 off the coast of Chile, and it caused a tsunami that killed approximately 2,000 people in Chile, 61 people 15 hours later in Hawaii, and 122 people 22 hours later in Japan.



Child earthquake tsunami: Map showing the extent of the tsunami generated by the Chile earthquake.

Tsunami Warning Systems

The hazards presented by tsunamis have brought many countries in the Pacific basin to establish tsunami warning systems. A warning may begin with an alert by a geological society that an earthquake large enough to disturb the ocean's surface (for instance, magnitude 7.0 or higher) has occurred. Meteorological agencies may then report unusual changes in sea level, and then the warning centre may combine this information with data on the depth and features of the ocean floor in order to estimate the path, magnitude, and arrival time of the tsunami. Depending on the distance from the seismic disturbance, government authorities may have several hours' notice to order the evacuation of coastal areas. The Pacific Tsunami Warning Center, located near Honolulu, Hawaii, was established in 1949, three years after a tsunami generated by a submarine earthquake near the Aleutian Islands struck the island of Hawaii around Hilo, killing more than 170 people. It serves as one of two regional warning centres for the United States—the other is located in Palmer, Alaska—and since 1965 it has also served as the warning centre for 26 countries organized by UNESCO's Intergovernmental Oceanographic Commission into the International Coordination Group for the Tsunami Warning System in the Pacific. Following the disaster of December 2004, UNESCO set a goal of establishing similar systems for the Indian Ocean and eventually the entire globe.

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6

Mitigation and Prevention of Hazards

The actions which are taken for the reduction or elimination of long-term harm that can be caused by hazards and disasters is termed as hazard mitigation. Prevention of hazards refers to the preventive and protective actions that aid in lessening the scale of impact from a hazard. This chapter closely examines the key aspects of mitigation and prevention of hazards such as establishing temporary shelters and keeping food and water safe after a disaster.

Temporary Shelter

The number of natural disasters has drastically increased in the last decades, having a considerable impact on the built environment. Most of the buildings suffer extensive damages, many of them collapse entirely, and the destruction of houses is one of the most visible effects of a disaster, causing high numbers of homeless people.

It is widely accepted that in order to bring back the livelihoods of the affected communities, the reconstruction programme should start as soon as possible (United Nations Disaster Relief Coordinator e UNDRO). Housing provision plays a crucial role on those programs since it is one of the most important needs for people and essential for their well-being. A house is a space for people to live in, providing conditions for family life, comfort, protection and privacy. After a disaster the needs for housing should have a quick response because losing a house is more than a physical deprivation, it is losing dignity, identity and privacy.

Providing a house is a fundamental step to establish some sense of normalcy in the life of the affected community, as well as to prevent the rising of deaths and the spread of diseases, increasing conditions to personal hygiene and giving protection against external factors like weather. Post-disaster housing provides privacy, protection and better health conditions for victims, which are decisive requirements to start a recovery and reconstruction programme after a disaster.

However, post-disaster scenarios have all the factors to produce inadequate solutions, mainly due to the need for a rapid and large-scale action under chaotic conditions, and previous studies have presented many problems related to post-disaster housing. As a consequence, very often post-disaster housing solutions fail their objectives.

Post-disaster reconstruction is a complex process and providing temporary housing seems to be one of the most decisive tasks since it allows conditions for people to progressively return to normal life. It has been used after the most large-scale disasters, but in the same way it has been criticized for being unsustainable and culturally inadequate.

What is Temporary Housing after Disasters?

Temporary housing is one of the eight basic types of post-disaster shelter provision. Considering temporary housing a shelter type, the classification proposed by UNDRO seems to reflect what Quarantelli considers the variety of unclear and inconsistent ways the terms shelter and housing are used in disaster literature. Proposing a definition of four distinct stages of housing that may be employed in post-disaster situations, Quarantelli makes a distinction between sheltering and housing. While sheltering refers to a place to stay during the immediate aftermath of the disaster suspending daily activities, housing denotes the return to household responsibilities and daily routine . Based on this distinction, the four stages are: (1) emergency shelter e a place where survivors stay for a short period of time during the height of the emergency, which can be in the house of a friend or in a public shelter; (2) temporary shelter used for an expected short stay, ideally no more than a few weeks after the disaster, this may be a tent, a public mass shelter, etc.; (3) temporary housing the place where the survivors can reside temporarily, usually planned for six months to three years, returning to their normal daily activities, and can take the form of a prefabricated house, a rented house, etc.; (4) permanent housing return to the rebuilt house or resettle in a new one to live permanently.

This way, temporary housing can be defined as (1) an object, which means the physical structure people reside in after a disaster; (2) a part of the post-disaster re-housing programme; (3) a place that serves the function to shelter people during the period since the disaster occurs until they are resettled in a permanent place to live.

Importance of Temporary Housing

Following the concept of Quarantelli, temporary housing is extremely important to recover after disasters, allowing people to return to their normal activities such as work, cooking, housekeeping, school, socializing, etc. People are protected in shelters but cannot resume daily life, and so it is impracticable to stay longer in them. Likewise, temporary shelters may rapidly decay due to the external factors, and the need to get people out of them in order to be replaced in more durable and resistant solutions also emphasizes the importance to provide temporary housing. Since reconstruction lasts long, there is a time gap that needs to be bridged over, and temporary housing seems to be the evident option. It is the moment when uncertainty is replaced by security, allowing families to regain the necessary tranquillity to reorganize their future. This way, temporary housing helps people to feel safe and to have a social recognition. Temporary housing is also crucial to promote the success of the overall reconstruction, since it allows adequate time for proper community planning to reduce risk and increase sustainability for future construction (Johnson, 2008). Moreover, after a disaster it is crucial to provide temporary housing as soon as possible to offer a comfort level consistent with the common standard of living. This way, even in a temporary location, temporary housing is extremely important to promote the return to normalcy in a chaotic and uncertain situation after a disaster, being a necessary step in reconstruction programmes.

(a) (b)

Ready-made units: (a) temporary housing units ready to be transported and (b) local assembly of units.

Different Types of Temporary Housing Solutions

Due to its importance, it has often been used after large-scale disasters by the formal temporary housing projects or top-down approaches, which means that units are provided by governments and non-governmental organisations (NGOs). Most of these solutions are prefabricated, mass-produced and standardized, and two main groups can be identified: ready-made units and kit supplies. The ready-made units are housing solutions totally constructed in factory that just need to be transported to the site where they will be placed. Since these solutions usually involve complex transport systems, some projects try to simplify their transportation dividing the unit in a few parts to be quickly assembled on site.

Even so, those solutions are not easy to move to areas with difficult access and also need heavy transport systems, which is why many projects are developed based on kit solutions. The kit concept also tries to benefit from the advantages of prefabrication, but instead of producing finished units it produces the small elements that constitute the unit. The elements have to be assembled in place, thus sometimes the participation of local people in the construction or assembly process is possible. This way, kit solutions facilitates transportation and the local assembly, since the elements are small, light and easy to handle.

Problems with Temporary Housing Solutions

In spite of being a way to promote successful reconstruction programs, allowing survivors to resume their life activities, temporary housing is also a controversial issue of disasters reconstruction and has received criticism mainly due to problems of sustainability and cultural inadequacy issues. A considerable part of post-disaster temporary housing programs have been unsustainable and culturally inadequate as a result of unsuccessful strategies, misunderstandings about users' real needs and misconceptions in dealing with local conditions and resources.

Kit solutions: assembly process by local community and cluster of the Paper Log Houses designed by Shigeru Ban.

Sustainability Problems

Post-disaster temporary housing solutions seem to have sustainability problems in two ways: they are (1) unsustainable in terms of costs and (2) unsustainable in terms of environmental issues.

Most of the times the solutions provided are not produced in the region where the disaster occurred. Importing and transporting the units or materials required to rehouse all the victims may involve extremely high costs. According to UNDRO, a temporary house unit can cost more than a permanent one and some authors refer that it may be three times more expensive. Besides the costs associated to the units, there are the expenses with the whole infrastructures needed to make temporary settlements functional (roads, water, sewerage, electricity, etc.). This way, temporary housing becomes a very expensive kind of solution in relation to its lifespan because it implies huge investments in units that will only be used during a short period of time. As a consequence, much discussion has been centered on the question whether temporary housing is really needed, due to longer reconstruction processes, or rather an overspending that represents an important consumption of resources that are crucial for permanent reconstruction . As a result, the works of permanent reconstruction may be delayed and people have to stay in temporary units longer than it was planned. Since those temporary settlements are not planned for long periods, some social problems can appear. Beyond the questions about costs and their effects on the overall reconstruction, importing the units means long delays in the process of resettlement due to the time needed to produce, transport and place the units on the site.

Making temporary housing comfortable and resistant enough, even considering its ephemeral condition, usually means supplying structures that are more durable than the short time for which they will be required. Consequently, the units are still usable after their intended period of use and the problem is what to do with the large amount of structures. Since most of the times there is no plan for that, the units are simply dismantled or deconstructed without any concern about the future of resultant elements. That kind of procedure is a notably unproductive approach that causes great resource losses. In the same way, the site where the temporary units were placed frequently becomes greatly polluted. After the units' removal, all the infrastructure, foundations, debris, garbage, etc., should be removed in order to restore the place as it was before being occupied. Yet sometimes it is not what happens, causing great environmental consequences. The cleaning works also represents additional costs, as well as the dismantling process which is as crucial and as costly as the construction process. As a result, temporary housing becomes environmentally unsustainable due to the great amount of resources needed to build the units, the lack of solutions for them after their usage, as well as because of the site pollution.

Cultural Inadequacy Problems

While trying to provide quick and economical housing, the formal sector has emphasized on standardization and technology oriented solutions. However, those solutions are usually what a restrained group of professionals consider appropriate and not what is suitable for local inhabitants, neglecting cultural and local conditions as well as user's needs.

Temporary housing projects continue to suffer from top-down problems of cost and cultural suitability. The units are usually produced in another country and sometimes intended to be used throughout the world. This concept of a universal or standard solution is not feasible because it ignores users' real needs, climatic variations, variations in cultural values and house forms, variations in family size, etc., imposing environments that may be culturally alien. A study developed by Caia, Ventimiglia, and Maass shows how the shape and materials are important to match the prototype of a home. The study also states that users react according to different type of units and the relocation in temporary housing is sometimes a relevant source of psychological stress. Thus, the way users become more attached to a specific type of housing unit may benefit their psychological well-being.

When solutions do not address users' needs and expectations, they often make changes and additions to cover their necessities. Since most of the times users do not have the appropriate skills and knowledge to handle with the new materials and construction techniques, they are not able to make secure modifications or ensure the maintenance, which make units more vulnerable to future disasters. In some extreme cases, people abandon the housing units provided because they cannot live in them, making all the investments in vain.

Some studies have presented alternative strategies and recommendations to avoid the problems. Most of them have insisted that principles such as community participation, usage of local resources and the development of solutions to reuse units are extremely advantageous to overcome temporary housing gaps.

Community participation and the use of local resources seem to be crucial concepts to find more sustainable and culturally adequate solutions. On one hand, local community is most of the times able to participate in reconstruction works. Indeed, studies have demonstrated that the first response to shelter needs after disasters has been provided by survivors themselves and also the idea that they are passive people waiting for help is a mistaken assumption The usage of local materials and construction techniques allows building housing solutions quickly and economically because there is no need to transport the materials nor to wait for specialized workforce. This way, it is possible to avoid the delays and costs of transportation as well as costs to buy foreign materials and pay external workforce. Since the local community have the knowledge to handle local materials and local construction techniques, the construction of temporary houses can start earlier, being more economic and sustainable.

On the other hand, users' satisfaction is closely related to their participation in the assessment of their own needs, being an important step to guarantee that solutions fit their expectations and are adequate to their lifestyles. In this way, local materials are more likely to be culturally and socially appropriate because people are familiar with them, and also because they provide better units' integration in the local environment.

In addition, the use of local materials and workforce improves local economy, and it makes easier the maintenance and modification of the units. Moreover, using the potential of the local community for housing reconstruction helps recovering a strong community spirit, sense of pride and well-being.

Units modifications: temporary housing unit before being used and after the user modifies it.

Temporary Housing Second Life

The concept of temporary means that the units are expected to be used during a predicted period of time and after that there is a need to find sustainable solutions for them. According to Johnson there are five possibilities: (1) long-term use of the units, often considered problematic due to social dysfunctions, illegal occupancy, high crime rates, etc.; (2) dismantling units and storing them to reuse in future disasters, which may cost as much as a new unit because the costs of dismantling, transporting, storing and reassembling; (3) sell the units, or parts of them, to recover some of the costs, although certainly less than a half of the initial investment; (4) demolish the units to sell or to donate its parts, but due to their final condition they often have little value; (5) reusing the units, which may involve additional costs to dismantle, transport and reassemble in the new location.

In spite of the possible additional costs, the reuse option seems to be an advantageous strategy because the units are a relevant resource for a recovering community. Proposing the re-design, re-use and recycle of temporary houses, Arslan states that units should be able to be re-used after the end of usage becoming permanent. The reuse and recycle may be: (a) for the same function and without additions to be used by low income families, students, etc.; (b) for the same function with additions to enlarge the house according to dweller's expectations; (c) for different functions, such as youth camps, holiday camps, etc. In the same train of thought, Johnson postulates that rental of temporary housing to low-income residents, reuse as new community buildings, and units acting as core for permanent housing are the most economically, socially and environmentally sustainable ways of reuse.

Independently from the functions of reuse, a 'second life' is an opportunity to enrich the high investments needed to provide units and to avoid sustainability problems. However, this is a fact that has been underestimated after many disasters, where temporary housing becomes problematic. In order to take advantage of the reuse potential it is imperative to provide the necessary conditions during the design phase.

Guidelines for Temporary Housing Solutions

Based on the facts that have been presented, it seems that some guidelines can be proposed to improve the outcomes of temporary housing projects. This study proposes five main principles: context understanding, community participation, local resources usage, planning ahead and design beyond units. A complete context understanding of the disaster area is a key to provide adequate housing solutions. Knowing the context means knowing all their characteristics, such as culture, traditions, social organization, economic and political systems, religious beliefs, climate, etc., and all these issues should be considered to develop temporary housing solutions. Thus, exact specifications for temporary housing solutions can only be given in a precise local context in order to provide solutions that match with their future users and environment. The starting-point in designing houses should be meeting people's aspirations and incorporating local forms of housing.

Achieving the previous goal is dependent on community participation in the process. The users' involvement on the assessment of their needs guarantees that solutions fit their needs, expectations and local living standards. Beyond their integration in the assessment of needs, their involvement in the construction works may have benefits for community recovery. However, some community-based approaches have had unexpected negative outcomes, Thus, not all kinds of participation are synonym of positive outcomes, and participation has to be locally decided according to the context.

Using local resources, such as materials, construction techniques and workforce, greatly contributes to reduce costs, to improve local economy and to provide better cultural and local integration. It also makes solutions more suitable and durable against local climate, maintaining them in a good state of repair. Moreover, it provides better maintenance and makes modifications easier for users, enabling, this way, the modification of the units according to their needs and possibilities over the time. Indeed, if carefully formulated, the indigenous and local solutions will probably be more effective, faster and better suit local needs. The use of local resources does not mean that innovation should not be used; if properly introduced and culturally integrated, some new materials and technologies may considerably contribute to improve housing solutions after disasters.

During the development of solutions it is crucial planning ahead, trying to create useful opportunities for their future usage. This study has discussed the advantages of some ways to reuse temporary units after their intended period of use and the importance of providing conditions to facilitate that reuse. During the designing phase it is crucial to create solutions as flexible as possible in order to make easier the required adaptations to reuse. It is also essential to make users capable of customizing and personalizing their units, making additions or modifications according to their needs and possibilities. In disaster scenarios housing is often a work place for families and flexibility is crucial to allow simple and quick transformations that make the unit able to accommodate these multifunctional spaces. Thus, flexibility is a crucial characteristic for temporary housing and has been defended by many authors. Likewise, simple construction systems that are easy to assembly and dismantle, and that use small elements, which are easier to handle, should be preferred.

The reversibility of the construction process proposed by Bologna is also a sustainable alternative for post-disaster housing units. This strategy proposes the possibility to reintroduce materials and spatial resources into another production cycle or to reintegrate them into the natural environment without production of waste or resides. Just like the reuse possibilities, the reversibility concept is only possible if properly planned ahead during the design phase.

Design beyond the unit plays a crucial role during the development of temporary houses. Having a unit that is properly adequate to users' needs and cultural issues, locally integrated, sustainable and economical does not mean that it will be well succeeded. The units' design is just an important part of the question since all the space surrounding them is extremely important for the success of the plan. The units' location has to be carefully established to ensure that people do not feel displaced, and that they are closer to their work places, services and amenities. Usually temporary housing units are built in periphery areas, which can cause social isolation and the need for extra infrastructure and services such as bus transportation, which represents more resources consumption. Besides the location, designing public spaces as squares, parks, gardens, etc., is decisive to provide opportunities for socializing, and that is essential to create community spirit, maintain social ties and it can be an opportunity to develop new ones. Recovering the sense of community is very important in post disaster situations and the real meaning of the term community is in the richness of social-relationships. In the same way, it is important to provide services such as schools, medical assistance points, community centers, shops, coffee shops, religious buildings, etc., in order to grant all the conditions for normal life in the temporary settlement.

The relation between the temporary housing units and these public spaces and buildings has to be carefully designed too. It is important to yield buffer zones from public domain to the units' private area in order to exist privacy among neighbors, as well as to facilitate social support and interaction. Even if these areas are not designed, free spaces should be considered so the users can create transitional areas like gardens. These spaces surrounding the units can also be used for cultivating zones or work spaces, which may be profitable for the families' economy. Since a settlement is not just a collection of individual households, design beyond the units is a key to create greater living environments for temporary settlements.

The principles proposed above intend to be important issues to consider while temporary housing solutions are being developed, mainly to help making appropriate choices and decisions. Therefore, from the standpoint of this study it is assumed that following those principles implies to consider crucial aspects for the quality of temporary housing units, such as protection, safety, privacy, comfort, standard of living, adequate dimensions, location, thermal and sound performance, lightning, ventilation, construction quality, durability, and many others.

Keeping Food and Water Safe after Disaster

If you are in a disaster or emergency, it's important that you take steps to prevent illness from unsafe food and water.

After a Disaster

- Food: Throw away food that may have come in contact with flood or storm water; perishable foods that have not been refrigerated properly due to power outages; and those with an unusual odor, color, or texture. Unsafe food can make you sick even if it looks, smells, and tastes normal. When in doubt, throw it out.

- Water: Do not use water you suspect or have been told is contaminated to wash dishes, brush your teeth, wash and prepare food, wash your hands, make ice, or make baby formula. Safe water for drinking, cooking, and personal hygiene includes bottled, boiled, or treated water. Your state, local, or tribal health department can make specific recommendations for boiling or treating water in your area.

Food

Identify and throw away food that may not be safe to eat. Do the following with food and containers that may have had contact with flood or storm water.

Throw away the following foods:

- Food that has an unusual odor, color, or texture. When in doubt, throw it out.
- Perishable foods (including meat, poultry, fish, eggs and leftovers) in your refrigerator when the power has been off for 4 hours or more.
- Food not in packages or cans.
- Canned foods or food containers that are bulging, opened, or damaged. Throw away the food if the container spurts liquid or foam when you open it or the food inside is discolored, is moldy, or smells bad.
- Packaged food: Throw away food containers with screw-caps, snap-lids, crimped caps, twist caps, flip tops, and snap-open, and home-canned foods because they cannot be disinfected. Throw away food in cardboard containers, including juice/milk/baby formula boxes.

How to reuse commercially prepared cans and retort pouches (like flexible, shelf-stable juice and seafood packages):

- Remove labels if they are removable.
- Brush or wipe away dirt or silt.
- Wash cans and pouches with soap and water, using hot water if available.
- Rinse cans and pouches with water that is safe for drinking, if available.
- Sanitize cans and pouches in one of two ways. 1.) Place them in a solution of 1 cup (8 oz/240 mL) of unscented household bleach in 5 gallons of water for 15 minutes. OR 2.) Submerge in a pot of water, bring to a boil, and continue boiling for 2 minutes.

- Re-label cans or pouches with a marker. Include the expiration date.
- Use food in reconditioned cans or pouches as soon as possible.

Thawed food that contains ice crystals can be refrozen or cooked. Freezers, if left unopened and full during a power outage, will keep food safe for 48 hours (24 hours if half full).

Store Food Safely

While the power is out, keep the refrigerator and freezer doors closed as much as possible.

Feeding Infants and Young Children when your Tap Water is Unsafe

- Breastfed infants should continue breastfeeding. For formula-fed infants, use ready-to-feed formula if possible. If using ready-to-feed formula is not possible, it is best to use bottled water to prepare powdered or concentrated formula when your tap water is unsafe. If bottled water is not available, check with local authorities to learn the status of your drinking water to see if boiling it will make it safe to drink. Use treated water to prepare formula only if you do not have bottled or boiled water.
- If water is contaminated with a chemical, boiling it will not remove the chemical or make it safe to consume.
- If you prepare infant formula with boiled water, let the formula cool sufficiently before giving it to an infant. Put a couple drops of formula on the back of your hand to see if it is too hot.
- Clean feeding bottles with bottled, boiled, or treated water before each use. Throw away baby bottle nipples or pacifiers that have been in contact with flood waters; they cannot be sanitized.
- Wash your hands before preparing formula and before feeding an infant. You can use alcohol-based hand sanitizer if water is limited or unsafe.

Clean and Sanitize Food-contact Surfaces that have been Flooded

Throw out wooden cutting boards, baby bottle nipples, and pacifiers if they have come into contact with flood waters because they cannot be properly sanitized. Clean and sanitize food-contact surfaces in a four-step process:

- Wash with soap and hot, clean water.
- Rinse with clean water.

- Sanitize by immersing for 1 minute in a solution of 1 cup (8 oz/240 mL) of unscented household chlorine bleach in 5 gallons of clean water.
- Allow to air dry.

Water

Safe Drinking Water

- After an emergency, especially after flooding, drinking water may not be available or safe to drink.
- Do not use water you suspect or have been told is unsafe to wash dishes, brush teeth, wash and prepare food, make ice, or make baby formula.
- Alcohol dehydrates the body, which increases the need for drinking water.
- Floods and other disasters can damage drinking water wells and lead to aquifer and well contamination. Flood waters can contaminate well water with livestock waste, human sewage, chemicals, and other contaminants which can lead to illness when used for drinking, bathing, and other hygiene activities.
- If your water comes from a private well that has been flooded, consider the following guidance for making water safe and for emergency water sources until you are certain your water is free of contaminants and safe to drink.

Make Water Safe

Water often can be made safe to drink by boiling, adding disinfectants, or filtering.

Water contaminated with fuel or toxic chemicals will not be made safe by boiling or disinfection. Use a different source of water if you know or suspect that water might be contaminated with fuel or toxic chemicals.

Boil Water

If you don’t have safe bottled water, you should boil water to make it safe. Boiling is the surest method to make water safer to drink by killing disease-causing organisms, including viruses, bacteria, and parasites.

You can improve the flat taste of boiled water by pouring it from one clean, disinfected container to another and then allowing it to stand for a few hours, OR by adding a pinch of salt for each quart or litter of boiled water.

If the water is cloudy:

- Filter it through a clean cloth, paper towel, or coffee filter OR allow it to settle.

- Draw off the clear water.
- Bring the clear water to a rolling boil for one minute (at elevations above 6,500 feet, boil for three minutes).
- Let the boiled water cool.
- Store the boiled water in clean sanitized containers with tight covers.

If the water is clear:

- Bring the clear water to a rolling boil for 1 minute (at elevations above 6,500 feet, boil for 3 minutes).
- Let the boiled water cool.
- Store the boiled water in clean, sanitized containers with tight covers.

Disinfectants

If you don't have clean, safe, bottled water and if boiling is not possible, you often can make water safer to drink by using a disinfectant, such as unscented household chlorine bleach, iodine, or chlorine dioxide tablets. These can kill most harmful organisms, such as viruses and bacteria. However, only chlorine dioxide tablets are effective in controlling more resistant organisms, such as the parasite Cryptosporidium. If the water is contaminated with a chemical, adding a disinfectant will not make it safe to drink.

To disinfect water using bleach:

- Bleach comes in different concentrations. Make sure you know the concentration of bleach you are using before using to disinfect drinking water. It should be on the label.
- Clean and disinfect water containers properly before each use. Use containers that are approved for water storage. Do not use containers previously used to store chemicals or other hazardous materials.
- If your water is cloudy, filter water through a clean cloth, paper towel, or coffee filter or allow it to settle, and then draw off the clear water.

When using 5-6% unscented liquid household chlorine bleaches:

- Add a little less than 1/8 teaspoon (8 drops or about 0.5 millilitres) for each gallon of clear water (or 2 drops of bleach for each litre or each quart of clear water).
    - If you do not have clear water or are not able to filter the water to make it clear, add a little less than ¼ teaspoon (16 drops, or about 1 millilitre) of

bleach for each gallon of cloudy water (or 4 drops of bleach for each litter or each quart of cloudy water). Stir the mixture well.

- Let it stand for at least 30 minutes before using.
- Store the disinfected water in clean, disinfected containers with tight covers.

When using 8.25% unscented liquid household chlorine bleaches:

- Add a little less than 1/8 teaspoon (6 drops or about 0.5 millilitres) of unscented liquid household chlorine (8.25%) bleach for each gallon of clear water (about 2 drops of bleach for each litre or each quart of clear water).
    - If you do not have clear water or are not able to filter the water to make it clear, add 1/8 teaspoon (12 drops, or about 1 millilitre) of bleach for each gallon of cloudy water (or 3 drops of bleach for each litre or each quart of cloudy water).
- Stir the mixture well.
- Let it stand for at least 30 minutes before using.
- Store the disinfected water in clean, sanitized containers with tight covers.

To disinfect water using iodine:

- Follow the manufacturer's instructions.
- Store the disinfected water in clean, sanitized containers with tight covers.

To disinfect water using chlorine dioxide tablets:

- Follow the manufacturer's instructions.
- Store the disinfected water in clean, disinfected containers with tight covers.

Filters

Many portable water filters can remove disease-causing parasites such as Cryptosporidium and Giardia from drinking water.

- If you are choosing a portable water filter, try to pick one that has a filter pore size small enough to remove both bacteria and parasites. Most portable water filters do not remove bacteria or viruses.
- Carefully read and follow the manufacturer's instructions for the water filter. After filtering, add a disinfectant such as iodine, chlorine, or chlorine dioxide to the filtered water to kill any viruses and remaining bacteria.

Finding Emergency Water Sources

Alternative sources of clean water can be found inside and outside the home. DO NOT DRINK water that has an unusual odor or color, or that you know or suspect might be contaminated with fuel or toxic chemicals; use a different source of water.

The following are possible sources of water:

- Water from your home's water heater tank (part of your drinking water system, not your home heating system).
- Melted ice cubes made with water that was not contaminated.
- Water from your home's toilet tank (not from the bowl), if it is clear and has not been chemically treated with toilet cleaners such as those that change the color of the water.
- Liquid from canned fruit and vegetables.
- Water from swimming pools and spas that hasn't been contaminated with flood or storm water can be used for personal hygiene, cleaning, and related uses, but not for drinking.

Outside the Home

Flood waters can contaminate well water and rivers, streams, and lakes with livestock waste, human sewage, chemicals, and other contaminants which can lead to illness when used for drinking, bathing, and other hygiene activities.

Water from sources outside the home must be treated as described in Make Water Safe in an Emergency, because it could be contaminated with livestock waste or human sewage. If you suspect or know the water is contaminated with toxic chemicals or fuels, it cannot be made safe and you should not drink or bathe in this water.

Possible sources of water that could be made safe by treatment include:

- Rainwater;
- Streams, rivers, and other moving bodies of water;
- Ponds and lakes;
- Natural springs.

Unsafe Water Sources

Never use water from the following sources:

- Radiators;
- Hot water boilers (part of your home heating system);

- Water beds (fungicides added to the water and/or chemicals in the vinyl may make water unsafe for use).

Private Drinking Water Wells

Floods and other disasters can damage or contaminate wells. Dug wells, bored wells, and other wells less than 50 feet deep are more likely to be contaminated, even if damage is not apparent.

- After a disaster, it is safest to drink bottled water until you are certain that your water is free of contaminants and safe to drink.
- If extensive flooding has occurred or you suspect that the well may be contaminated, DO NOT drinks the water. Use a safe water supply like bottled or treated water.
- Contact your local, state, or tribal health department for specific advice on wells and testing.
- Water contaminated with fuel or toxic chemicals will not be made safe by boiling or disinfection. Until you know the water is safe, use bottled water or some other safe supply of water.
- If you suspect your water has fuel or chemical contamination, contact your local health department for specific advice.

Water Sanitation and Hygiene

WASH refers to the provision of safe water for drinking, washing and domestic activities, the safe removal and final disposal of waste (faecal and solid waste disposal) and health promotion activities to encourage protective healthy behavioural practices amongst the affected population.

Inadequate WASH can restrict medical treatment in health facilities; degrade environmental conditions and increase community vulnerability.

Hazards, natural or manmade, can compromise vital water and waste management infrastructure. Water scarcity is projected to increase as a result of climate change. WASH is essential to meet the Sustainable Development Goals related to environmental sustainability and health.

What are the Health Risks?

Inadequate provision of WASH can lead to an increased risk of several diseases including: diarrhoea, hepatitis A, cholera, typhoid, dysentery, intestinal helminths, malaria and trachoma.

Infection can be transmitted:

- Through consumption of water or food that has been contaminated through environment, washing or cooking.
- By hand to mouth when availability of water for personal hygiene is reduced.
- Vectors (e.g. flies and mosquitoes) which breed near waste sites and stagnant water.

Inadequate management of human excreta poses a serious health risk due to potential contamination and loss of local water sources.

Children's excreta can be particularly high risk: it is more infectious than adults, yet often perceived by communities to be less so.

Lack of adequate WASH restricts the functioning and safe practices of health facilities and health workers.1 Pathogenic risks from exposure to medical waste include: hepatitis B & C, HIV, viral haemorrhagic fevers, skin, respiratory and gastro-enteric infections. It is estimated that 20% of health care waste is infectious.

Risk Management Considerations

Governments and communities can manage disaster risk from WASH by:

- Designing, building and maintaining water and sanitation systems which include simple modifications to withstand the risks of disasters.
- Carrying out vulnerability assessments of community supplies of water and sanitation systems to assess ability to provide essential services in the event of a disaster.
- Engaging and consulting the community in planning WASH services to identify culturally and socially acceptable interventions which will be effective, long lasting and sustainable.
- Ensuring a multi-sectoral approach in all aspects of disaster risk management for WASH, including disaster response planning.
- Providing an adequate quantity of safe water and accessible sanitation services during a disaster to reduce risk of infections.
- Preventing infection spread through education, facilities and soap for hand washing to promote hygienic practices.
- Referring to SPHERE on the minimum standards during disaster response for individuals, camps and health facilities.

- Ensuring that people in shelters and temporary camps have access to safe water and sanitation.
- Ensuring health facilities and health care providers have adequate water supplies to support delivery of life-saving and quality health care services, infection prevention and hygiene promotion in emergency situations.
- Disinfection and treatment of water as per SPHERE or WHO recommendations.
- Preventing defecation, especially by children, in areas which could contaminate water supplies.
- Providing safe disposal of clinical waste and vaccinations to protect health care workers and waste handlers against prevalent infections such as Hepatitis B.

Disaster Management

As per Disaster Management Act, 2005, "disaster management" means a continuous and integrated process of planning, organising, coordinating and implementing measures which are necessary or expedient for:

- Prevention of danger or threat of any disaster;
- Mitigation or reduction of risk of any disaster or its severity or consequences;
- Capacity-building;
- Preparedness to deal with any disaster;
- Prompt response to any threatening disaster situation or disaster;
- Assessing the severity or magnitude of effects of any disaster; evacuation, rescue and relief;
- Rehabilitation and reconstruction.

Disaster Management can be defined as the organization and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies, in particular preparedness, response and recovery in order to lessen the impact of disasters.

Disaster management includes administrative decisions and operational activities that involve:

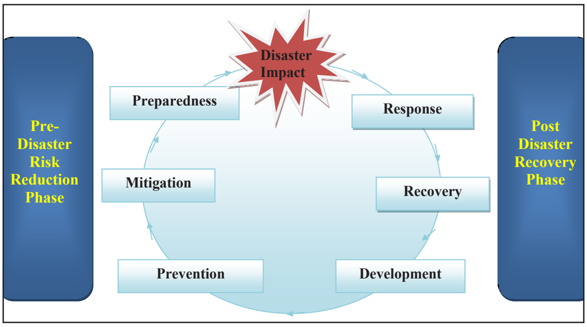
- Prevention
- Mitigation

- Preparedness
- Response
- Recovery
- Rehabilitation

Disaster management involves all levels of government. Nongovernmental and community based organizations play a vital role in the process. Modern disaster management goes beyond post-disaster assistance. It now includes pre-disaster planning and preparedness activities, organizational planning, training, information management, public relations and many other fields. Crisis management is important, but is only a part of the responsibility of a disaster manager. The newer paradigm is the Total Risk Management (TRM) which takes a holistic approach to risk reduction.

Disaster Management Cycle

The traditional approach to disaster management has been to regard it as a number of phased sequences of action or a continuum. These can be represented as a disaster management cycle. The basic disaster management cycle consex of six main activities.



Key Phases of Disaster Management

There are three key phases of activity within disaster management:

1. Pre-disaster: Before a disaster to reduce the potential for human, material or environmental losses caused by hazards and to ensure that these losses are minimized when the disaster actually strikes.
2. During Disaster: It is to ensure that the needs and provisions of victims are met to alleviate and minimize suffering.
3. Post-disaster: After a disaster to achieve rapid and durable recovery which does not reproduce the original vulnerable conditions.

Traditionally people think of disaster management only in term of the emergency relief period and post disaster rehabilitation. Instead of allocated funds before an event to ensure prevention and preparedness. A successful disaster management planning must encompass the situation that occurs before, during and after disasters.

Pre-disaster Phase

Prevention and Mitigation

Reducing the risk of disasters involves activities, which either reduce or modify the scale and intensity of the threat faced or by improving the conditions of elements at risk.

Although the term “prevention” is often used to embrace the wide diversity of measures to protect persons and property its use is not recommended since it is misleading in its implicit suggestion that natural disasters are preventable. The use of the term reduction to describe protective or preventive actions that lessen the scale of impact is therefore preferred. Mitigation embraces all measures taken to reduce both the effects of the hazard itself and the vulnerable conditions to it in order to reduce the scale of a future disaster.

In addition to these physical measures, mitigation should also be aimed at reducing the physical, economic and social vulnerability to threats and the underlying causes for this vulnerability. Therefore, mitigation may incorporate addressing issues such as land ownership, tenancy rights, wealth distribution, implementation of earthquake resistant building codes, etc.

Preparedness

This brings us to the all-important issue of disaster preparedness. The process embraces a measure that enables governments, communities and individuals to respond rapidly to disaster situations to cope with them effectively. Preparedness includes for example, the formulation of viable emergency plans, the development of warning systems, the maintenance of inventories, public awareness and education and the training of personnel. It may also embrace search and rescue measures as well as evacuation plans for areas that may be “at risk” from a recurring disaster. All preparedness planning needs to be supported by appropriate rules and regulations with clear allocation of responsibilities and budgetary provision.

Early Warning

This is the process of monitoring the situation in communities or areas known to be vulnerable to slow onset hazards, and passing the knowledge of the pending hazard to people in harm’s way. To be effective, warnings must be related to mass education and training of the population who know what actions they must take when warned.

The Disaster Impact

This refers to the real-time event of a hazard occurring and affecting elements at risk. The duration of the event will depend on the type of threat; ground shaking may only occur in a matter of seconds during an earthquake while flooding may take place over a longer sustained period.

During Disaster Phase

Response

This refers to the first stage response to any calamity, which include for examples such as setting up control rooms, putting the contingency plan in action, issue warning, action for evacuation, taking people to safer areas, rendering medical aid to the needy etc., simultaneously rendering relief to the homeless, food, drinking water, clothing etc. to the needy, restoration of communication, disbursement of assistance in cash or kind.

The emergency relief activities undertaken during and immediately following a disaster, which includes immediate relief, rescue, and the damage needs assessment and debris clearance.

The Post-disaster Phase

- Recovery: Recovery is used to describe the activities that encompass the three overlapping phases of emergency relief, rehabilitation and reconstruction.
- Rehabilitation: Rehabilitation includes the provision of temporary public utilities and housing as interim measures to assist long-term recovery.
- Reconstruction: Reconstruction attempts to return communities to improved pre-disaster functioning. It includes such as the replacement of buildings; infrastructure and lifeline facilities so that long-term development prospects are enhanced rather than reproducing the same conditions, which made an area or population vulnerable in the first place.
- Development: In an evolving economy, the development process is an ongoing activity. Longterm prevention/disaster reduction measures for examples like construction of embankments against flooding, irrigation facilities as drought proofing measures, increasing plant cover to reduce the occurrences of landslides, land use planning, construction of houses capable of withstanding the onslaught of heavy rain/wind speed and shocks of earthquakes are some of the activities that can be taken up as part of the development plan.

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We would like to thank the editorial team for lending their expertise to make the book truly unique. They have played a crucial role in the development of this book. Without their invaluable contributions this book wouldn't have been possible. They have made vital efforts to compile up to date information on the varied aspects of this subject to make this book a valuable addition to the collection of many professionals and students.

This book was conceptualized with the vision of imparting up-to-date and integrated information in this field. To ensure the same, a matchless editorial board was set up. Every individual on the board went through rigorous rounds of assessment to prove their worth. After which they invested a large part of their time researching and compiling the most relevant data for our readers.

The editorial board has been involved in producing this book since its inception. They have spent rigorous hours researching and exploring the diverse topics which have resulted in the successful publishing of this book. They have passed on their knowledge of decades through this book. To expedite this challenging task, the publisher supported the team at every step. A small team of assistant editors was also appointed to further simplify the editing procedure and attain best results for the readers.

Apart from the editorial board, the designing team has also invested a significant amount of their time in understanding the subject and creating the most relevant covers. They scrutinized every image to scout for the most suitable representation of the subject and create an appropriate cover for the book.

The publishing team has been an ardent support to the editorial, designing and production team. Their endless efforts to recruit the best for this project, has resulted in the accomplishment of this book. They are a veteran in the field of academics and their pool of knowledge is as vast as their experience in printing. Their expertise and guidance has proved useful at every step. Their uncompromising quality standards have made this book an exceptional effort. Their encouragement from time to time has been an inspiration for everyone.

The publisher and the editorial board hope that this book will prove to be a valuable piece of knowledge for students, practitioners and scholars across the globe.

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