Natural Hazards and Disaster Management

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ISBN: 978-1-9789-6552-2

Cataloging-in-Publication Data

Natural hazards and disaster management / Lily Hill.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-9789-6552-2
1. Natural disasters. 2. Hazard mitigation. 3. Natural disasters--Management.
4. Emergency management. I. Hill, Lily.
GB5014 .N38 2021
363.34--dc23

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PREFACE

This book is a culmination of my many years of practice in this field. I attribute the success of this book to my support group. I would like to thank my parents who have showered me with unconditional love and support and my peers and professors for their constant guidance.

A major adverse event that results from natural processes of the Earth is known as natural disaster. It includes volcanic eruptions, earthquakes, tsunamis, floods, hurricanes, tornadoes and other geological processes. Natural hazards often cause major loss of lives and damage to property. They are classified into geological disasters, hydrological disasters, meteorological disasters, and wildfire and space disasters. Geological disasters include avalanches, landslides, sinkholes, etc. Hydrological disasters include tsunami, floods, limnic eruptions, etc. Meteorological disasters include cyclonic storms, blizzards, hailstorms, ice storms and heat waves. Different approaches, evaluations, methodologies and advanced studies on natural hazards and disasters have been included in this book. It provides comprehensive insights into this field. This book, with its detailed analyses and data, will prove immensely beneficial to professionals and students involved in this area at various levels.

The details of chapters are provided below for a progressive learning:

Chapter – What are Natural Disasters and Hazards?

Any natural phenomenon which negatively impacts the human health and the environment can be classified as a natural hazard or disaster. Some examples of such hazards include floods, volcanic eruptions, earthquakes, tsunamis, etc. This is an introductory chapter which will introduce briefly all the significant aspects of natural hazards and disasters.

Chapter – Types of Weather Hazards

The meteorological phenomena which have the potential to adversely affect human life and cause damage are classified as weather hazards. The common weather hazards include thunderstorm, wildfire, tornado, cyclone, etc. All such hazards have been carefully analyzed in this chapter.

Chapter – Geologic Hazards

Geologic hazards refer to the geologic conditions which can cause loss of life and property. Such hazards include avalanche, earthquake, volcanic eruptions, landslides, etc. The topics elaborated in this chapter will help in gaining a better perspective of such geologic hazards.

Chapter – Common Hydrologic Hazards

Hydrologic hazards include hazards which are caused by water such as flood, tsunami, etc. This chapter has been carefully written to provide an easy understanding of the varied facets of these hydrologic hazards.

Chapter – Disaster Management

Disaster management is the judicious use of resources to deal with any form of disaster. It includes minimizing the effects on human life and property. This chapter discusses in detail the theories and methodologies related to disaster management.

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What are Natural Disasters and Hazards?

CHAPTER 1

Any natural phenomenon which negatively impacts the human health and the environment can be classified as a natural hazard or disaster. Some examples of such hazards include floods, volcanic eruptions, earthquakes, tsunamis, etc. This is an introductory chapter which will introduce briefly all the significant aspects of natural hazards and disasters.

NATURAL DISASTERS

Natural disaster or natural hazard is 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 neighbors 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.

Cause of Natural Disaster

- There are different types of natural disasters and depending on different types of disasters the causes are also different. For example, the causes of an earthquake cannot be the same as that of forest-re. Natural disasters are caused due to different reasons like soil erosion, seismic activity, tectonic movements, air pressure, and ocean currents etc. natural disaster is not a new phenomenon these natural events have occurred since the earth began forming and continue to cause serious damage and loss of life all over the globe from many years. The root causes of most of the natural disasters that occur on earth can be attributed to the imbalance created in our environment. This imbalance may either be in the form of air pollution, noise pollution or water pollution and the collective effect of these imbalances are also one of the few reasons for the natural disaster. Though it also a fact that we cannot blame anyone because this is just one of the few reasons. Natural disasters like earthquake, oods etc have also occurred in past era when the human was far away from modernization. So it would not be fair enough to blame modernization for the same.

- Natural activities taking place in the earth's crust, as well as surface, are the main reasons for these disasters. Seismic activity caused by earthquakes have been the root cause of volcanoes erupting and typhoons. It has been studied that the continents sit on huge plates that occasionally shift and when these plates shift they cause an increase in pressure underneath the earth's surface which is also a cause of natural disasters. Tectonic movements in the earth's crust are responsible for the earthquakes, which at times can get really dangerous and may lead to some heavy loss of life and property. In areas where volcanoes have formed by solidied magma, pressure from gasses and magma can explode or erupt to send tons of ash into the atmosphere.
- The activity of the moon determines the ocean waves which can get really high during the full moon and at times these can be really dangerous. It was also observed that deadly December 2004 tsunami also occurred on a full moon night. The earthquake was caused when the Indian Plate was subducted by the Burma Plate and triggered a series of devastating tsunamis along the coasts of most landmasses bordering the Indian Ocean, killing over 230,000 people in fourteen countries, and inundating coastal communities with waves up to 30 meters (98 ft) high. It was one of the deadliest natural disasters in recorded history. Indonesia was the hardest-hit country, followed by Sri Lanka, India, and Thailand.
- Changing ocean currents are also dangerous at times and can result in changes in water temperature which could result in a global food shortage by killing sh and ocean plant life. These changing oceanic currents could also adversely affect the intensity as well as the frequency of storms. Tornadoes which are really dangerous are often formed by the interaction of high and low-pressure air and these have proved to be really dangerous as well as devastating for many communities in the area of America, especially the area of Tornado Alley. Air pressure, high and low determines whether or not we have thunderstorms, rain and hurricanes. Flooding and high winds are caused by the crashing together of low and high-pressure air. Damage caused by ooding and hurricanes along coastal cities and towns can be really difcult to overcome for their victims.
- Natural Disasters are a set of naturally occurring events which can directly or indirectly cause severe threats to human health and well-being and adversely affects the human life for quite some time. It has been witnessed that the natural disasters have their root causes in the normal activities of the earth. However during the past few years, we have witnessed some rapid modernization and growth, man's increased knowledge and technology has served to trigger for some natural disasters. Flooding and erosion can occur are really prone to the areas where mining, deforestation, and manufacturing have taken place. Global warming, which could eventually affect the ocean currents, has its roots in modern man's overuse of fossil fuels. Earthquakes resulting as a result of tectonic movements and movements of plates inside the earth's crust can also be triggered by drilling, bombing, mining, and construction.

NATURAL HAZARDS

A natural hazard is a threat of a naturally occurring event will have a negative effect on humans. This negative effect is what we call a natural disaster. In other words when the hazardous threat actually happens and harms humans, we call the event a natural disaster.

Natural Hazards (and the resulting disasters) are the result of naturally occurring processes that have operated throughout Earth's history.

- Most hazardous process are also Geologic Processes.
- Geologic processes effect every human on the Earth all of the time, but are most noticeable when they cause loss of life or property. If the process that poses the hazard occurs and destroys human life or property, then a natural disaster has occurred. Among the natural hazards and possible disasters to be considered are:
    - Earthquakes
    - Volcanic Eruptions
    - Tsunami
    - Landslides
    - Subsidence
    - Floods
    - Droughts
    - Hurricanes
    - Tornadoes
    - Asteroid Impacts
- All of these processes have been operating throughout Earth history, but the processes have become hazardous only because they negatively affect us as human beings. Important Point - There would be no natural disasters if it were not for humans. Without humans these are only natural events.
- Risk is characteristic of the relationship between humans and geologic processes. We all take risks everyday. The risk from natural hazards, while it cannot be eliminated, can, in some cases be understood in a such a way that we can minimize the hazard to humans, and thus minimize the risk. To do this, we need to understand something about the processes that operate, and understand the energy required for the process. Then, we can develop an action to take to minimize the risk. Such minimization of risk is called hazard mitigation.
- Although humans can sometimes influence natural disasters (for example when poor levee design results in a flood), other disasters that are directly generated by humans, such as oil and toxic material spills, pollution, massive automobile or train wrecks, airplane crashes, and human induced explosions, are considered technological disasters, and will not be considered in this course, except when they occur as a secondary result of a natural disaster.
- Some of the questions we hope to answer for each possible natural disaster are:
    - Where is each type of hazard likely to be present and why?
    - What scientific principles govern the processes responsible for the disasters?
    - How often do these hazards develop into disasters?
    - How can each type of disaster be predicted and/or mitigated?

Natural disasters are produced by processes that have been operating since the Earth formed. Such processes are beneficial to us as humans because they are responsible for things that make the Earth a habitable planet for life. For example:

- Throughout Earth history, volcanism has been responsible for producing much of the water present on the Earth's surface, and for producing the atmosphere.

- Earthquakes are one of the processes responsible for the formation of mountain ranges which which direct water to flow downhill to form rivers and lakes.
- Erosional processes, including flooding, landslides, and windstorms replenishes soil and helps sustain life.

Such processes are only considered hazardous when they adversely affect humans and their activities.

Classification of Natural Hazards and Disasters

Natural Hazards and the natural disasters that result can be divided into several different categories:

- Geologic Hazards - These are the main subject of this course and include:
    - Earthquakes
    - Volcanic Eruptions
    - Tsunami
    - Landslides
    - Floods
    - Subsidence
    - Impacts with space objects
- Atmospheric Hazards - These are also natural hazards but processes operating in the atmosphere are mainly responsible. They will also be considered in this course, and include:
    - Tropical Cyclones
    - Tornadoes
    - Droughts
    - Severe Thunderstorms
    - Lightening
- Other Natural Hazards - These are hazards that may occur naturally, but don't fall in to either of the categories above. They will not be considered to any great extent in this course, but include:
    - Insect infestations
    - Disease epidemics
    - Wildfires

Natural Hazards can also be divided into catastrophic hazards, which have devastating consequences to huge numbers of people, or have a worldwide effect, such as impacts with large space objects, huge volcanic eruptions, world-wide disease epidemics, and world-wide droughts. Such catastrophic hazards only have a small chance of occurring, but can have devastating results if they do occur.

Natural Hazards can also be divided into rapid onset hazards, such as Volcanic Eruptions, Earthquakes, Flash floods, Landslides, Severe Thunderstorms, Lightening, and wildfires, which develop with little warning and strike rapidly. Slow onset hazards, like drought, insect infestations, and disease epidemics take years to develop.

Anthropogenic Hazards

These are hazards that occur as a result of human interaction with the environment. They include Technological Hazards, which occur due to exposure to hazardous substances, such as radon, mercury, asbestos fibers, and coal dust. They also include other hazards that have formed only through human interaction, such as acid rain, and contamination of the atmosphere or surface waters with harmful substances, as well as the potential for human destruction of the ozone layer and potential global warming.

Effects of Hazards

Hazardous process of all types can have primary, secondary, and tertiary effects:

- Primary Effects occur as a result of the process itself. For example water damage during a flood or collapse of buildings during an earthquake, landslide, or hurricane.
- Secondary Effects occur only because a primary effect has caused them. For example, fires ignited as a result of earthquakes, disruption of electrical power and water service as a result of an earthquake, flood, or hurricane, or flooding caused by a landslide into a lake or river.
- Tertiary Effects are long-term effects that are set off as a result of a primary event. These include things like loss of habitat caused by a flood, permanent changes in the position of river channel caused by flood, crop failure caused by a volcanic eruption etc.

Vulnerability to Hazards and Disasters

Vulnerability refers the way a hazard or disaster will affect human life and property Vulnerability to a given hazard depends on:

- Proximity to a possible hazardous event.
- Population density in the area proximal to the event.
- Scientific understanding of the hazard.
- Public education and awareness of the hazard.
- Existence or non-existence of early-warning systems and lines of communication.
- Availability and readiness of emergency infrastructure.

- Construction styles and building codes.
- Cultural factors that influence public response to warnings.

In general, less developed countries are more vulnerable to natural hazards than are industrialized countries because of lack of understanding, education, infrastructure, building codes, etc. Poverty also plays a role - since poverty leads to poor building structure, increased population density, and lack of communication and infrastructure.

Human intervention in natural processes can also increase vulnerability by:

- Development and habitation of lands susceptible to hazards, For example, building on floodplains subject to floods, sea cliffs subject to landslides, coastlines subject to hurricanes and floods, or volcanic slopes subject to volcanic eruptions.
- Increasing the severity or frequency of a natural disaster. For example: overgrazing or deforestation leading to more severe erosion (floods, landslides), mining groundwater leading to subsidence, construction of roads on unstable slopes leading to landslides, or even contributing to global warming, leading to more severe storms.

Affluence can also play a role, since affluence often controls where habitation takes place, for example along coastlines, or on volcanic slopes. Affluence also likely contributes to global warming, since it is the affluent societies that burn the most fossil fuels adding CO_2 to the atmosphere.

Assessing Hazards and Risk

Hazard Assessment consists of determining the following:

- When and where hazardous processes have occurred in the past.
- The severity of the physical effects of past hazardous processes (magnitude).
- The frequency of occurrence of hazardous processes.
- The likely effects of a process of a given magnitude if it were to occur now.
- And, making all this information available in a form useful to planners and public officials responsible for making decisions in event of a disaster.

Risk Assessment involves not only the assessment of hazards from a scientific point of view, but also the socio-economic impacts of a hazardous event. Risk is a statement of probability that an event will cause x amount of damage, or a statement of the economic impact in monetary terms that an event will cause. Risk assessment involves:

- Hazard assessment.
- Location of buildings, highways, and other infrastructure in the areas subject to hazards.
- Potential exposure to the physical effects of a hazardous situation.
- The vulnerability of the community when subjected to the physical effects of the event.

Risk assessment aids decision makers and scientists to compare and evaluate potential hazards, set priorities on what kinds of mitigation are possible, and set priorities on where to focus resources and further study.

Prediction and Warning

Risk and vulnerability can sometimes be reduced if there is an adequate means of predicting a hazardous event.

Prediction

Prediction involves:

- A statement of probability that an event will occur based on scientific observation.
- Such observation usually involves monitoring of the process in order to identify some kind of precursor event(s) - an anomalous small physical change that may be known to lead to a more devastating event. - Examples:
    - Hurricanes are known to pass through several stages of development: tropical depression - tropical storm - hurricane. Once a tropical depression is identified, monitoring allows meteorologists to predict how long the development will take and the eventual path of the storm.
    - Volcanic eruptions are usually preceded by a sudden increase in the number of earthquakes immediately below the volcano and changes in the chemical composition of the gases emitted from a volcanic vent. If these are closely monitored, volcanic eruptions can be often be predicted with reasonable accuracy.

Forecasting

Sometimes the word “forecast” is used synonymously with prediction and other times it is not:

- In the prediction of floods, hurricanes, and other weather related phenomena the word forecast refers to short-term prediction in terms of the magnitude, location, date, and time of an event. Most of us are familiar with weather forecasts.
- In the prediction of earthquakes, the word forecast is used in a much less precise way - referring to a long-term probability that is not specific in terms of the exact time that the event will occur. For example: Prior to the October 17 1989 Loma Prieta Earthquake (also know as the World Series Earthquake) the U.S. Geological Survey had forecast a 50% probability that a large earthquake would occur in this area within the next 30 years. Even after the event, the current forecast is for a 63% probability that a major earthquake will occur in this area in the next 30 years.

Early Warning

A warning is a statement that a high probability of a hazardous event will occur, based on a prediction or forecast. If a warning is issued, it should be taken as a statement that “normal routines of life should be altered to deal with the danger imposed by the imminent event”.

The effectiveness of a warning depends on:

- The timeliness of the warning.
- Effective communications and public information systems to inform the public of the imminent danger.
- The credibility of the sources from which the warning came.

If warnings are issued too late, or if there is no means of disseminating the information, then there will not be time enough or responsiveness to the warning. If warnings are issued irresponsibly without credible data or sources, then they will likely be ignored. Thus, the people responsible for taking action in the event of a potential disaster will not respond.

Frequency of Natural Disasters

Again, it is important to understand that natural disasters result from natural processes that affect humans adversely.

First - Size Matters

For example:

- Humans coexist with rivers all the time and benefit from them as a source of water and transportation. Only when the volume of water in the river becomes greater than the capacity of the stream channel is there a resulting disaster.
- Small earthquakes occur all of the time with no adverse effects.Only large earthquakes cause disasters.

Second - Location

For example:

- A volcanic on an isolated uninhabited island will not result in a natural disaster.
- A large earthquake in an unpopulated area will not result in a disaster.
- A hurricane that makes landfall on a coast where few people live, will not result in a disaster.

So, what we have to worry about is large events that strike areas where humans live.

Thus, in natural hazards studies, it is important to understand the relationship between frequency of an event and the size of the event. Size is often referred to a magnitude.

For just about any event, statistical analysis will reveal that larger events occur less frequently than small events.

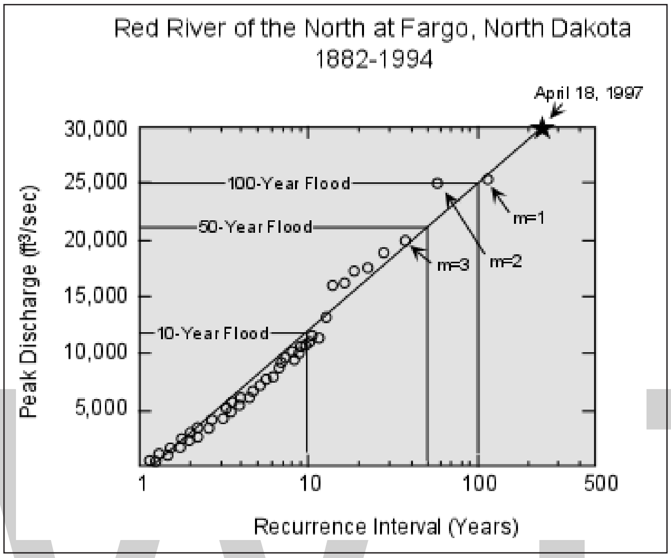
Statistical analysis of some types of events for specific locations allow one to determine the return period or recurrence interval.

Examples:

Flood Frequency

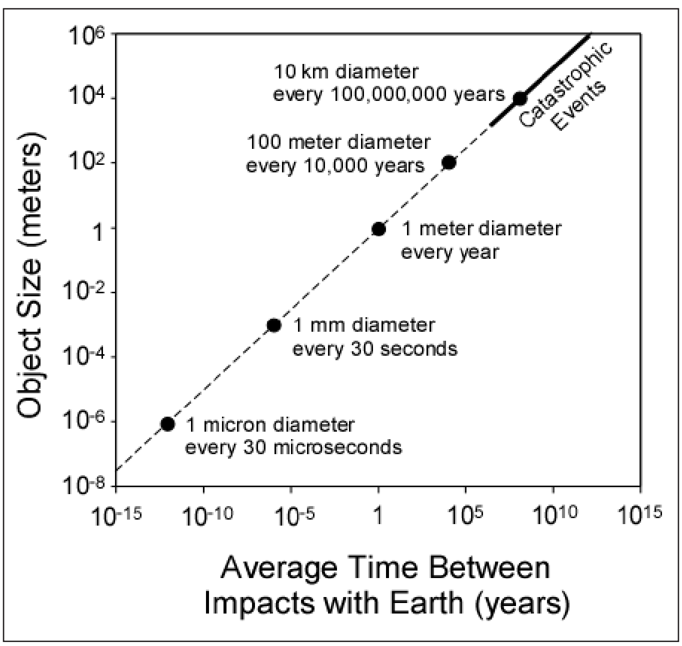
For any river, high discharge events are rare.

Large discharge events occur much less frequently than small discharge events.



Meteorite Impacts

Although we as humans have not had the opportunity (fortunately) of observing large asteroid or meteorite impacts, the data suggest that impacts of large asteroids (1 km or larger) occurs only once every 10 million years.



WEATHER HAZARDS

A weather hazard is an extreme weather event that threatens people or property.

Frost and High Temperature

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. Crops in north-west India experience frost of moderate to severe intensity. 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:

- The temperature of the plant is increased by increasing the soil temperature. The soil temperature can be increased by giving irrigation to the crop.
- By covering the plants with glass or plastic covers. In this way, the temperature of the plants rises.
- 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. Heat wave generally extends from north-west India right up to Orissa and Andhra coast. Every year highest severity of heat waves is found in Uttar Pradesh and Bihar states.

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 remain 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 increases 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 phenomena 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,
- Seasonal droughts,
- Contingent droughts, and
- Invisible droughts.

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 can not be predicted. The crops stand wilt under the influence of these three droughts.

Invisible Droughts

These droughts can not 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. Northern and Eastern parts of India are prone to floods, where agricultural crops are adversely affected. The floods cause a greater loss of life and property than any other natural disaster.

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. This type 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 melt 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 thousands 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. In India hailstorms occur during winter season.

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 diameter of the chimney vary from 10 meter to 100 meter or even 1km to 2 km. 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. This 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.

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.

A lightening flash hitting a tree and earth suface.

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.

GEOLOGICAL HAZARDS

A geologic hazard is one of several types of adverse geologic conditions capable of causing damage or loss of property and life. These hazards consist of sudden phenomena and slow phenomena:

Huge landslide at La Conchita.

Sudden phenomena include:

- Avalanches (snow, rock, or air & snow) and its runout.
- Earthquakes and earthquake-triggered phenomena such as tsunamis.
- Forest fires (espec. in Mediterranean areas) leading to deforestation.
- Geomagnetic storms.
- Ice jams (Eisstoß) on rivers or glacial lake outburst floods below a glacier.
- Landslide (lateral displacement of earth materials on a slope or hillside).
- Mudflows (avalanche-like muddy flow of soft/wet soil and sediment materials, narrow landslides).
- Pyroclastic flows.
- Rock falls, rock slides, (rock avalanche) and debris flows.
- Torrents (flash floods, rapid floods or heavy current creeks with irregular course).
- Volcanic eruptions, lahars and ash falls.

Norris geyser at Yellowstone NP.

Gradual or slow phenomena include

- Alluvial fans (e.g. at the exit of canyons or side valleys).
- Caldera development (volcanoes).
- Geyser deposits.
- Ground settlement due to consolidation of compressible soils or due to collapseable soils.
- Ground subsidence, sags and sinkholes.
- Liquefaction (settlement of the ground in areas underlain by loose saturated sand/silt during an earthquake event).

- Sand dune migration.
- Shoreline and stream erosion.
- Thermal springs.

Sometime the hazard is instigated by man through the careless location of developments or construction in which the conditions were not taken into account.

Geologic Hazard Evaluation and Mitigation

Geologic hazards are typically evaluated by engineering geologists who are educated and trained in interpretation of landforms and earth process, earth-structure interaction, and in geologic hazard mitigation. The engineering geologist provides recommendations and designs to mitigate for geologic hazards. Trained hazard mitigation planners also assist local communities to identify strategies for mitigating the effects of such hazards and developing plans to implement these measures. Mitigation can include a variety of measures:

- Geologic hazards may be avoided by relocation.
- The stability of sloping earth can be improved by the construction of retaining walls, which may use techniques such as slurry walls, shear pins, tiebacks, soil nails or soil anchors. Larger projects may use gabions and other forms of earth buttress.
- Shorelines and streams are protected against scour and erosion using revetments and riprap.
- The soil or rock itself may be improved by means such as dynamic compaction, injection of grout or concrete, and mechanically stabilized earth.
- Additional mitigation methods include deep foundations, tunnels, surface and subdrain systems, and other measures.
- Planning measures include regulations prohibiting development near hazard-prone areas and adoption of building codes.

Eisstoß Feb.2006 Vienna, Austria (Donauinsel)

Glacier just above Grindelwald, Switzerland

HYDROLOGIC HAZARDS

Hydrological disasters is a violent, sharp and harmful amendment either in quality of earth's water or in distribution or movement of water ashore below the surface or in atmosphere.

A flood is associate overflow of associate expanse of water that submerges land. The EU Floods directive defines a flood as a brief covering by water of land not unremarkably lined by water. within the sense of "flowing water", the word might also be applied to the influx of the tide. Flooding might result from the degree of water at intervals a body of water, like a watercourse or lake, that overflows or breaks levees, with the result that a number of the water escapes its usual boundaries. whereas the dimensions of a lake or alternative body of water can vary with seasonal changes in precipitation and snow soften, it\'s not a major flood unless the water covers land employed by man sort of a village, town or alternative settled space, roads, expanses of farmland, etc.

Some of the foremost notable floods include:

- The Johnstown Flood of 1889 wherever over 2200 individuals lost their lives once the South Fork Dam holding back Lake Conemaugh skint.
- The Hwang Ho (Yellow River) in China floods notably typically. the nice Flood of 1931 caused between 800,000 and 4,000,000 deaths.
- The nice Flood of 1993 was one among the foremost pricey floods in us history.
- The North Sea flood of 1953 that killed 2251 individuals within the European nation and japanese England.
- The 1998 Chang Floods, in China, left fourteen million individuals homeless.
- The 2000 African nation flood lined a lot of the country for 3 weeks, leading to thousands of deaths, and feat the country blasted for years afterwards.
- The 2005 metropolis floods that killed 1094 individuals.
- The 2010 Asian nation floods, broken crops and infrastructure, claiming several lives.

Tropical cyclones may result in in depth flooding in 1970:

- Typhoon Semitic deity, that stricken China in 1975.
- Hurricane Katrina, that stricken New Orleans, Louisiana in 2005.
- Cyclone Yasi, that stricken Australia in 2011.

A limnic eruption happens once a gas, typically greenhouse emission, suddenly erupts from deep lake water, sitting the threat of suffocative life, placental mammal and humans. Such associate eruption might also cause tsunamis within the lake because the rising gas displaces water. Scientists believe landslides, volcanic activity, or explosions will trigger such associate eruption. To date, solely 2 limnic eruptions are ascertained and recorded:

- In 1984, in Cameroon, a limnic eruption in Lake Monoun caused the deaths of thirty seven close residents.

- At close Lake Nyos in one986 a far larger eruption killed between 1,700 and 1,800 individuals by asphyxiation.

Tsunamis are often caused by subsurface earthquakes because the one caused by the 2004 Indian Ocean Earthquake, or by landslides like the one that occurred at Lituya Bay, Alaska.

- The 2004 Indian Ocean Earthquake created the Boxing Day moving ridge.
- On March eleven, 2011, a moving ridge occurred close to Fukushima, Japan and unfold through the Pacific.

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Types of Weather Hazards

CHAPTER 2

The meteorological phenomena which have the potential to adversely affect human life and cause damage are classified as weather hazards. The common weather hazards include thunderstorm, wildfire, tornado, cyclone, etc. All such hazards have been carefully analyzed in this chapter.

THUNDERSTORM

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.

There are two major aspects of thunderstorms: their meteorology (i.e., their formation, structure, and distribution) and their electrification (i.e., the generation of lightning and thunder).

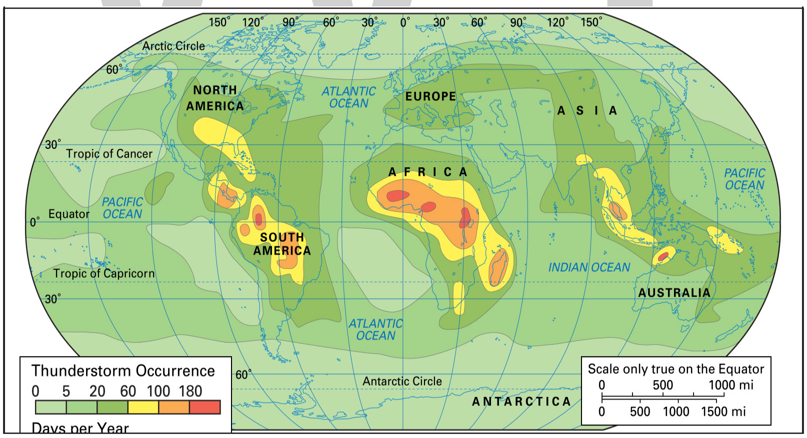
Thunderstorm Formation and Structure

Vertical Atmospheric Motion

Most brief but violent disturbances in Earth's wind systems involve large areas of ascending and descending air. Thunderstorms are no exception to this pattern. In technical terms, a thunderstorm is said to develop when the atmosphere becomes "unstable to vertical motion." Such an instability can arise whenever relatively warm, light air is overlain by cooler, heavier air. Under such conditions the cooler air tends to sink, displacing the warmer air upward. If a sufficiently large volume of air rises, an updraft (a strong current of rising air) will be produced. If the updraft is moist, the water will condense and form clouds; condensation in turn will release latent heat energy, further fueling upward air motion and increasing the instability.

Once upward air motions are initiated in an unstable atmosphere, rising parcels of warm air accelerate as they rise through their cooler surroundings because they have a lower density and are more buoyant. This motion can set up a pattern of convection wherein heat and moisture are transported upward and cooler and drier air is transported downward. Areas of the atmosphere where vertical motion is relatively strong are called cells, and when they carry air to the upper troposphere (the lowest layer of the atmosphere), they are called deep cells. Thunderstorms develop when deep cells of moist convection become organized and merge, and then produce precipitation and ultimately lightning and thunder.

Upward motions can be initiated in a variety of ways in the atmosphere. A common mechanism is by the heating of a land surface and the adjacent layers of air by sunlight. If surface heating is sufficient, the temperatures of the lowest layers of air will rise faster than those of layers aloft, and the air will become unstable. The ability of the ground to heat up quickly is why most thunderstorms form over land rather than oceans. Instability can also occur when layers of cool air are warmed from below after they move over a warm ocean surface or over layers of warm air. Mountains, too, can trigger upward atmospheric motion by acting as topographic barriers that force winds to rise. Mountains also act as high-level sources of heat and instability when their surfaces are heated by the Sun.



World patterns of thunderstorm frequency.

Thunderstorms occur most often in the tropical latitudes over land, where the air is most likely to heat quickly and form strong updrafts.

The huge clouds associated with thunderstorms typically start as isolated cumulus clouds that develop vertically into domes and towers. If there is enough instability and moisture and the background winds are favourable, the heat released by condensation will further enhance the buoyancy of the rising air mass. The cumulus clouds will grow and merge with other cells to form a cumulus congestus cloud extending even higher into the atmosphere (6,000 metres [20,000 feet] or more above the surface). Ultimately, a cumulonimbus cloud will form, with its characteristic anvil-shaped top, billowing sides, and dark base. Cumulonimbus clouds typically produce large amounts of precipitation.

Types of Thunderstorms

At one time, thunderstorms were classified according to where they occurred—for example, as local, frontal, or orographic (mountain-initiated) thunderstorms. Today it is more common to classify storms according to the characteristics of the storms themselves, and such characteristics depend largely on the meteorological environment in which the storms develop. The United States National Weather Service has defined a severe thunderstorm as any storm that produces a tornado, winds greater than 26 metres per second (94 km [58 miles] per hour), or hail with a diameter greater than 1.9 cm (0.75 inch).

Isolated Thunderstorms

Isolated thunderstorms tend to occur where there are light winds that do not change dramatically with height and where there is abundant moisture at low and middle levels of the atmosphere—that is, from near the surface of the ground up to around 10,000 metres (33,000 feet) in altitude. These storms are sometimes called air-mass or local thunderstorms. They are mostly vertical in structure, are relatively short-lived, and usually do not produce violent weather at the ground. Aircraft and radar measurements show that such storms are composed of one or more convective cells, each of which goes through a well-defined life cycle. Early in the development of a cell, the air motions are mostly upward, not as a steady, uniform stream but as one that is composed of a series of rising eddies. Cloud and precipitation particles form and grow as the cell grows. When the accumulated load of water and ice becomes excessive, a downdraft starts. The downward motion is enhanced when the cloud particles evaporate and cool the air—almost the reverse of the processes in an updraft. At maturity, the cell contains both updrafts and downdrafts in close proximity. In its later stages, the downdraft spreads throughout the cell and diminishes in intensity as precipitation falls from the cloud. Isolated thunderstorms contain one or more convective cells in different stages of evolution. Frequently, the downdrafts and associated outflows from a storm trigger new convective cells nearby, resulting in the formation of a multiple-cell thunderstorm.

Rain and lightning during a thunderstorm in Arizona.

Solar heating is an important factor in triggering local, isolated thunderstorms. Most such storms occur in the late afternoon and early evening, when surface temperatures are highest.

Multiple-Cell Thunderstorms and Mesoscale Convective Systems

Violent weather at the ground is usually produced by organized multiple-cell storms, squall lines, or a supercell. All of these tend to be associated with a mesoscale disturbance (a weather system of intermediate size, that is, 10 to 1,000 km [6 to 600 miles] in horizontal extent). Multiple-cell storms have several updrafts and downdrafts in close proximity to one another. They occur in clusters of cells in various stages of development moving together as a group. Within the cluster one cell dominates for a time before weakening, and then another cell repeats the cycle. In squall lines, thunderstorms form in an organized line and create a single, continuous gust front (the leading edge of a storm's outflow from its downdraft). Supercell storms have one intense updraft and downdraft.

Lightning: cloud-to-ground Cloud-to-ground lightning discharge in a field from a cumulonimbus cloud.

Sometimes the development of a mesoscale weather disturbance causes thunderstorms to develop over a region hundreds of kilometres in diameter. Examples of such disturbances include frontal wave cyclones (low-pressure systems that develop from a wave on a front separating warm and cool air masses) and low-pressure troughs at upper levels of the atmosphere. The resulting pattern of storms is called a mesoscale convective system (MCS). Severe multiple-cell thunderstorms and supercell storms are frequently associated with MCSs. Precipitation produced by these systems typically includes rainfall from convective clouds and from stratiform clouds (cloud layers with a large horizontal extent). Stratiform precipitation is primarily due to the remnants of older cells with a relatively low vertical velocity—that is, with limited convection occurring.

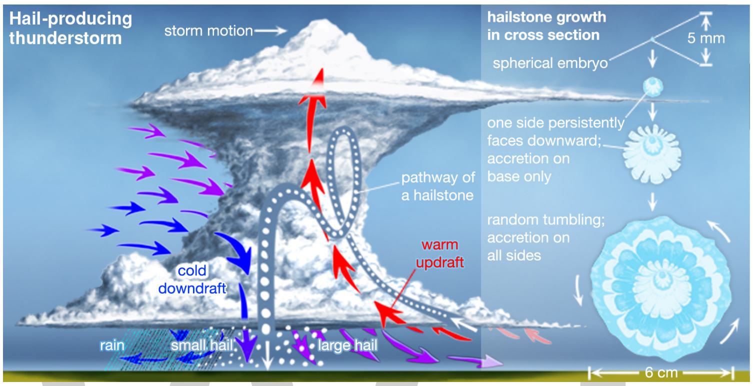
Thunderstorms can be triggered by a cold front that moves into moist, unstable air. Sometimes squall lines develop in the warm air mass tens to hundreds of kilometres ahead of a cold front. The tendency of prefrontal storms to be more or less aligned parallel to the front indicates that they are initiated by atmospheric disturbances caused by the front.

In the central United States, severe thunderstorms commonly occur in the springtime, when cool westerly winds at middle levels (3,000 to 10,000 metres [10,000 to 33,000 feet] in altitude) move over warm and moist surface air flowing northward from the Gulf of Mexico. The resulting broad region of instability produces MCSs that persist for many hours or even days.

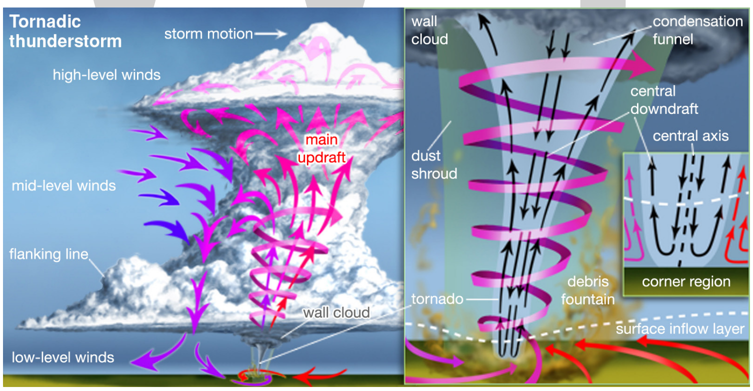
In the tropics, the northeast trade winds meet the southeast trades near the Equator, and the resulting intertropical convergence zone (ITCZ) is characterized by air that is both moist and unstable. Thunderstorms and MCSs appear in great abundance in the ITCZ; they play an important role in the transport of heat to upper levels of the atmosphere and to higher latitudes.

Supercell Storms

When environmental winds are favourable, the updraft and downdraft of a storm become organized and twist around and reinforce each other. The result is a long-lived supercell storm. These storms are the most intense type of thunderstorm. In the central United States, supercells typically have a broad, intense updraft that enters from the southeast and brings moist surface air into the storm. The updraft rises, rotates counterclockwise, and exits to the east, forming an anvil. Updraft speeds in supercell storms can exceed 40 metres (130 feet) per second and are capable of suspending hailstones as large as grapefruit. Supercells can last two to six hours. They are the most likely storm to produce spectacular wind and hail damage as well as powerful tornadoes.



In above figure, Hail-producing thunderstorm (Left) A hailstone can travel through much of the height of the storm during its development and may make multiple vertical loops. (Right) Most hailstones are formed by accretion around a nucleus (spherical embryo). Peculiarly shaped hailstones are generally the product of multiple stones fusing together.



In above figure, (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.

Physical Characteristics of Thunderstorms

Aircraft and radar measurements show that a single thunderstorm cell extends to an altitude of

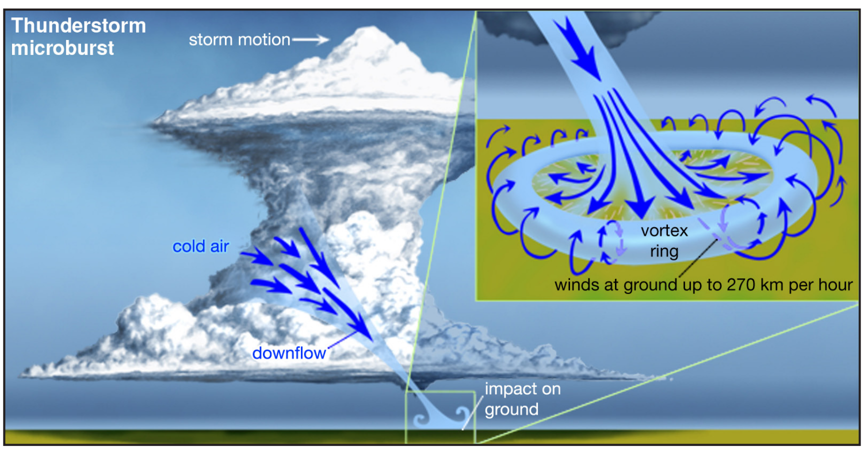
8,000 to 10,000 metres (26,000 to 33,000 feet) and lasts about 30 minutes. An isolated storm usually contains several cells in different stages of evolution and lasts about an hour. A large storm can be many tens of kilometres in diameter with a top that extends to altitudes above 18 km (10 miles), and its duration can be many hours.

Updrafts and Downdrafts

The updrafts and downdrafts in isolated thunderstorms are typically between about 0.5 and 2.5 km (0.3 and 1.6 miles) in diameter at altitudes of 3 to 8 km (1.9 to 5 miles). The updraft diameter may occasionally exceed 4 km (2.5 miles). Closer to the ground, drafts tend to have a larger diameter and lower speeds than do drafts higher in the cloud. Updraft speeds typically peak in the range of 5 to 10 metres (16 to 33 feet) per second, and speeds exceeding 20 metres (66 feet) per second are common in the upper parts of large storms. Airplanes flying through large storms at altitudes of about 10,000 metres (33,000 feet) have measured updrafts exceeding 30 metres (98 feet) per second. The strongest updrafts occur in organized storms that are many tens of kilometres in diameter, and lines or zones of such storms can extend for hundreds of kilometres.

Downbursts

Sometimes thunderstorms will produce intense downdrafts that create damaging winds on the ground. These downdrafts are referred to as macrobursts or microbursts, depending on their size. A macroburst is more than 4 km (2.5 miles) in diameter and can produce winds as high as 60 metres per second, or 215 km per hour (200 feet per second, or 135 miles per hour). A microburst is smaller in dimension but produces winds as high as 75 metres per second, or 270 km per hour (250 feet per second, or 170 miles per hour) on the ground. When the parent storm forms in a wet, humid environment, the microburst will be accompanied by intense rainfall at the ground. If the storm forms in a dry environment, however, the precipitation may evaporate before it reaches the ground (such precipitation is referred to as virga), and the microburst will be dry.



Thunderstorm microburst

In above figure, (Left) The air that forms the microburst is initially "dammed" aloft by the strength of the storm's updraft then cascades downward in a high-velocity, narrow column (less than 4 km, or 2.5 miles, in diameter). (Right, inset) Microbursts are very dangerous to aircraft and can create great damage on the ground. In the absence of observers, microburst damage can often be distinguished from that of a tornado by the presence of a "starburst" pattern of destruction radiating from a central point.

Downbursts are a serious hazard to aircraft, especially during takeoffs and landings, because they produce large and abrupt changes in the wind speed and direction near the ground.

Vertical Extent

In general, an active cloud will rise until it loses its buoyancy. A loss of buoyancy is caused by precipitation loading when the water content of the cloud becomes heavy enough, or by the entrainment of cool, dry air, or by a combination of these processes. Growth can also be stopped by a capping inversion, that is, a region of the atmosphere where the air temperature decreases slowly, is constant, or increases with height.

Thunderstorms typically reach altitudes above 10,000 metres (33,000 feet) and sometimes more than 20,000 metres (66,000 feet). When the instability is high, the atmosphere moist, and winds favourable, thunderstorms can extend to the tropopause, that is, the boundary between the troposphere and the stratosphere. The tropopause is characterized by air temperatures that are nearly constant or increasing with height, and it is a region of great stability. Occasionally the momentum of an updraft carries it into the stratosphere, but after a short distance the air in the top of the updraft becomes cooler and heavier than the surrounding air, and the overshoot ceases. The height of the tropopause varies with both latitude and season. It ranges from about 10,000 to 15,000 metres (33,000 to 50,000 feet) and is higher near the Equator.

When a cumulonimbus cloud reaches a capping inversion or the tropopause, it spreads outward and forms the anvil cloud so characteristic of most thunderstorms. The winds at anvil altitudes typically carry cloud material downwind, and sometimes there are weak cells of convection embedded in the anvil.

Turbulence

An airplane flying through a thunderstorm is commonly buffeted upward and downward and from side to side by turbulent drafts in a storm. Atmospheric turbulence causes discomfort for the crew and passengers and also subjects the aircraft to undesirable stresses.

Turbulence can be quantified in various ways, but frequently a g unit, equal to the acceleration of gravity (9.8 metres per second squared, or 32.2 feet per second squared), is used. A gust of 1 g will cause severe aircraft turbulence. In the upper part of violent thunderstorms, vertical accelerations of about 3 g have been reported.

Movement of Thunderstorms

The motion of a thunderstorm across the land is determined primarily by the interactions of its updrafts and downdrafts with steering winds in the middle layers of the atmosphere in which the storm develops. The speed of isolated storms is typically about 20 km (12 miles) per hour, but some storms move much faster. In extreme circumstances, a supercell storm may move 65 to 80 km (about 40 to 50 miles) per hour. Most storms continually evolve and have new cells developing while old ones dissipate. When winds are light, an individual cell may move very little, less than two kilometres, during its lifetime; however, in a larger storm, new cells triggered by the outflow from downdrafts can give the appearance of rapid motion. In large, multicell storms, the new cells tend to form to the right of the steering winds in the Northern Hemisphere and to the left in the Southern Hemisphere.

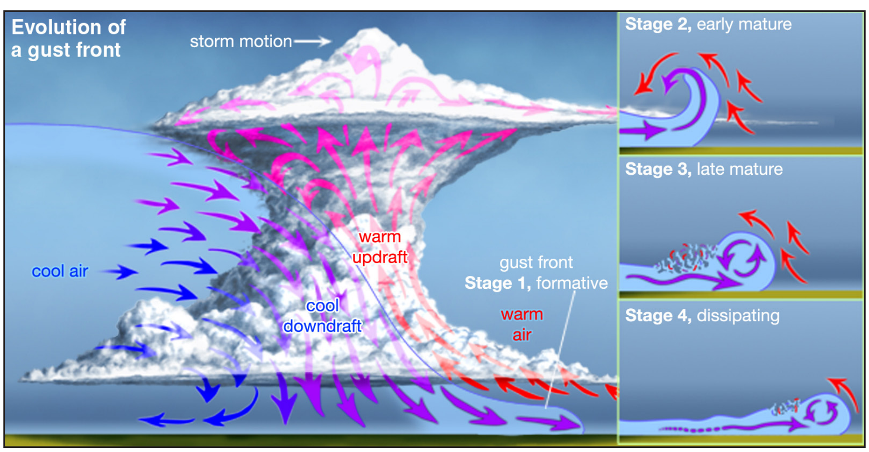
Energy

The energy that drives thunderstorms comes primarily from the latent heat that is released when water vapour condenses to form cloud drops. For every gram of water that is condensed, about 600 calories of heat are released to the atmosphere. When water drops freeze in the upper parts of the cloud, another 80 calories per gram are released. The release of latent heat energy in an updraft is converted, at least in part, to the kinetic energy of the air motions. A rough estimate of the total energy in a thunderstorm can be made from the total quantity of water that is precipitated by the cloud. In a typical case, this energy is about 10^7 kilowatt-hours, roughly equivalent of a 20-kiloton nuclear explosion (though it is released over a broader area and in a longer span of time). A large, multicell storm can easily be 10 to 100 times more energetic.

Weather under Thunderstorms

Downdrafts and Gust Fronts

Thunderstorm downdrafts originate at altitudes where the air temperature is cooler than at ground level, and they are kept cool even as they sink to warmer levels by the evaporation of water and melting of ice particles. Not only is the sinking air more dense than its surroundings, but it carries a horizontal momentum that is different from the surrounding air. If the descending air originated at a height of 10,000 metres (33,000 feet), for example, it might reach the ground with a horizontal velocity much higher than the wind at the ground. When such air hits the ground, it usually moves outward ahead of the storm at a higher speed than the storm itself. This is why an observer on the ground watching a thunderstorm approach can often feel a gust of cool air before the storm passes overhead. The outspreading downdraft air forms a pool some 500 to 2,000 metres (about 1,600 to 6,500 feet) deep, and often there is a distinct boundary between the cool air and the warm, humid air in which the storm developed. The passage of such a gust front is easily recognized as the wind speed increases and the air temperature suddenly drops. Over a five-minute period, a cooling of more than 5 °C (9 °F) is not unusual, and cooling twice as great is not unknown.



Evolution of a gust front (Left) During a thunderstorm a large column of cold air, originating high in the thundercloud, can descend rapidly to form a gust front. (Right, inset) Fed by the main downdraft, the gust front flows in a turbulent layer along the ground and can extend far from the main body of the storm. A gust front is often felt by observers as a sudden cool wind arriving well in advance of a storm.

Rainfall

In extreme circumstances, the gust front produced by a downburst may reach 50 metres (about 160 feet) per second or more and do extensive damage to property and vegetation. Severe winds occur most often when organized lines of thunderstorms develop in an environment where the middle-level winds are very strong. Under such conditions, people might think the winds were caused by a tornado. If a funnel cloud is not observed, the character of the wind damage can indicate the source. Tornadoes blow debris in a tight circular pattern, whereas the air from a thunderstorm outflow pushes it mostly in one direction.

By the time the cool air arrives, rain usually is reaching the surface. Sometimes all the raindrops evaporate while falling, and the result is a dry thunderstorm. At the other extreme, severe multiple-cell and supercell storms can produce torrential rain and hail and cause flash floods.

In small thunderstorms, peak five-minute rainfall rates can exceed 120 mm (4.7 inches) per hour, but most rainfalls are about one-tenth this amount. The average thunderstorm produces about 2,000 metric tons (220,000 short tons) of rain, but large storms can produce 10 times more rainfall. Large, organized storms that are associated with mesoscale convective systems can generate 10^{10} to 10^{12} kg of rainfall.

WILDFIRE

Wildfires are blazes that are uncontrolled and fueled by different types of weather, dry underbrush, and wind, which burn land by the acres and take over everything in their paths, in just a few minutes. There are typically about 100,000 wildfires in the United States every year. Over 9 million acres of land have been destroyed due to treacherous wildfires.

Climate warming from increasing greenhouse gas emissions is forecast to dramatically increase the risk of very large, damaging wildfires over the next several decades, a new NOAA-funded study says. Here is an interesting piece of topic which says that risk of large U.S. wildfires are predicted by mid-century.

Causes of Wildfires

1. Human beings are the number one cause of wildfires in the United States. Many of these wildfires are caused by cigarette butts being left on the land, campfires that have been left unmonitored, as well as intentional acts of arson. 90% of the wildfires in the U.S. are caused by people. Below are few of the man-made causes of wildfires.
   - Burning Debris: It is pretty common to burn yard waste in many places. While it is legal to do so, it may cause fires at many places when things go out of hand. Winds play a major role in wildfires. They can cause flames of a burning debris to spread into forests or farms or fields.
   - Unattended Campfires: Camping can be of great fun for both young and old age people. Unattended campfires can put things out of control and can cause wildfires. It is therefore recommended to choose safe location for a campfire that is away from ignitable objects and is stocked with a bucket of water and a shovel.
   - Equipment Failure or Engine Sparks: A running engine can spew hot sparks when things go wrong. Car crashes have been known to start fires quickly and that is why it is common to see firefighters rush to the scene in anticipation of a fire. Small engine sparks can give way to high flames if that vehicle is operating in a field or a forest.
   - Cigarettes: Cigarettes are another common cause of wildfires. It is common for people to throw the cigarette bud on the ground knowing that it is still burning. Smokers must understand that a small negligence on their part can cause huge impact on the environment and surrounding areas.
   - Fireworks: Fireworks are fun to shoot off but special care needs to be taken when they are in the hands of amateurs. Fireworks must be avoided even when there is small chance that they could start a wildfire. If not handled properly that may end up as flames in unwanted territory.
   - Arson: Arson is the act of setting fire to property, vehicles or any other thing with the intention to cause damage. A person who commits this crime is called an arsonist. Arson is sometime done by people to their own property in order to receive compensation. Arson may account for 30% of all wildfire cases.
2. Mother Nature is responsible for other 10% of wildfires in the United States.
   - Lightening: Lightening can cause wildfires, especially the type of lightning called "hot lightning", which can last for a relatively long time. When it strikes, it can produce a spark which can set off a forest or a field.
   - Volcanic Eruption: Hot burning lava, from volcanic eruptions, also causes wildfires.

Effects of Wildfires

1. Wildfires take away homes, wildlife, as well as vegetation. All of the inhabitants of the wildlife environment now are found homeless. People often lose their houses as well if the fires are close enough to human housing. Vegetation is now obsolete if this area is near a farm or near the food of other inhabitants. Millions of dollars are spent repairing these damages and re-building homes and areas of vegetation.

2. The soil in the area of the wildfire has been completely destroyed. The soils in the forest are made with decaying nutrients and debris that have a lot of natural ingredients that help make the earth what it is. When a wildfire hits this soil it becomes too hot and all of those nutrients are gone for good.
3. Animals lose their lives. It is sad but true fact that birds, squirrels, rabbits, and other wildlife animals are no longer a part of this great earth.
4. Trees and plants are gone as well. Trees and plants help to produce oxygen in the world. The less trees and plants there are the less clean air we have to breathe. With no plants or trees, the animals that did survive no longer have anything to eat.
5. Too much water in the soil can cause erosion. Firefighters use a great deal of water to put out these vicious wildfires. Too much water in the soil causes it to erode and make it useless.
6. Large amounts of smoke is released into the air which makes it difficult to breathe and also causes air pollution.
7. Unfortunately, some human lives are also lost in wildfires. Typically people who are fighting the fire who lose their lives trying to save others.
8. Ash and smoke can cause serious health problems to humans who suffer from allergies and other medical problems. This same smoke and ash has the ability to permanently damage the lungs and the throat.
9. Incomes and jobs are lost for workers in the agricultural field whose field crops and animals were destroyed by the wildfire. When people are out of work the economy suffers which makes it difficult to recover.
10. Insurance premiums soar sky high after a wildfire because now everyone is looking to obtain some kind of insurance to prevent such devastating losses. People are unable to afford these premiums even when they need them the most.
11. There will be restricted recreational areas that will not be able to be accessed until the area is clear of debris and is determined to be safe to inhabit or visit.
12. The loss of animals has the ability to also create extinction for certain animals and other creatures of the forest.

Solutions to Wildfires

1. Make sure you are following all of the local regulations and laws regarding burning fires during various times of day, year, and what materials and substances are permitted to be burned. If you do not see a sign with the rules find a park ranger or someone close by and keep a list of the rules and regulations on hand.
2. Keep up to date with the weather forecast so you are sure not to burn any substances while there are high winds or other treacherous conditions. Certain areas are more prone to wildfires than others so make sure that you check with the area to see if they are more at risk than other areas. The Wildland Fire Assessment System will give you an updated map on which areas are more at risk. Weather is one of the biggest reasons why wildfires occur. Always keep in mind the weather before you ever even plan your trip.
3. Only light fires in areas that are easily controlled locations. Make sure when you are creating fire pits or other fires that you are doing so in areas that are controlled and fires cannot spread into other areas. A fire will need to be contained so that it will be easy to put out especially if a dangerous situation would arise.
4. Do not burn any materials that are combustible or unusual in nature. Do not throw garbage onto campfires or any other materials that should not be burned. You should only be using materials that are organic such as leaves, woods, or yard waste. If you put unusual materials into a fire it is only going to make the fire spread at a rapid rate which causes more problems for the area you are in.
5. If you are a cigarette smoker it is important not to smoke cigarettes where you are not supposed to. If you do smoke you need to make sure that you put your cigarette out completely before disposing of it. Under no circumstances should you throw cigarettes onto the ground. Make sure they are completely put out and dispose of them properly. Most camping and picnic areas do not allow smoking so if you are going to smoke you need to know the rules beforehand.
6. Teach your children the rules and safety precautions of camping and being outdoors. Make sure they know to stay away from fires and to always allow an adult to start and put out fires. Many wildfires are caused by unattended children near fires. Teaching them the ways of nature could make all of the difference.

Wildfires are an unfortunate occurrence but they can be prevented. Learn the rules of the area in which you are camping in and make sure you are following them explicitly. They are extremely dangerous and cause quite a bit of dangerous to our land and the habitat of many creatures. Following the rules could save the lives and homes of many people and blessed creatures that are on this earth. Humans are the number one cause of wildfires and can be the number one solution as well.

GEOMAGNETIC STORMS

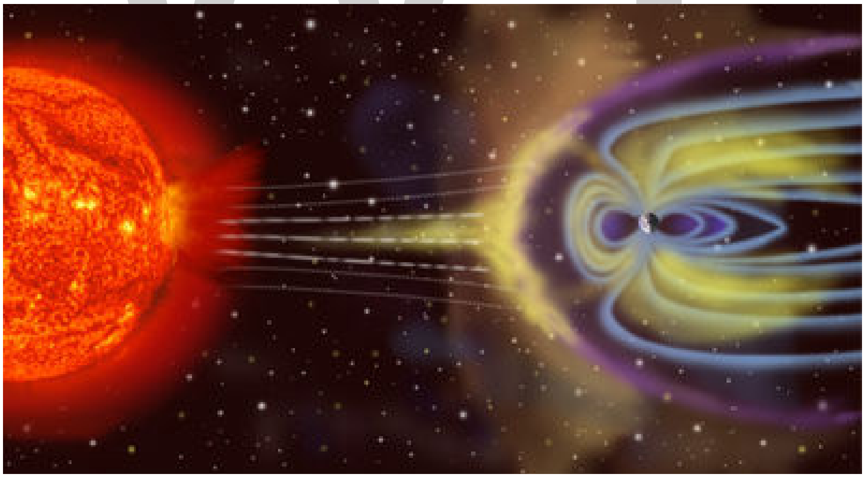
A geomagnetic storm (commonly referred to as a solar storm) is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field that interacts with the Earth's magnetic field.

The disturbance that drives the storm may be a solar coronal mass ejection (CME) or a co-rotating interaction region (CIR), a high speed solar wind originating from a coronal hole. The frequency of geomagnetic storms increases and decreases with the sunspot cycle. During solar maximum, geomagnetic storms occur more often, with the majority driven by CME's. During solar minimum, storms are mainly driven by CIR's (though CIR storms are more frequent at solar maximum than at minimum).

The increase in the solar wind pressure initially compresses the magnetosphere. The solar wind's magnetic field interacts with the Earth's magnetic field and transfers an increased energy into the magnetosphere. Both interactions cause an increase in plasma movement through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere. During the main phase of a geomagnetic storm, electric current in the magnetosphere creates a magnetic force that pushes out the boundary between the magnetosphere and the solar wind.

Several space weather phenomena tend to be associated with or are caused by a geomagnetic storm. These include solar energetic particle (SEP) events, geomagnetically induced currents (GIC), ionospheric disturbances that cause radio and radar scintillation, disruption of navigation by magnetic compass and auroral displays at much lower latitudes than normal.

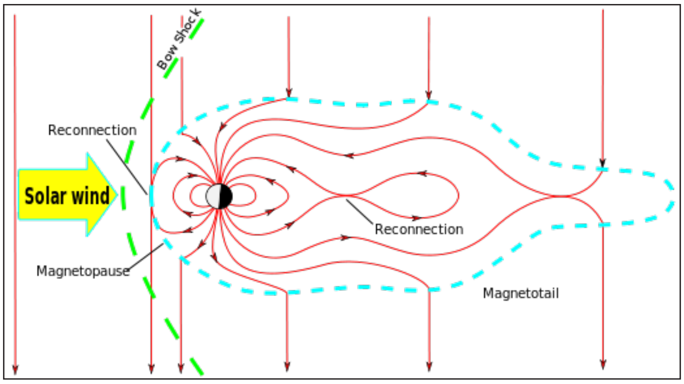
The largest recorded geomagnetic storm, the Carrington Event in September 1859, took down parts of the recently created US telegraph network, starting fires and shocking some telegraph operators. In 1989, a geomagnetic storm energized ground induced currents that disrupted electric power distribution throughout most of Quebec and caused aurorae as far south as Texas.



Artist's depiction of solar wind particles interacting with Earth's magnetosphere. Sizes are not to scale.

Interactions with Planetary Processes

The solar wind also carries with it the Sun's magnetic field. This field will have either a North or South orientation. If the solar wind has energetic bursts, contracting and expanding the magnetosphere, or if the solar wind takes a southward polarization, geomagnetic storms can be expected. The southward field causes magnetic reconnection of the dayside magnetopause, rapidly injecting magnetic and particle energy into the Earth's magnetosphere.



Magnetosphere in the near-Earth space environment.

During a geomagnetic storm, the ionosphere's F2 layer becomes unstable, fragments, and may even disappear. In the northern and southern pole regions of the Earth, auroras are observable.

Instruments

Magnetometers monitor the auroral zone as well as the equatorial region. Two types of radar, coherent scatter and incoherent scatter, are used to probe the auroral ionosphere. By bouncing signals off ionospheric irregularities, which move with the field lines, one can trace their motion and infer magnetospheric convection.

Spacecraft instruments include:

- Magnetometers, usually of the flux gate type. Usually these are at the end of booms, to keep them away from magnetic interference by the spacecraft and its electric circuits.
- Electric sensors at the ends of opposing booms are used to measure potential differences between separated points, to derive electric fields associated with convection. The method works best at high plasma densities in low Earth orbit; far from Earth long booms are needed, to avoid shielding-out of electric forces.
- Radio sounders from the ground can bounce radio waves of varying frequency off the ionosphere, and by timing their return determine the electron density profile—up to its peak, past which radio waves no longer return. Radio sounders in low Earth orbit aboard the Canadian Alouette 1 and Alouette 2, beamed radio waves earthward and observed the electron density profile of the "topside ionosphere". Other radio sounding methods were also tried in the ionosphere.
- Particle detectors include a Geiger counter, as was used for the original observations of the Van Allen radiation belt. Scintillator detectors came later, and still later "channeltron" electron multipliers found particularly wide use. To derive charge and mass composition, as well as energies, a variety of mass spectrograph designs were used. For energies up to about 50 keV (which constitute most of the magnetospheric plasma) time-of-flight spectrometers (e.g. "top-hat" design) are widely used.

Computers have made it possible to bring together decades of isolated magnetic observations and extract average patterns of electrical currents and average responses to interplanetary variations.

They also run simulations of the global magnetosphere and its responses, by solving the equations of magnetohydrodynamics (MHD) on a numerical grid. Appropriate extensions must be added to cover the inner magnetosphere, where magnetic drifts and ionospheric conduction need to be taken into account. So far the results are difficult to interpret, and certain assumptions are needed to cover small-scale phenomena.

Geomagnetic Storm Effects

Disruption of Electrical Systems

It has been suggested that a geomagnetic storm on the scale of the solar storm of 1859 today would cause billions or even trillions of dollars of damage to satellites, power grids and radio communications, and could cause electrical blackouts on a massive scale that might not be repaired for weeks, months, or even years. Such sudden electrical blackouts may threaten food production.

Mains Electricity Grid

When magnetic fields move about in the vicinity of a conductor such as a wire, a geomagnetically induced current is produced in the conductor. This happens on a grand scale during geomagnetic storms (the same mechanism also influenced telephone and telegraph lines before fiber optics) on all long transmission lines. Long transmission lines (many kilometers in length) are thus subject to damage by this effect. Notably, this chiefly includes operators in China, North America, and Australia, especially in modern high-voltage, low-resistance lines. The European grid consists mainly of shorter transmission circuits, which are less vulnerable to damage.

The (nearly direct) currents induced in these lines from geomagnetic storms are harmful to electrical transmission equipment, especially transformers—inducing core saturation, constraining their performance (as well as tripping various safety devices), and causing coils and cores to heat up. In extreme cases, this heat can disable or destroy them, even inducing a chain reaction that can overload transformers. Most generators are connected to the grid via transformers, isolating them from the induced currents on the grid, making them much less susceptible to damage due to geomagnetically induced current. However, a transformer that is subjected to this will act as an unbalanced load to the generator, causing negative sequence current in the stator and consequently rotor heating.

According to a study by Metatech corporation, a storm with a strength comparable to that of 1921 would destroy more than 300 transformers and leave over 130 million people without power in the United States, costing several trillion dollars. The Daily Mail even claims that a massive solar flare could knock out electric power for months, but these predictions are contradicted by a NERC report that concludes that a geomagnetic storm would cause temporary grid instability but no widespread destruction of high-voltage transformers. The report points out that the widely quoted Quebec grid collapse was not caused by overheating transformers but by the near-simultaneous tripping of seven relays.

Besides the transformers being vulnerable to the effects of a geomagnetic storm, electricity companies can also be affected indirectly by the geomagnetic storm. For instance, internet service providers may go down during geomagnetic storms (and/or remain non-operational long after). Electricity companies may have equipment requiring a working internet connection to function, so during the period the internet service provider is down, the electricity too may not be distributed.

By receiving geomagnetic storm alerts and warnings (e.g. by the Space Weather prediction Center; via Space Weather satellites as SOHO or ACE), power companies can minimize damage to power transmission equipment, by momentarily disconnecting transformers or by inducing temporary blackouts. Preventative measures also exist, including preventing the inflow of GICs into the grid through the neutral-to-ground connection.

Communications

High frequency (3–30 MHz) communication systems use the ionosphere to reflect radio signals over long distances. Ionospheric storms can affect radio communication at all latitudes. Some frequencies are absorbed and others are reflected, leading to rapidly fluctuating signals and unexpected propagation paths. TV and commercial radio stations are little affected by solar activity, but ground-to-air, ship-to-shore, shortwave broadcast and amateur radio (mostly the bands below 30 MHz) are frequently disrupted. Radio operators using HF bands rely upon solar and geomagnetic alerts to keep their communication circuits up and running.

Military detection or early warning systems operating in the high frequency range are also affected by solar activity. The over-the-horizon radar bounces signals off the ionosphere to monitor the launch of aircraft and missiles from long distances. During geomagnetic storms, this system can be severely hampered by radio clutter. Also some submarine detection systems use the magnetic signatures of submarines as one input to their locating schemes. Geomagnetic storms can mask and distort these signals.

The Federal Aviation Administration routinely receives alerts of solar radio bursts so that they can recognize communication problems and avoid unnecessary maintenance. When an aircraft and a ground station are aligned with the Sun, high levels of noise can occur on air-control radio frequencies. This can also happen on UHF and SHF satellite communications, when an Earth station, a satellite and the Sun are in alignment. In order to prevent unnecessary maintenance on satellite communications systems aboard aircraft AirSatOne provides a live feed for geophysical events from NOAA's Space Weather Prediction Center. AirSatOne's live feed allows users to view observed and predicted space storms. Geophysical Alerts are important to flight crews and maintenance personnel to determine if any upcoming activity or history has or will have an effect on satellite communications, GPS navigation and HF Communications.

Telegraph lines in the past were affected by geomagnetic storms. Telegraphs used a single long wire for the data line, stretching for many miles, using the ground as the return wire and fed with DC power from a battery; this made them (together with the power lines mentioned below) susceptible to being influenced by the fluctuations caused by the ring current. The voltage/current induced by the geomagnetic storm could have diminished the signal, when subtracted from the battery polarity, or to overly strong and spurious signals when added to it; some operators learned to disconnect the battery and rely on the induced current as their power source. In extreme cases the induced current was so high the coils at the receiving side burst in flames, or the operators received electric shocks. Geomagnetic storms affect also long-haul telephone lines, including undersea cables unless they are fiber optic.

Damage to communications satellites can disrupt non-terrestrial telephone, television, radio and Internet links. The National Academy of Sciences reported in 2008 on possible scenarios of widespread disruption in the 2012–2013 solar peak.

Navigation Systems

Systems such as GPS, LORAN and the now-defunct OMEGA are adversely affected when solar activity disrupts their signal propagation. The OMEGA system consisted of eight transmitters located throughout the world. Airplanes and ships used the very low frequency signals from these transmitters to determine their positions. During solar events and geomagnetic storms, the system gave navigators information that was inaccurate by as much as several miles. If navigators had been alerted that a proton event or geomagnetic storm was in progress, they could have switched to a backup system.

GPS signals are affected when solar activity causes sudden variations in the density of the ionosphere, causing the GPS signals to scintillate (like a twinkling star). The scintillation of satellite signals during ionospheric disturbances is studied at HAARP during ionospheric modification experiments. It has also been studied at the Jicamarca Radio Observatory.

One technology used to allow GPS receivers to continue to operate in the presence of some confusing signals is Receiver Autonomous Integrity Monitoring (RAIM). However, RAIM is predicated on the assumption that a majority of the GPS constellation is operating properly, and so it is much less useful when the entire constellation is perturbed by global influences such as geomagnetic storms. Even if RAIM detects a loss of integrity in these cases, it may not be able to provide a useful, reliable signal.

Satellite Hardware Damage

Geomagnetic storms and increased solar ultraviolet emission heat Earth's upper atmosphere, causing it to expand. The heated air rises, and the density at the orbit of satellites up to about 1,000 km (621 mi) increases significantly. This results in increased drag, causing satellites to slow and change orbit slightly. Low Earth Orbit satellites that are not repeatedly boosted to higher orbits slowly fall and eventually burn up.

Skylab's 1979 destruction is an example of a spacecraft reentering Earth's atmosphere prematurely as a result of higher-than-expected solar activity. During the great geomagnetic storm of March 1989, four of the Navy's navigational satellites had to be taken out of service for up to a week, the U.S. Space Command had to post new orbital elements for over 1000 objects affected and the Solar Maximum Mission satellite fell out of orbit in December the same year.

The vulnerability of the satellites depends on their position as well. The South Atlantic Anomaly is a perilous place for a satellite to pass through.

As technology has allowed spacecraft components to become smaller, their miniaturized systems have become increasingly vulnerable to the more energetic solar particles. These particles can physically damage microchips and can change software commands in satellite-borne computers.

Another problem for satellite operators is differential charging. During geomagnetic storms, the number and energy of electrons and ions increase. When a satellite travels through this energized environment, the charged particles striking the spacecraft differentially charge portions of the spacecraft. Discharges can arc across spacecraft components, harming and possibly disabling them.

Bulk charging (also called deep charging) occurs when energetic particles, primarily electrons, penetrate the outer covering of a satellite and deposit their charge in its internal parts. If sufficient charge accumulates in any one component, it may attempt to neutralize by discharging to other components. This discharge is potentially hazardous to the satellite's electronic systems.

Geologic Exploration

Earth's magnetic field is used by geologists to determine subterranean rock structures. For the most part, these geodetic surveyors are searching for oil, gas or mineral deposits. They can accomplish this only when Earth's field is quiet, so that true magnetic signatures can be detected. Other geophysicists prefer to work during geomagnetic storms, when strong variations in the Earth's normal subsurface electric currents allow them to sense subsurface oil or mineral structures. This technique is called magnetotellurics. For these reasons, many surveyors use geomagnetic alerts and predictions to schedule their mapping activities.

Pipelines

Rapidly fluctuating geomagnetic fields can produce geomagnetically induced currents in pipelines. This can cause multiple problems for pipeline engineers. Pipeline flow meters can transmit erroneous flow information and the corrosion rate of the pipeline is dramatically increased. If engineers incorrectly attempt to balance the current during a geomagnetic storm, corrosion rates may increase even more. Pipeline managers thus receive space weather alerts and warnings to allow them to implement defensive measures.

Radiation Hazards to Humans

Intense solar flares release very-high-energy particles that can cause radiation poisoning.

Earth's atmosphere and magnetosphere allow adequate protection at ground level, but astronauts are subject to potentially lethal doses of radiation. The penetration of high-energy particles into living cells can cause chromosome damage, cancer and other health problems. Large doses can be immediately fatal.

Solar protons with energies greater than 30 MeV are particularly hazardous.

Solar proton events can also produce elevated radiation aboard aircraft flying at high altitudes. Although these risks are small, monitoring of solar proton events by satellite instrumentation allows the occasional exposure to be monitored and evaluated and eventually flight paths and altitudes adjusted in order to lower the absorbed dose of the flight crews.

Effect on Animals

Scientists are still studying whether or not animals are affected by this, some suggesting this is why whales beach themselves. Some have stated the possibility that other migrating animals including birds and honey bees, might be affected since they also use magnetoreception to navigate, and geomagnetic storms alter the Earth's magnetic fields temporarily.

TORNADO

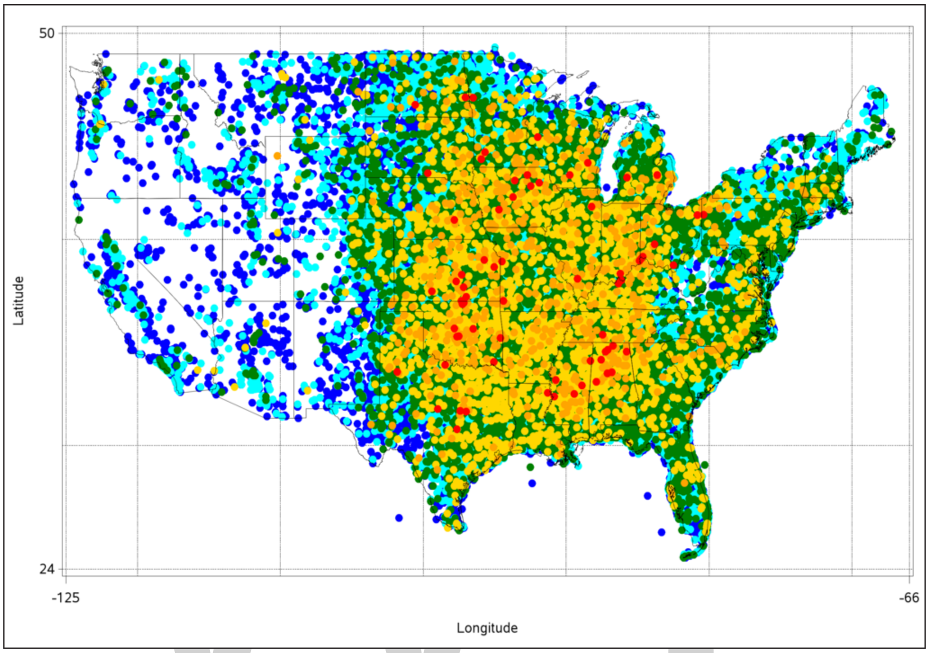
A tornado is a rapidly rotating column of air that is in contact with both the surface of the Earth and a cumulonimbus cloud or, in rare cases, the base of a cumulus cloud. The windstorm is often referred to as a twister, whirlwind or cyclone, although the word cyclone is used in meteorology to name a weather system with a low-pressure area in the center around which, from an observer looking down toward the surface of the earth, winds blow counterclockwise in the Northern Hemisphere and clockwise in the Southern. Tornadoes come in many shapes and sizes, and they are often visible in the form of a condensation funnel originating from the base of a cumulonimbus cloud, with a cloud of rotating debris and dust beneath it. Most tornadoes have wind speeds less than 110 miles per hour (180 km/h), are about 250 feet (80 m) across, and travel a few miles (several kilometers) before dissipating. The most extreme tornadoes can attain wind speeds of more than 300 miles per hour (480 km/h), are more than two miles (3 km) in diameter, and stay on the ground for dozens of miles (more than 100 km).

Various types of tornadoes include the multiple vortex tornado, landspout, and waterspout. Waterspouts are characterized by a spiraling funnel-shaped wind current, connecting to a large cumulus or cumulonimbus cloud. They are generally classified as non-supercellular tornadoes that develop over bodies of water, but there is disagreement over whether to classify them as true tornadoes. These spiraling columns of air frequently develop in tropical areas close to the equator and are less common at high latitudes. Other tornado-like phenomena that exist in nature include the gustnado, dust devil, fire whirl, and steam devil.

Tornadoes occur most frequently in North America, particularly in central and southeastern regions of the United States colloquially known as tornado alley, as well as in Southern Africa, northwestern and southeast Europe, western and southeastern Australia, New Zealand, Bangladesh and adjacent eastern India, and southeastern South America. Tornadoes can be detected before or as they occur through the use of Pulse-Doppler radar by recognizing patterns in velocity and reflectivity data, such as hook echoes or debris balls, as well as through the efforts of storm spotters.

A tornado near Anadarko, Oklahoma, 1999. The funnel is the thin tube reaching from the cloud to the ground. The lower part of this tornado is surrounded by a translucent dust cloud, kicked up by the tornado's strong winds at the surface. The wind of the tornado has a much wider radius than the funnel itself.

There are several scales for rating the strength of tornadoes. The Fujita scale rates tornadoes by damage caused and has been replaced in some countries by the updated Enhanced Fujita Scale. An F0 or EF0 tornado, the weakest category, damages trees, but not substantial structures. An F5 or EF5 tornado, the strongest category, rips buildings off their foundations and can deform large skyscrapers. The similar TORRO scale ranges from a T0 for extremely weak tornadoes to T11 for the most powerful known tornadoes. Doppler radar data, photogrammetry, and ground swirl patterns (trochoidal marks) may also be analyzed to determine intensity and assign a rating.



All tornadoes in the Contiguous United States, 1950–2013, plotted by midpoint, highest F-scale on top, Alaska and Hawaii negligibl.

Characteristics

Size and Shape

Most tornadoes take on the appearance of a narrow funnel, a few hundred yards (meters) across, with a small cloud of debris near the ground. Tornadoes may be obscured completely by rain or dust. These tornadoes are especially dangerous, as even experienced meteorologists might not see them. Tornadoes can appear in many shapes and sizes.

Small, relatively weak landspouts may be visible only as a small swirl of dust on the ground. Although the condensation funnel may not extend all the way to the ground, if associated surface winds are greater than 40 mph (64 km/h), the circulation is considered a tornado. A tornado with a nearly cylindrical profile and relative low height is sometimes referred to as a "stovepipe" tornado. Large single-vortex tornadoes can look like large wedges stuck into the ground, and so are known as "wedge tornadoes" or "wedges". The "stovepipe" classification is also used for this type of tornado if it otherwise fits that profile. A wedge can be so wide that it appears to be a block of dark clouds, wider than the distance from the cloud base to the ground. Even experienced storm observers may not be able to tell the difference between a low-hanging cloud and a wedge tornado from a distance. Many, but not all major tornadoes are wedges.

Tornadoes in the dissipating stage can resemble narrow tubes or ropes, and often curl or twist into complex shapes. These tornadoes are said to be "roping out", or becoming a "rope tornado". When they rope out, the length of their funnel increases, which forces the winds within the funnel to weaken due to conservation of angular momentum. Multiple-vortex tornadoes can appear as a family of swirls circling a common center, or they may be completely obscured by condensation, dust, and debris, appearing to be a single funnel.

A wedge tornado, nearly a mile wide, which hit Binger.

In the United States, tornadoes are around 500 feet (150 m) across on average and travel on the ground for 5 miles (8.0 km). However, there is a wide range of tornado sizes. Weak tornadoes, or strong yet dissipating tornadoes, can be exceedingly narrow, sometimes only a few feet or couple meters across. One tornado was reported to have a damage path only 7 feet (2.1 m) long. On the other end of the spectrum, wedge tornadoes can have a damage path a mile (1.6 km) wide or more. A tornado that affected Hallam, Nebraska on May 22, 2004, was up to 2.5 miles (4.0 km) wide at the ground, and a tornado in El Reno, Oklahoma on May 31, 2013 was approximately 2.6 miles (4.2 km) wide, the widest on record.

In terms of path length, the Tri-State Tornado, which affected parts of Missouri, Illinois, and Indiana on March 18, 1925, was on the ground continuously for 219 miles (352 km). Many tornadoes which appear to have path lengths of 100 miles (160 km) or longer are composed of a family of tornadoes which have formed in quick succession; however, there is no substantial evidence that this occurred in the case of the Tri-State Tornado. In fact, modern reanalysis of the path suggests that the tornado may have begun 15 miles (24 km) further west than previously thought.

A rope tornado in its dissipating stage, found near Tecumseh, Oklahoma.

Appearance

Tornadoes can have a wide range of colors, depending on the environment in which they form. Those that form in dry environments can be nearly invisible, marked only by swirling debris at the base of the funnel. Condensation funnels that pick up little or no debris can be gray to white. While traveling over a body of water (as a waterspout), tornadoes can turn white or even blue. Slow-moving funnels, which ingest a considerable amount of debris and dirt, are usually darker, taking on the color of debris. Tornadoes in the Great Plains can turn red because of the reddish tint of the soil, and tornadoes in mountainous areas can travel over snow-covered ground, turning white.

Lighting conditions are a major factor in the appearance of a tornado. A tornado which is "back-lit" (viewed with the sun behind it) appears very dark. The same tornado, viewed with the sun at the observer's back, may appear gray or brilliant white. Tornadoes which occur near the time of sunset can be many different colors, appearing in hues of yellow, orange, and pink.

Dust kicked up by the winds of the parent thunderstorm, heavy rain and hail, and the darkness of night are all factors which can reduce the visibility of tornadoes. Tornadoes occurring in these conditions are especially dangerous, since only weather radar observations, or possibly the sound of an approaching tornado, serve as any warning to those in the storm's path. Most significant tornadoes form under the storm's updraft base, which is rain-free, making them visible. Also, most tornadoes occur in the late afternoon, when the bright sun can penetrate even the thickest clouds. Night-time tornadoes are often illuminated by frequent lightning.

There is mounting evidence, including Doppler on Wheels mobile radar images and eyewitness accounts, that most tornadoes have a clear, calm center with extremely low pressure, akin to the eye of tropical cyclones. Lightning is said to be the source of illumination for those who claim to have seen the interior of a tornado.

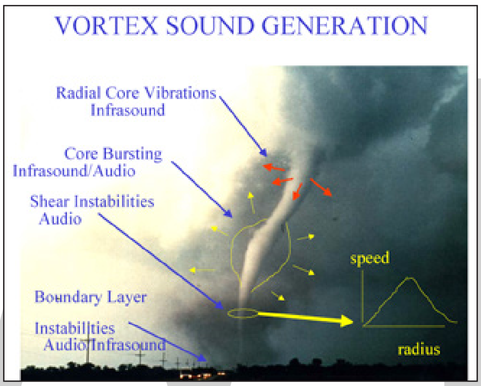
In the top picture, the tornado is lit with the sunlight focused from behind the camera, thus the funnel appears bluish. In the lower image, where the camera is facing the opposite direction, the sun is behind the tornado, giving it a dark appearance.

Rotation

Tornadoes normally rotate cyclonically (when viewed from above, this is counterclockwise in the northern hemisphere and clockwise in the southern). While large-scale storms always rotate cyclonically due to the Coriolis effect, thunderstorms and tornadoes are so small that the direct influence of the Coriolis effect is unimportant, as indicated by their large Rossby numbers. Supercells and tornadoes rotate cyclonically in numerical simulations even when the Coriolis effect is neglected. Low-level mesocyclones and tornadoes owe their rotation to complex processes within the supercell and ambient environment.

Approximately 1 percent of tornadoes rotate in an anticyclonic direction in the northern hemisphere. Typically, systems as weak as landspouts and gustnadoes can rotate anticyclonically, and usually only those which form on the anticyclonic shear side of the descending rear flank downdraft (RFD) in a cyclonic supercell. On rare occasions, anticyclonic tornadoes form in association with the mesoanticyclone of an anticyclonic supercell, in the same manner as the typical cyclonic tornado, or as a companion tornado either as a satellite tornado or associated with anticyclonic eddies within a supercell.

Sound and Seismology



An illustration of generation of infrasound in tornadoes by the Earth System ResearchLaboratory's Infrasound Program.

Tornadoes emit widely on the acoustics spectrum and the sounds are caused by multiple mechanisms. Various sounds of tornadoes have been reported, mostly related to familiar sounds for the witness and generally some variation of a whooshing roar. Popularly reported sounds include a freight train, rushing rapids or waterfall, a nearby jet engine, or combinations of these. Many tornadoes are not audible from much distance; the nature of and the propagation distance of the audible sound depends on atmospheric conditions and topography.

The winds of the tornado vortex and of constituent turbulent eddies, as well as airflow interaction with the surface and debris, contribute to the sounds. Funnel clouds also produce sounds. Funnel clouds and small tornadoes are reported as whistling, whining, humming, or the buzzing of innumerable bees or electricity, or more or less harmonic, whereas many tornadoes are reported as a continuous, deep rumbling, or an irregular sound of "noise".

Since many tornadoes are audible only when very near, sound is not to be thought of as a reliable warning signal for a tornado. Tornadoes are also not the only source of such sounds in severe thunderstorms; any strong, damaging wind, a severe hail volley, or continuous thunder in a thunderstorm may produce a roaring sound.

Tornadoes also produce identifiable inaudible infrasonic signatures.

Unlike audible signatures, tornadic signatures have been isolated; due to the long distance propagation of low-frequency sound, efforts are ongoing to develop tornado prediction and detection devices with additional value in understanding tornado morphology, dynamics, and creation. Tornadoes also produce a detectable seismic signature, and research continues on isolating it and understanding the process.

Electromagnetic, Lightning, and Other Effects

Tornadoes emit on the electromagnetic spectrum, with sferics and E-field effects detected. There are observed correlations between tornadoes and patterns of lightning. Tornadic storms do not contain more lightning than other storms and some tornadic cells never produce lightning at all. More often than not, overall cloud-to-ground (CG) lightning activity decreases as a tornado touches the surface and returns to the baseline level when the tornado dissipates. In many cases, intense tornadoes and thunderstorms exhibit an increased and anomalous dominance of positive polarity CG discharges. Electromagnetics and lightning have little or nothing to do directly with what drives tornadoes (tornadoes are basically a thermodynamic phenomenon), although there are likely connections with the storm and environment affecting both phenomena.

Luminosity has been reported in the past and is probably due to misidentification of external light sources such as lightning, city lights, and power flashes from broken lines, as internal sources are now uncommonly reported and are not known to ever have been recorded. In addition to winds, tornadoes also exhibit changes in atmospheric variables such as temperature, moisture, and pressure. For example, on June 24, 2003 near Manchester, South Dakota, a probe measured a 100 mbar (hPa) (2.95 inHg) pressure decrease. The pressure dropped gradually as the vortex approached then dropped extremely rapidly to 850 mbar (hPa) (25.10 inHg) in the core of the violent tornado before rising rapidly as the vortex moved away, resulting in a V-shape pressure trace. Temperature tends to decrease and moisture content to increase in the immediate vicinity of a tornado.

Life Cycle

Supercell Relationship

A sequence of images showing the birth of a tornado. First, the rotating cloud base lowers. This lowering becomes a funnel, which continues descending while winds build near the surface, kicking up dust and debris and causing damage. As the pressure continues to drop, the visible funnel extends to the ground. This tornado, near Dimmitt, Texas, was one of the best-observed violent tornadoes in history.

Formation

Composite of eight images shot in sequence as a tornado formed in Kansas in 2016

As the mesocyclone lowers below the cloud base, it begins to take in cool, moist air from the downdraft region of the storm. The convergence of warm air in the updraft and cool air causes a rotating wall cloud to form. The RFD also focuses the mesocyclone's base, causing it to draw air from a smaller and smaller area on the ground. As the updraft intensifies, it creates an area of low pressure at the surface. This pulls the focused mesocyclone down, in the form of a visible condensation funnel. As the funnel descends, the RFD also reaches the ground, fanning outward and creating a gust front that can cause severe damage a considerable distance from the tornado. Usually, the funnel cloud begins causing damage on the ground (becoming a tornado) within a few minutes of the RFD reaching the ground.

Maturity

Initially, the tornado has a good source of warm, moist air flowing inward to power it, and it grows until it reaches the "mature stage". This can last anywhere from a few minutes to more than an hour, and during that time a tornado often causes the most damage, and in rare cases can be more than one mile (1.6 km) across. The low pressured atmosphere at the base of the tornado is essential to the endurance of the system. Meanwhile, the RFD, now an area of cool surface winds, begins to wrap around the tornado, cutting off the inflow of warm air which previously fed the tornado.

Dissipation

As the RFD completely wraps around and chokes off the tornado's air supply, the vortex begins to weaken, and become thin and rope-like. This is the "dissipating stage", often lasting no more than a few minutes, after which the tornado ends. During this stage the shape of the tornado becomes highly influenced by the winds of the parent storm, and can be blown into fantastic patterns. Even though the tornado is dissipating, it is still capable of causing damage. The storm is contracting into a rope-like tube and, due to conservation of angular momentum, winds can increase at this point.

As the tornado enters the dissipating stage, its associated mesocyclone often weakens as well, as the rear flank downdraft cuts off the inflow powering it. Sometimes, in intense supercells, tornadoes can develop cyclically. As the first mesocyclone and associated tornado dissipate, the storm's inflow may be concentrated into a new area closer to the center of the storm and possibly feed a new mesocyclone. If a new mesocyclone develops, the cycle may start again, producing one or more new tornadoes. Occasionally, the old (occluded) mesocyclone and the new mesocyclone produce a tornado at the same time.

Although this is a widely accepted theory for how most tornadoes form, live, and die, it does not explain the formation of smaller tornadoes, such as landspouts, long-lived tornadoes, or tornadoes with multiple vortices. These each have different mechanisms which influence their development—however, most tornadoes follow a pattern similar to this one.

Types

Multiple Vortex

A multiple-vortex tornado outside Dallas.

A multiple-vortex tornado is a type of tornado in which two or more columns of spinning air rotate about their own axis and at the same time around a common center. A multi-vortex structure can occur in almost any circulation, but is very often observed in intense tornadoes. These vortices often create small areas of heavier damage along the main tornado path. This is a phenomenon that is distinct from a satellite tornado, which is a smaller tornado which forms very near a large, strong tornado contained within the same mesocyclone. The satellite tornado may appear to "orbit" the larger tornado (hence the name), giving the appearance of one, large multi-vortex tornado. However, a satellite tornado is a distinct circulation, and is much smaller than the main funnel.

Waterspout

A waterspout is defined by the National Weather Service as a tornado over water. However, researchers typically distinguish "fair weather" waterspouts from tornadic (i.e. associated with a mesocyclone) waterspouts. Fair weather waterspouts are less severe but far more common, and are similar to dust devils and landspouts. They form at the bases of cumulus congestus clouds over tropical and subtropical waters. They have relatively weak winds, smooth laminar walls, and typically travel very slowly. They occur most commonly in the Florida Keys and in the northern Adriatic Sea. In contrast, tornadic waterspouts are stronger tornadoes over water. They form over water similarly to mesocyclonic tornadoes, or are stronger tornadoes which cross over water. Since they form from severe thunderstorms and can be far more intense, faster, and longer-lived than fair weather waterspouts, they are more dangerous. In official tornado statistics, waterspouts are generally not counted unless they affect land, though some European weather agencies count waterspouts and tornadoes together.

A waterspout near the Florida Keys in 1969.

Landspout

A landspout, or dust-tube tornado, is a tornado not associated with a mesocyclone. The name stems from their characterization as a "fair weather waterspout on land". Waterspouts and landspouts share many defining characteristics, including relative weakness, short lifespan, and a small, smooth condensation funnel which often does not reach the surface. Landspouts also create a distinctively laminar cloud of dust when they make contact with the ground, due to their differing mechanics from true mesoform tornadoes. Though usually weaker than classic tornadoes, they can produce strong winds which could cause serious damage.

Similar Circulations

Gustnado

A gustnado, or gust front tornado, is a small, vertical swirl associated with a gust front or downburst. Because they are not connected with a cloud base, there is some debate as to whether or not gustnadoes are tornadoes. They are formed when fast moving cold, dry outflow air from a thunderstorm is blown through a mass of stationary, warm, moist air near the outflow boundary, resulting in a "rolling" effect (often exemplified through a roll cloud). If low level wind shear is strong enough, the rotation can be turned vertically or diagonally and make contact with the ground. The result is a gustnado. They usually cause small areas of heavier rotational wind damage among areas of straight-line wind damage.

Dust Devil

A dust devil (also known as a whirlwind) resembles a tornado in that it is a vertical swirling column of air. However, they form under clear skies and are no stronger than the weakest tornadoes. They form when a strong convective updraft is formed near the ground on a hot day. If there is enough low level wind shear, the column of hot, rising air can develop a small cyclonic motion that can be seen near the ground. They are not considered tornadoes because they form during fair weather and are not associated with any clouds. However, they can, on occasion, result in major damage.

A dust devil in Arizona.

Fire Whirls

Small-scale, tornado-like circulations can occur near any intense surface heat source. Those that occur near intense wildfires are called fire whirls. They are not considered tornadoes, except in the rare case where they connect to a pyrocumulus or other cumuliform cloud above. Fire whirls usually are not as strong as tornadoes associated with thunderstorms. They can, however, produce significant damage.

Steam Devils

A steam devil is a rotating updraft between 50 and 200 meters wide that involves steam or smoke. These formations do not involve high wind speeds, only completing a few rotations per minute. Steam devils are very rare. They most often form from smoke issuing from a power plant's smokestack. Hot springs and deserts may also be suitable locations for a tighter, faster-rotating steam devil to form. The phenomenon can occur over water, when cold arctic air passes over relatively warm water.

Intensity and Damage

Tornado Rating Classifications

The Fujita scale and the Enhanced Fujita Scale rate tornadoes by damage caused. The Enhanced Fujita (EF) Scale was an update to the older Fujita scale, by expert elicitation, using engineered wind estimates and better damage descriptions. The EF Scale was designed so that a tornado rated on the Fujita scale would receive the same numerical rating, and was implemented starting in the United States in 2007. An EF0 tornado will probably damage trees but not substantial structures, whereas an EF5 tornado can rip buildings off their foundations leaving them bare and even deform large skyscrapers. The similar TORRO scale ranges from a T0 for extremely weak tornadoes to T11 for the most powerful known tornadoes. Doppler weather radar data, photogrammetry, and ground swirl patterns (cycloidal marks) may also be analyzed to determine intensity and award a rating.

A house displaying EF1 damage. The roof and garage door have been damaged, but walls and supporting structures are still intact.

Tornadoes vary in intensity regardless of shape, size, and location, though strong tornadoes are typically larger than weak tornadoes. The association with track length and duration also varies, although longer track tornadoes tend to be stronger. In the case of violent tornadoes, only a small portion of the path is of violent intensity, most of the higher intensity from subvortices.

<table>
<tr><th>F0
EF0</th><th>F1
EF1</th><th>F2
EF2</th><th>F3
EF3</th><th>F4
EF4</th><th>F5
EF5</th></tr>
<tr><td colspan="2">Weak</td><td colspan="2">Strong</td><td colspan="2">Violent</td></tr>
<tr><td colspan="2"></td><td colspan="4">Significant</td></tr>
<tr><td colspan="3"></td><td colspan="3">Intense</td></tr>
</table>

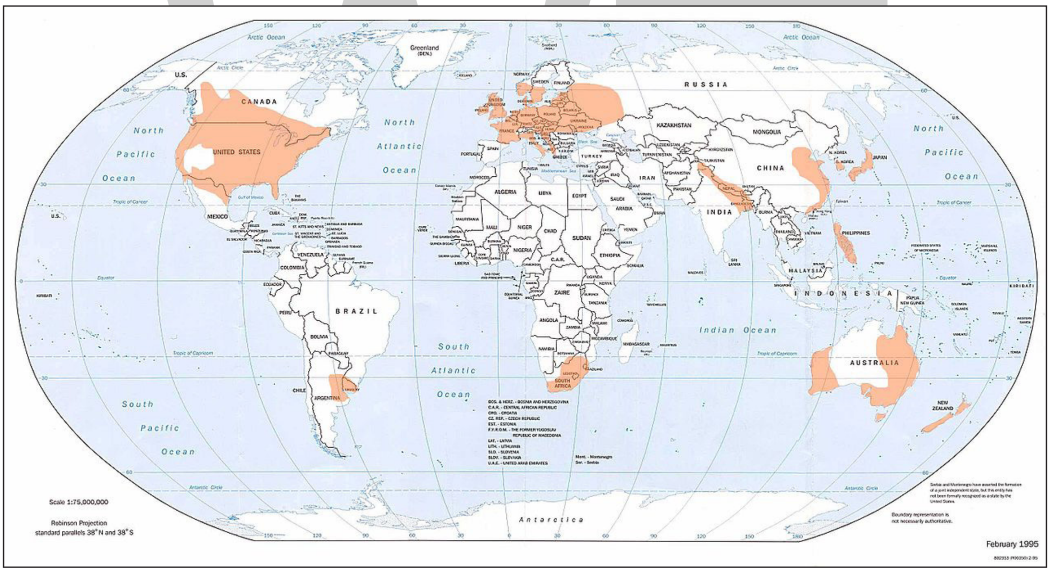
In the United States, 80% of tornadoes are EF0 and EF1 (T0 through T3) tornadoes. The rate of occurrence drops off quickly with increasing strength—less than 1% are violent tornadoes (EF4, T8 or stronger). Outside Tornado Alley, and North America in general, violent tornadoes are extremely rare. This is apparently mostly due to the lesser number of tornadoes overall, as research shows that tornado intensity distributions are fairly similar worldwide. A few significant tornadoes occur annually in Europe, Asia, southern Africa, and southeastern South America, respectively.

Climatology

The United States has the most tornadoes of any country, nearly four times more than estimated in all of Europe, excluding waterspouts. This is mostly due to the unique geography of the continent.

North America is a large continent that extends from the tropics north into arctic areas, and has no major east-west mountain range to block air flow between these two areas. In the middle latitudes, where most tornadoes of the world occur, the Rocky Mountains block moisture and buckle the atmospheric flow, forcing drier air at mid-levels of the troposphere due to downsloped winds, and causing the formation of a low pressure area downwind to the east of the mountains. Increased westerly flow off the Rockies force the formation of a dry line when the flow aloft is strong, while the Gulf of Mexico fuels abundant low-level moisture in the southerly flow to its east. This unique topography allows for frequent collisions of warm and cold air, the conditions that breed strong, long-lived storms throughout the year. A large portion of these tornadoes form in an area of the central United States known as Tornado Alley. This area extends into Canada, particularly Ontario and the Prairie Provinces, although southeast Quebec, the interior of British Columbia, and western New Brunswick are also tornado-prone. Tornadoes also occur across northeastern Mexico.

The United States averages about 1,200 tornadoes per year, followed by Canada, averaging 62 reported per year. NOAA's has a higher average 100 per year in Canada. The Netherlands has the highest average number of recorded tornadoes per area of any country (more than 20, or 0.0013 per sq mi (0.00048 per km^2), annually), followed by the UK (around 33, or 0.00035 per sq mi (0.00013 per km^2), per year), although those are of lower intensity, briefer and cause minor damage.

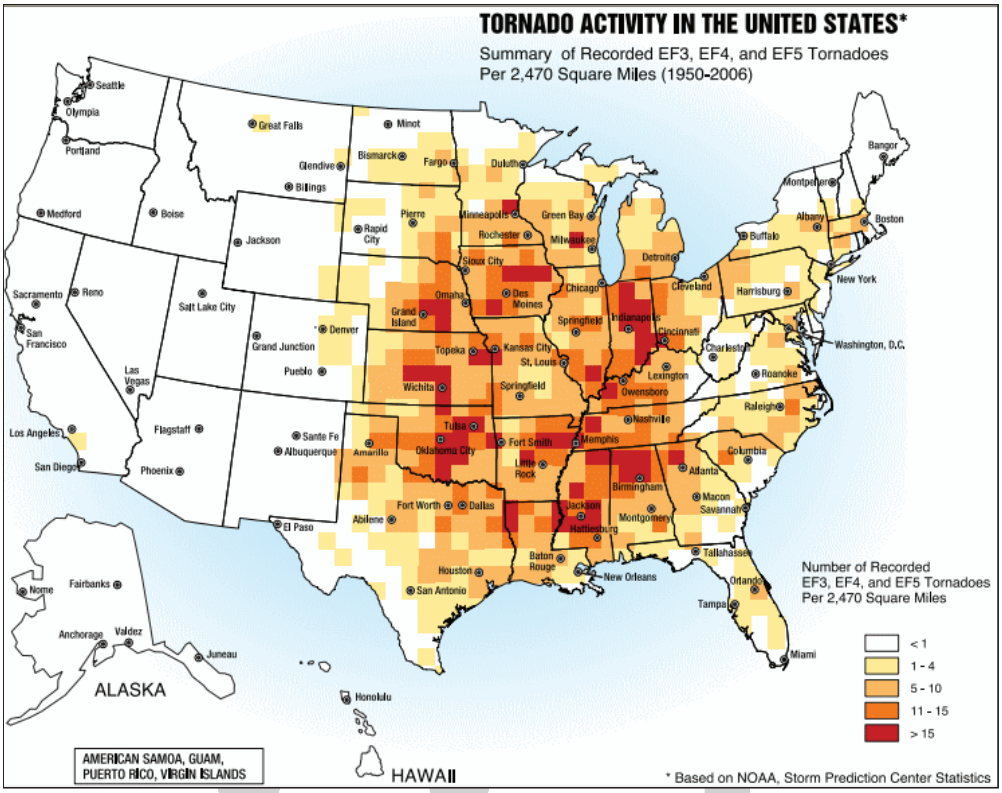


Areas worldwide where tornadoes are most likely, indicated by orange shading.

Tornadoes kill an average of 179 people per year in Bangladesh, the most in the world. Reasons for this include the region's high population density, poor construction quality, and lack of tornado safety knowledge. Other areas of the world that have frequent tornadoes include South Africa, the La Plata Basin area, portions of Europe, Australia and New Zealand, and far eastern Asia.

Tornadoes are most common in spring and least common in winter, but tornadoes can occur any time of year that favorable conditions occur. Spring and fall experience peaks of activity as those are the seasons when stronger winds, wind shear, and atmospheric instability are present. Tornadoes are focused in the right front quadrant of landfalling tropical cyclones, which tend to occur in the late summer and autumn. Tornadoes can also be spawned as a result of eyewall mesovortices, which persist until landfall.

Tornado occurrence is highly dependent on the time of day, because of solar heating. Worldwide, most tornadoes occur in the late afternoon, between 3 pm and 7 pm local time, with a peak near 5 pm. Destructive tornadoes can occur at any time of day. The Gainesville Tornado of 1936, one of the deadliest tornadoes in history, occurred at 8:30 am local time.



Intense tornado activity in the United States. The darker-colored areas denote the area commonly referred to as Tornado Alley.

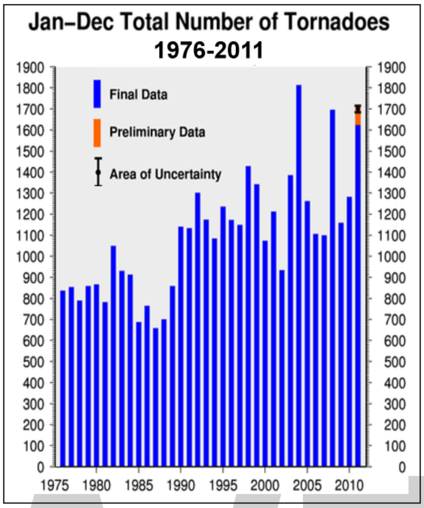
The United Kingdom has the highest incidence of tornadoes, measured by unit area of land, than any other country in the world. Unsettled conditions and weather fronts transverse the Islands at all times of the years and are responsible for spawning the tornadoes, which consequently form at all times of the year. The United Kingdom has at least 34 tornadoes per year and possibly as many as 50, more than any other country in the world relative to its land area. Most tornadoes in the United Kingdom are weak, but they are occasionally destructive. For example, the Birmingham tornado of 2005 and the London tornado of 2006 both registered F2 on the Fujita scale and both caused significant damage and injury.

Associations with Climate and Climate Change

Associations with various climate and environmental trends exist. For example, an increase in the sea surface temperature of a source region (e.g. Gulf of Mexico and Mediterranean Sea) increases atmospheric moisture content. Increased moisture can fuel an increase in severe weather and tornado activity, particularly in the cool season.

Some evidence does suggest that the Southern Oscillation is weakly correlated with changes in tornado activity, which vary by season and region, as well as whether the ENSO phase is that of

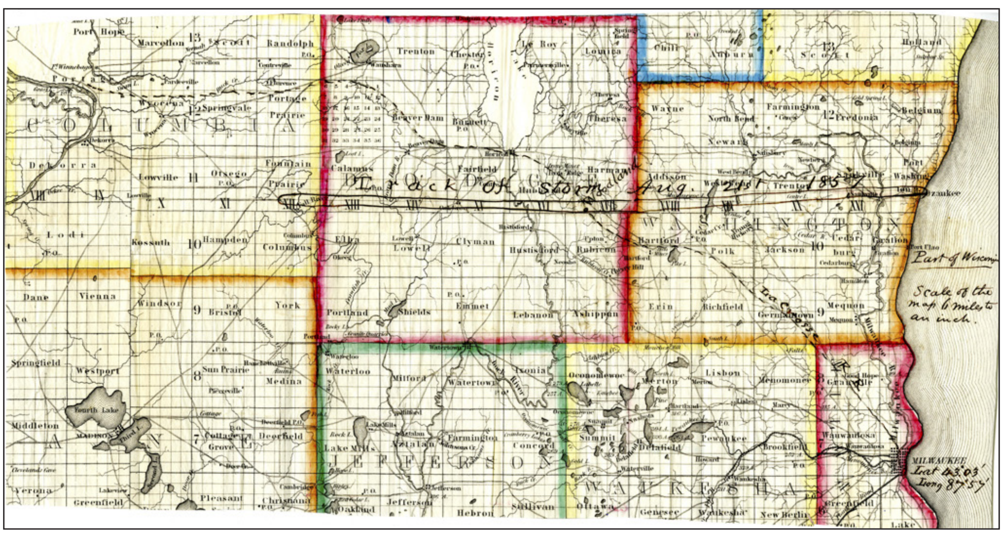
El Niño or La Niña. Research has found that fewer tornadoes and hailstorms occur in winter and spring in the U.S. central and southern plains during El Niño, and more occur during La Niña, than in years when temperatures in the Pacific are relatively stable. Ocean conditions could be used to forecast extreme spring storm events several months in advance.



U. S. Annual January–December Tornado Count
1976–2011 from NOAA National Climatic Data Center.

Climatic shifts may affect tornadoes via teleconnections in shifting the jet stream and the larger weather patterns. The climate-tornado link is confounded by the forces affecting larger patterns and by the local, nuanced nature of tornadoes. Although it is reasonable to suspect that global warming may affect trends in tornado activity, any such effect is not yet identifiable due to the complexity, local nature of the storms, and database quality issues. Any effect would vary by region.

Detection



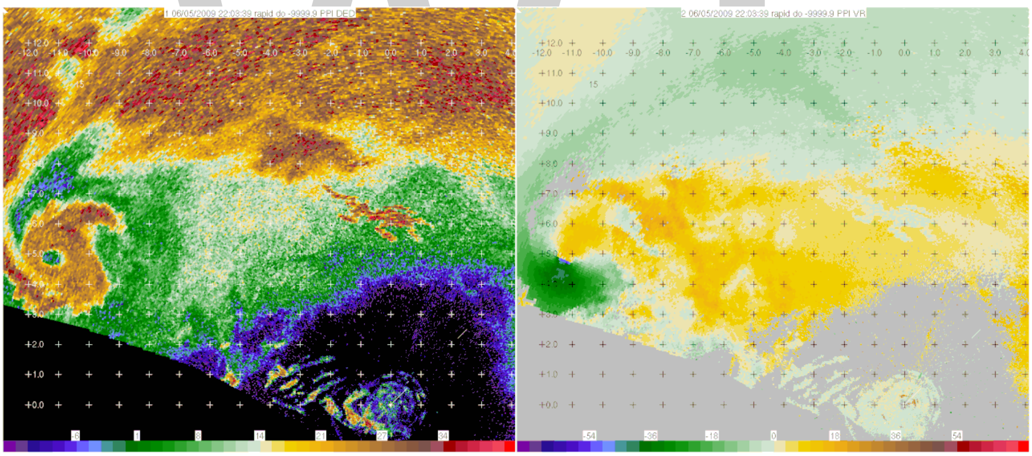
Path of a tornado across Wisconsin on August 21, 1857.

Rigorous attempts to warn of tornadoes began in the United States in the mid-20th century. Before the 1950s, the only method of detecting a tornado was by someone seeing it on the ground.

Often, news of a tornado would reach a local weather office after the storm. However, with the advent of weather radar, areas near a local office could get advance warning of severe weather. The first public tornado warnings were issued in 1950 and the first tornado watches and convective outlooks came about in 1952. In 1953, it was confirmed that hook echoes were associated with tornadoes. By recognizing these radar signatures, meteorologists could detect thunderstorms probably producing tornadoes from several miles away.

Radar

Today, most developed countries have a network of weather radars, which serves as the primary method of detecting hook signatures that are likely associated with tornadoes. In the United States and a few other countries, Doppler weather radar stations are used. These devices measure the velocity and radial direction (towards or away from the radar) of the winds within a storm, and so can spot evidence of rotation in storms from over one hundred miles (160 km) away. When storms are distant from a radar, only areas high within the storm are observed and the important areas below are not sampled. Data resolution also decreases with distance from the radar. Some meteorological situations leading to tornadogenesis are not readily detectable by radar and tornado development may occasionally take place more quickly than radar can complete a scan and send the batch of data. Doppler radar systems can detect mesocyclones within a supercell thunderstorm. This allows meteorologists to predict tornado formations throughout thunderstorms.



A Doppler on Wheels radar loop of a hook echo and associated mesocyclone in Goshen County, Wyoming on June 5, 2009. Strong mesocyclones show up as adjacent areas of yellow and blue (on other radars, bright red and bright green), and usually indicate an imminent or occurring tornado.

Storm Spotting

In the mid-1970s, the U.S. National Weather Service (NWS) increased its efforts to train storm spotters so they could spot key features of storms that indicate severe hail, damaging winds, and tornadoes, as well as storm damage and flash flooding. The program was called Skywarn, and the spotters were local sheriff's deputies, state troopers, firefighters, ambulance drivers, amateur radio operators, civil defense (now emergency management) spotters, storm chasers, and ordinary citizens. When severe weather is anticipated, local weather service offices request these spotters to look out for severe weather and report any tornadoes immediately, so that the office can warn of the hazard.

Spotters usually are trained by the NWS on behalf of their respective organizations, and report to them. The organizations activate public warning systems such as sirens and the Emergency Alert System (EAS), and they forward the report to the NWS. There are more than 230,000 trained Skywarn weather spotters across the United States.

In Canada, a similar network of volunteer weather watchers, called Canwarn, helps spot severe weather, with more than 1,000 volunteers. In Europe, several nations are organizing spotter networks under the auspices of Skywarn Europe and the Tornado and Storm Research Organisation (TORRO) has maintained a network of spotters in the United Kingdom since 1974.

Storm spotters are required because radar systems such as NEXRAD do not really detect tornadoes; merely signatures which hint at the presence of tornadoes. Radar may give a warning before there is any visual evidence of a tornado or an imminent one, but ground truth from an observer can either verify the threat or determine that a tornado is not imminent. The spotter's ability to see what radar can't is especially important as distance from the radar site increases, because the radar beam becomes progressively higher in altitude further away from the radar, chiefly due to curvature of Earth, and the beam also spreads out.

Visual Evidence

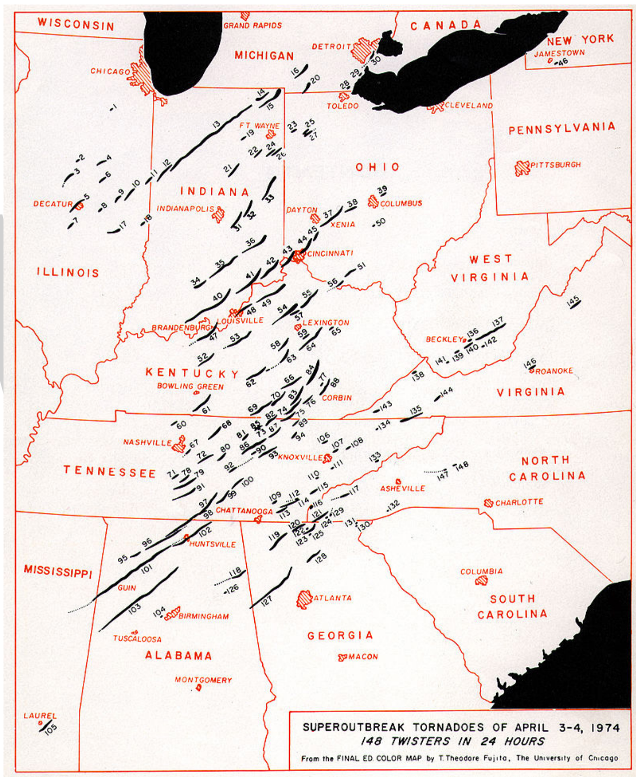
A rotating wall cloud with rear flank downdraft clear slot evident to its left rear.

Storm spotters are trained to discern whether or not a storm seen from a distance is a supercell. They typically look to its rear, the main region of updraft and inflow. Under that updraft is a rain-free base, and the next step of tornadogenesis is the formation of a rotating wall cloud. The vast majority of intense tornadoes occur with a wall cloud on the backside of a supercell.

Evidence of a supercell is based on the storm's shape and structure, and cloud tower features such as a hard and vigorous updraft tower, a persistent, large overshooting top, a hard anvil (especially when backsheared against strong upper level winds), and a corkscrew look or striations. Under the storm and closer to where most tornadoes are found, evidence of a supercell and the likelihood of a tornado includes inflow bands (particularly when curved) such as a "beaver tail", and other clues such as strength of inflow, warmth and moistness of inflow air, how outflow- or inflow-dominant a storm appears, and how far is the front flank precipitation core from the wall cloud. Tornadogenesis is most likely at the interface of the updraft and rear flank downdraft, and requires a balance between the outflow and inflow.

Only wall clouds that rotate spawn tornadoes, and they usually precede the tornado between five and thirty minutes. Rotating wall clouds may be a visual manifestation of a low-level mesocyclone. Barring a low-level boundary, tornadogenesis is highly unlikely unless a rear flank downdraft occurs, which is usually visibly evidenced by evaporation of cloud adjacent to a corner of a wall cloud. A tornado often occurs as this happens or shortly afterwards; first, a funnel cloud dips and in nearly all cases by the time it reaches halfway down, a surface swirl has already developed, signifying a tornado is on the ground before condensation connects the surface circulation to the storm. Tornadoes may also develop without wall clouds, under flanking lines and on the leading edge. Spotters watch all areas of a storm, and the cloud base and surface.

Extremes



A map of the tornado paths in the Super Outbreak.

The most record-breaking tornado in recorded history was the Tri-State Tornado, which roared through parts of Missouri, Illinois, and Indiana on March 18, 1925. It was likely an F5, though tornadoes were not ranked on any scale in that era. It holds records for longest path length (219 miles; 352 km), longest duration (about 3.5 hours), and fastest forward speed for a significant tornado (73 mph; 117 km/h) anywhere on Earth. In addition, it is the deadliest single tornado in United States history (695 dead). The tornado was also the costliest tornado in history at the time (unadjusted for inflation), but in the years since has been surpassed by several others if population changes over time are not considered. When costs are normalized for wealth and inflation, it ranks third today.

The deadliest tornado in world history was the Daultipur-Salturia Tornado in Bangladesh on April 26, 1989, which killed approximately 1,300 people. Bangladesh has had at least 19 tornadoes in its history kill more than 100 people, almost half of the total in the rest of the world.

The most extensive tornado outbreak on record was the 2011 Super Outbreak, which spawned 360 confirmed tornadoes over the southeastern United States – 216 of them within a single 24-hour period. The previous record was the 1974 Super Outbreak which spawned 148 tornadoes.

While direct measurement of the most violent tornado wind speeds is nearly impossible, since conventional anemometers would be destroyed by the intense winds and flying debris, some tornadoes have been scanned by mobile Doppler radar units, which can provide a good estimate of the tornado's winds. The highest wind speed ever measured in a tornado, which is also the highest wind speed ever recorded on the planet, is 301 ± 20 mph (484 ± 32 km/h) in the F5 Bridge Creek-Moore, Oklahoma, tornado which killed 36 people. Though the reading was taken about 100 feet (30 m) above the ground, this is a testament to the power of the strongest tornadoes.

Storms that produce tornadoes can feature intense updrafts, sometimes exceeding 150 mph (240 km/h). Debris from a tornado can be lofted into the parent storm and carried a very long distance. A tornado which affected Great Bend, Kansas, in November 1915, was an extreme case, where a "rain of debris" occurred 80 miles (130 km) from the town, a sack of flour was found 110 miles (180 km) away, and a cancelled check from the Great Bend bank was found in a field outside of Palmyra, Nebraska, 305 miles (491 km) to the northeast. Waterspouts and tornadoes have been advanced as an explanation for instances of raining fish and other animals.

Safety

Damage from the Birmingham tornado of 2005. An unusually strong example of a tornado event in the United Kingdom, the Birmingham Tornado resulted in 19 injuries, mostly from falling trees.

Though tornadoes can strike in an instant, there are precautions and preventative measures that people can take to increase the chances of surviving a tornado. Authorities such as the Storm Prediction Center advise having a pre-determined plan should a tornado warning be issued. When a warning is issued, going to a basement or an interior first-floor room of a sturdy building greatly increases chances of survival. In tornado-prone areas, many buildings have storm cellars on the property. These underground refuges have saved thousands of lives.

Some countries have meteorological agencies which distribute tornado forecasts and increase levels of alert of a possible tornado (such as tornado watches and warnings in the United States and Canada). Weather radios provide an alarm when a severe weather advisory is issued for the local area, though these are mainly available only in the United States. Unless the tornado is far away and highly visible, meteorologists advise that drivers park their vehicles far to the side of the road (so as not to block emergency traffic), and find a sturdy shelter. If no sturdy shelter is nearby, getting low in a ditch is the next best option. Highway overpasses are one of the worst places to take shelter during tornadoes, as the constricted space can be subject to increased wind speed and funneling of debris underneath the overpass.

Myths and Misconceptions

The 1999 Salt Lake City tornado disproved several misconceptions, including the idea that tornadoes cannot occur in cities.

Folklore often identifies a green sky with tornadoes, and though the phenomenon may be associated with severe weather, there is no evidence linking it specifically with tornadoes. It is often thought that opening windows will lessen the damage caused by the tornado. While there is a large drop in atmospheric pressure inside a strong tornado, it is unlikely that the pressure drop would be enough to cause the house to explode. Opening windows may actually increase the severity of the tornado's damage. A violent tornado can destroy a house whether its windows are open or closed.

Another commonly held misconception is that highway overpasses provide adequate shelter from tornadoes. This belief is partly inspired by widely circulated video captured during the 1991 tornado outbreak near Andover, Kansas, where a news crew and several other people take shelter under an overpass on the Kansas Turnpike and safely ride out a tornado as it passes by. However, a highway overpass is a dangerous place during a tornado, and the subjects of the video remained safe due to an unlikely combination of events: the storm in question was a weak tornado, the tornado did not directly strike the overpass, and the overpass itself was of a unique design. Due to the Venturi effect, tornadic winds are accelerated in the confined space of an overpass. Indeed, in the 1999 Oklahoma tornado outbreak of May 3, 1999, three highway overpasses were directly struck by tornadoes, and at each of the three locations there was a fatality, along with many life-threatening injuries. By comparison, during the same tornado outbreak, more than 2000 homes were completely destroyed, with another 7000 damaged, and yet only a few dozen people died in their homes.

An old belief is that the southwest corner of a basement provides the most protection during a tornado. The safest place is the side or corner of an underground room opposite the tornado's direction of approach (usually the northeast corner), or the central-most room on the lowest floor. Taking shelter in a basement, under a staircase, or under a sturdy piece of furniture such as a workbench further increases chances of survival.

There are areas which people believe to be protected from tornadoes, whether by being in a city, near a major river, hill, or mountain, or even protected by supernatural forces. Tornadoes have been known to cross major rivers, climb mountains, affect valleys, and have damaged several city centers. As a general rule, no area is safe from tornadoes, though some areas are more susceptible than others.

Fire Whirl

A fire whirl, also commonly known as a fire devil, or, (in many cases erroneously) as a fire tornado, firenado, fire swirl, or fire twister, is a whirlwind induced by a fire and often (at least partially) composed of flame or ash. These start with a whirl of wind, often made visible by smoke, and may occur when intense rising heat and turbulent wind conditions combine to form whirling eddies of air. These eddies can contract a tornado-like vortex that sucks in debris and combustible gases.

Fire whirls are sometimes colloquially called fire tornadoes, but are not usually classifiable as tornadoes as the vortex in most cases does not extend from the surface to cloud base. Also, even in such cases, those fire whirls very rarely are classic tornadoes, as their vorticity derives from surface winds and heat-induced lifting, rather than from a tornadic mesocyclone aloft, although a handful of suspected cases of the latter are known.

Formation

A fire whirl consists of a burning core and a rotating pocket of air. A fire whirl can reach up to 2,000 °F (1,090 °C). Fire whirls become frequent when a wildfire, or especially firestorm, creates its own wind, which can spawn large vortices. Even bonfires often have whirls on a smaller scale and tiny fire whirls have been generated by very small fires in laboratories.

Most of the largest fire whirls are spawned from wildfires. They form when a warm updraft and convergence from the wildfire are present. They are usually 10–50 m (33–164 ft) tall, a few meters (several feet) wide, and last only a few minutes. Some, however, can be more than 1 km (0.6 mi) tall, contain wind speeds over 200 km/h (120 mph), and persist for more than 20 minutes.

Fire whirls can uproot trees that are 15 m (49 ft) tall or more. These can also aid the ‘spotting’ ability of wildfires to propagate and start new fires as they lift burning materials such as tree bark. These burning embers can be blown away from the fireground by the stronger winds aloft.

Fire Whirls can be common within the vicinity of a plume during a volcanic eruption. These range from small to large and form from a variety of mechanisms, including those akin to typical fire-whirl processes, but can result in Cumulonimbus flammagenitus (cloud) spawning landspouts and waterspouts or even to develop mesoyclone-like updraft rotation of the plume itself and/or of the cumulonimbi, which can spawn tornadoes similar to those in supercells. Pyrocumulonimbi generated by large fires on rare occasion also develops in a similar way.

Classification

There are currently three widely recognized types of fire whirls:

- Stable and centered over burning area.
- Stable or transient, downwind of burning area.
- Steady or transient, centered over an open area adjacent to an asymmetric burning area with wind.

There is evidence suggesting that the fire whirl in the Hifukusho-ato area, during the 1923 Great Kantō earthquake, was of type 3. Other mechanism and firewhirl dynamics may exist.

STORM

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

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

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

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

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

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

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

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

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

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

Other Important Types of Cyclones

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

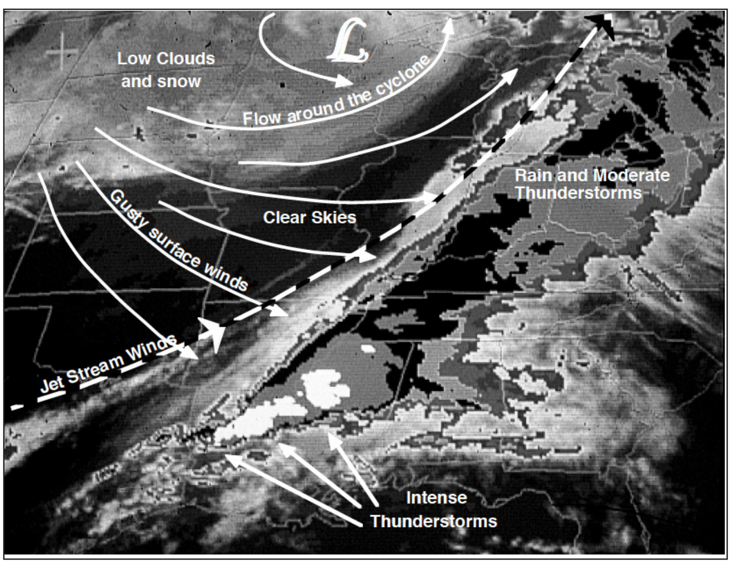
Another type of cyclone, called a mesocyclone, arises in association with thunderstorms. In some special situations, a large portion of a single thunderstorm can be in cyclonic rotation. A thunderstorm that has this characteristic is called a supercell thunderstorm, and is almost always accompanied by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

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

Observations, Technology and Forecasting

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

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



An example of the distribution of various types of stormy weather within an extratropical cyclone. The center of the large-scale cyclone is denoted with a script "L" and various types of storms, including thunderstorms, rainstorms, and snowstorms are indicated on an infrared satellite image.

Streamlines of wind flow at selected places at the surface and along the jet stream aloft are also indicated On the satellite image, cloud top temperatures are shown with various shades of gray; the image has been artificially enhanced by changing the shading abruptly at certain specified temperatures. The very coldest, and therefore the highest, clouds are indicated by the lightest gray shades.

DERECHO

A derecho is a widespread, long-lived, straight-line wind storm that is associated with a fast-moving group of severe thunderstorms known as a mesoscale convective system.

Derechos can cause hurricane-force winds, tornadoes, heavy rains, and flash floods. In many cases, convection-induced winds take on a bow echo (backward “C”) form of squall line, often forming beneath an area of diverging upper tropospheric winds, and in a region of both rich low-level moisture and warm-air advection. Derechos move rapidly in the direction of movement of their associated storms, similar to an outflow boundary (gust front), except that the wind remains sustained for a greater period of time (often increasing in strength after onset), and may exceed hurricane-force. A derecho-producing convective system may remain active for many hours and, occasionally, over multiple days.

A warm-weather phenomenon, derechos occur mostly in summer, especially during June, July, and August in the Northern Hemisphere, within areas of moderately strong instability and moderately strong vertical wind shear. However, derechos may occur at any time of the year, and can occur as frequently at night as during the day.

Various studies since the 1980s have shed light on the physical processes responsible for the production of widespread damaging winds by thunderstorms. In addition, it has become apparent that the most damaging derechos are associated with particular types of mesoscale convective systems that are self-perpetuating (meaning that the convective systems are not strongly dependent on the larger-scale meteorological processes such as those associated with blizzard-producing winter storms and strong cold fronts). In addition, the term “derecho” sometimes is misapplied to convectively-generated wind events that are not particularly well-organized or long-lasting. For these reasons, a more precise, physically-based definition of “derecho” has been introduced within the meteorological community.

A shelf cloud along the leading edge of a derecho photographed in Minnesota.

Development

Organized areas of thunderstorm activity reinforce pre-existing frontal zones, and can outrun cold fronts. The resultant mesoscale convective system (MCS) often forms at the point of the strongest divergence of the upper-level flow in the area of greatest low-level inflow and convergence. The convection tends to move east or toward the equator, roughly parallel to low-level thickness lines and usually somewhat to the right of the mean tropospheric flow. When the convection is strongly linear or slightly curved, the MCS is called a squall line, with the strongest winds typically occurring just behind the leading edge of the significant wind shift and pressure rise.

Classic derechos occur with squall lines that contain bow- or spearhead-shaped features as seen by weather radar that are known as bow echoes or spearhead echoes. Squall lines typically “bow out” due to the formation of a mesoscale high pressure system which forms within the stratiform rain area behind the initial convective line. This high pressure area is formed due to strong descending air currents behind the squall line, and could come in the form of a downburst. The size of the bow may vary, and the storms associated with the bow may die and redevelop.

During the cool season within the Northern Hemisphere, derechos generally develop within a pattern of mid-tropospheric southwesterly winds, in an environment of low to moderate atmospheric instability (caused by relative warmth and moisture near ground level, with cooler air aloft, as measured by convective available potential energy), and high values of vertical wind shear (20 m/s [72 km/h; 39 kn; 45 mph]) within the lowest 5 km [16,000 feet] of the atmosphere).

Warm season derechos in the Northern Hemisphere most often form in west to northwesterly flow at mid-levels of the troposphere, with moderate to high levels of thermodynamic instability.

Classification and Criteria

A common definition is a thunderstorm complex that produces a damaging wind swath of at least 400 km (250 miles), featuring a concentrated area of convectively-induced wind gusts exceeding 30 m/s (90 km/h; 50 kn; 60 mph). According to the National Weather Service (NWS) criterion, a derecho is classified as a band of storms that have winds of at least 30 m/s (90 km/h; 50 kn; 60 mph) along the entire span of the storm front, maintained over a time span of at least six hours. Some studies add a requirement that no more than two or three hours separate any two successive wind reports. A more recent, more physically-based definition of “derecho” proposes that the term be reserved for use with convective systems that not only contain unique radar-observed features such as bow echoes and mesovortices, but also for events that produce damage swaths at least 100 km (60 miles) wide and 650 km (400 miles) long.

Four types of derechos are generally recognized:

- Serial derecho – This type of derecho is usually associated with a very deep low.
    - Single-bow – A very large bow echo around or upwards of 400 km (250 miles) long. This type of serial derecho is less common than the multi-bow kind. An example of a single-bow serial derecho is the derecho that occurred in association with the October 2010 North American storm complex.

    - Multi-bow – Multiple bow derechos are embedded in a large squall line typically around 400 km (250 miles) long. One example of a multi-bow serial derecho is a derecho that occurred during the 1993 Storm of the Century in Florida. Because of embedded supercells, tornadoes can spin out of these types of derechos. This is a much more common type of serial derecho than the single-bow kind. Multi-bow serial derechos can be associated with line echo wave patterns (LEWPs) on weather radar.

- Progressive derecho – A line of thunderstorms take the bow-shape and may travel for hundreds of miles along stationary fronts. Examples of this include “Hurricane Elvis” in 2003 and the Boundary Waters-Canadian Derecho of 4–5 July 1999. Tornado formation is less common in a progressive than serial type.

- Hybrid derecho – A derecho with characteristics of both a serial and progressive derecho. Similar to serial derechos and progressive derechos, these types of derechos are associated with a deep low, but are relatively small in size. An example is the Late-May 1998 tornado outbreak and derecho that moved through the central Northern Plains and the Southern Great Lakes on 30–31 May 1998.

- Low dewpoint derecho – A derecho that occurs in an environment of comparatively limited low-level moisture, with appreciable moisture confined to the mid-levels of the atmosphere. Such derechos most often occur between late fall and early spring in association with strong low pressure systems. Low dew point derechos are essentially organized bands of successive, dry downbursts. The Utah-Wyoming derecho of 31 May 1994 was an event of this type. It produced a 47 m/s (169 km/h; 91 kn; 105 mph) wind gust at Provo, Utah, where sixteen people were injured, and removed part of the roof of the Saltair Pavilion on the Great Salt Lake. Surface dew points along the path of the derecho were about 7–11 °C or in the mid 40s to low 50s °F.

Characteristics

Winds in a derecho can be enhanced by downburst clusters embedded inside the storm. These straight-line winds may exceed 45 m/s (161 km/h; 87 kn; 100 mph), reaching 58 m/s (210 km/h; 110 kn; 130 mph) in past events. Tornadoes sometimes form within derecho events, although such events are often difficult to confirm due to the additional damage caused by straight-line winds in the immediate area.

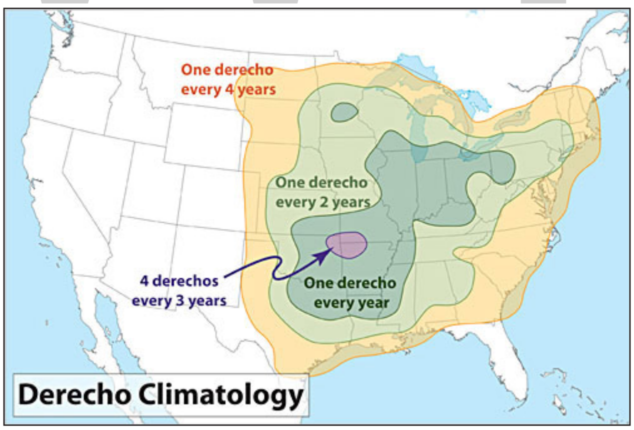
With the average tornado in the United States and Canada rating in the low end of the F/EF1 classification at 38 to 45 m/s (137 to 161 km/h; 74 to 87 kn; 85 to 100 mph) peak winds and most or all of the rest of the world even lower, derechos tend to deliver the vast majority of extreme wind conditions over much of the territory in which they occur. Datasets compiled by the United States National Weather Service and other organizations show that a large swath of the north-central United States, and presumably at least the adjacent sections of Canada and much of the surface of the Great Lakes, can expect winds from 38 to 54 m/s (137 to 193 km/h; 74 to 104 kn; 85 to 120 mph) over a significant area at least once in any 50-year period, including both convective events and extra-tropical cyclones and other events deriving power from baroclinic sources. Only in 40 to 65 percent or so of the United States resting on the coast of the Atlantic basin, and a fraction of the Everglades, are derechos surpassed in this respect — by landfalling hurricanes, which at their worst may have winds as severe as EF3 tornadoes.

Certain derecho situations are the most common instances of severe weather outbreaks which may become less favorable to tornado production as they become more violent; the height of 30–31 May 1998 upper Middle West-Canada-New York State derecho and the latter stages of significant tornado and severe weather outbreaks in 2003 and 2004 are only three examples of this. Some upper-air measurements used for severe-weather forecasting may reflect this point of diminishing return for tornado formation, and the mentioned three situations were instances during which the rare Particularly Dangerous Situation severe thunderstorm variety of severe weather watches were issued from the Storm Prediction Center of the U.S. National Oceanic & Atmospheric Administration.

Some derechos develop a radar signature resembling that of a hurricane in the low levels. They may have a central eye free of precipitation, with a minimum central pressure and surrounding bands of strong convection, but are really associated with an MCS developing multiple squall lines, and are not tropical in nature. These storms have a warm core, like other mesoscale convective systems. One such derecho occurred across the Midwestern U.S. on 21 July 2003. An area of convection developed across eastern Iowa near a weak stationary/warm front and ultimately matured, taking on the shape of a wavy squall line across western Ohio and southern Indiana. The system re-intensified after leaving the Ohio Valley, starting to form a large hook, with occasional hook echoes appearing along its eastern side. A surface low pressure center formed and became more impressive later in the day.

Location

Derechos in North America form predominantly from April to August, peaking in frequency from May into July. During this time of year, derechos are mostly found in the Midwestern United States and the U.S. Interior Highlands most commonly from Oklahoma and across the Ohio Valley. During mid-summer when a hot and muggy air mass covers the north-central U.S., they will often develop farther north into Manitoba or Northwestern Ontario, sometimes well north of the Canada–US border.



This image shows derecho frequency for the lower 48 United States.

North Dakota, Minnesota, and upper Michigan are also vulnerable to derecho storms when such conditions are in place. They often occur along stationary fronts on the northern periphery of where the most intense heat and humidity bubble exists. Late-year derechos are normally confined to Texas and the Deep South, although a late-summer derecho struck upper parts of the New York State area after midnight on 7 September 1998. Warm season derechos have greater instability than their cold season counterpart, while cool season derechos have greater shear than their warm season counterpart.

Although these storms most commonly occur in North America, derechos can occur elsewhere in the world, with a few areas relatively frequently. Outside North America, they sometimes are called by different names. For example, in Bangladesh and adjacent portions of India, a type of storm known as a "Nor'wester" may be a progressive derecho. One such event occurred on 10 July 2002 in Germany: a serial derecho killed eight people and injured 39 near Berlin. Derechos occur in southeastern South America (particularly Argentina and southern Brazil) and South Africa as well, and on rarer occasions, close to or north of the 60th parallel in northern Canada. Primarily a mid-latitudes phenomenon, derechos do occur in the Amazon Basin of Brazil. On 8 August 2010, a derecho struck Estonia and tore off the tower of Väike-Maarja Church. Derechos are occasionally observed in China.

Damage Risk

Trees felled by downbursts in the Boundary Waters.

Barn in Mount Solon.

Unlike other thunderstorms, which typically can be heard in the distance when approaching, a derecho seems to strike suddenly. Within minutes, extremely high winds can arise, strong enough to knock over highway signs and topple large trees. These winds are accompanied by spraying rain and frequent lightning from all directions. It is dangerous to drive under these conditions, especially at night, because of blowing debris and obstructed roadways. Downed wires and widespread power outages are likely but not always a factor. A derecho moves through quickly, but can do much damage in a short time.

Since derechos occur during warm months and often in places with cold winter climates, people who are most at risk are those involved in outdoor activities. Campers, hikers, and motorists are most at risk because of falling trees toppled over by straight-line winds. Wide swaths of forest have been felled by such storms. People who live in mobile homes are also at risk; mobile homes that are not anchored to the ground may be overturned from the high winds. Across the United States, Michigan and New York have incurred a significant portion of the fatalities from derechos. Prior to Hurricane Katrina, the death tolls from derechos and hurricanes were comparable for the United States.

Derechos may also severely damage an urban area's electrical distribution system, especially if these services are routed above ground. The derecho that struck Chicago, Illinois on 11 July 2011 left more than 860,000 people without electricity. The June 2012 North American derecho took out electrical power to more than 3.7 million customers starting in the Midwestern United States, across the central Appalachians, into the Mid-Atlantic States during a heat wave.

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 are 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.

Formation of Blizzards

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.

Ground Blizzards

Ground blizzards are particularly dangerous as they can unexpectedly occur after winter storms have passed.

During a ground blizzard, white-out conditions are created by snow and ice lifted up from the ground.

A ground blizzard is a weather condition that is characterized by the lifting up of the loose snow or ice on the ground. The lifted snow or ice is then blown away by a strong wind. The ground blizzard can occur with or without any form of precipitation and also when the sky is clear. It occurs when the Arctic cold front finds its way through the region, leading to an increase in winds and drop in temperature. If there are some loose snow on the ground, the strong wind quickly picks them up, creating a white-out condition. The minimum speed required for the wind to transport snow is 12 mph. if the wind is blowing faster, the snow is transported further, faster, and higher, leading to the white-out condition.

Characteristics of a Ground Blizzard

The term "ground blizzard" is associated with the lifting up, blowing, and drifting of snow or ice. However, there are some of the conditions that must be met for a weather condition to qualify as a ground blizzard. The criteria and conditions depend on the weather governing agency of a country. In the United States, the National Weather Service defines a blizzard as having a sustained wind of at least 35 mph with visibility maintained below 0.25 miles in a considerable blowing snow. The conditions must also prevail for at least three hours. In Canada, the Environment Canada maintains that the visibility must be less than 400 meters in a blowing snow and the speed of wind sustained at 40 mph or more for four hours or more and for at least six hours for Nunavut and Northwest Territories.

Types of Ground Blizzards

There are three types of ground blizzards; horizontal advection, vertical advection, and thermal-mechanical mixing conditions. In horizontal advection, the wind blowing across the surface of the earth has very little or no large-scale upward motion. For vertical advection, the blowing wind has a large-scale upward movement and lifts the loose snow into the atmosphere, leading to the formation of drifting waves of snow up to about 1,640 feet. Thermal-mechanical mixing type leads to the formation of massive rolls in the atmosphere. The massive rolls create waves of snow known as snow billows which can be observed from the space.

Difference between Blizzards and Ground Blizzards

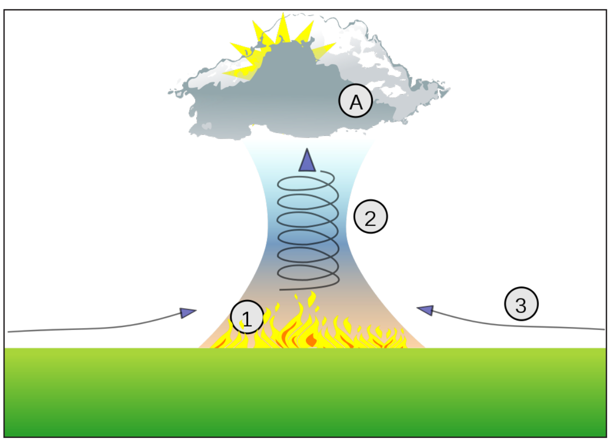
Blizzard and ground blizzard are sometimes confused or considered as the same. However, there is a major difference between the two. A ground blizzard is the lifting up and blowing away of loose snow or ice by a strong wind whereas a blizzard is a snowstorm characterized by falling of heavy snow and strong wing that last for at least three hours. Ground blizzard can occur in the absence of precipitation while for the blizzard to occur there must be precipitation in the form of falling snow.

FIRESTORM

View of one of the Tillamook Burn fires.

A firestorm is a conflagration which attains such intensity that it creates and sustains its own wind system. It is most commonly a natural phenomenon, created during some of the largest bushfires and wildfires. Although the term has been used to describe certain large fires, the phenomenon's determining characteristic is a fire with its own storm-force winds from every point of the compass. Firestorms have also occurred in cities, usually as a deliberate effect of targeted explosives, such as occurred as a result of the aerial firebombings of Hamburg, Dresden, firebombing of Tokyo and the atomic bombing of Hiroshima.

Mechanism



Firestorm: fire (1), updraft (2), strong gusty winds (3) (A) pyrocumulonimbus cloud.

A firestorm is created as a result of the stack effect as the heat of the original fire draws in more and more of the surrounding air. This draft can be quickly increased if a low-level jet stream exists over or near the fire. As the updraft mushrooms, strong inwardly-directed gusty winds develop around the fire, supplying it with additional air. This would seem to prevent the firestorm from spreading on the wind, but the tremendous turbulence created may also cause the strong surface inflow winds to change direction erratically. Firestorms resulting from the bombardment of urban areas in the Second World War were generally confined to the areas initially seeded with incendiary devices, and the firestorm did not appreciably spread outward. A firestorm may also develop into a mesocyclone and induce true tornadoes/fire whirls. This occurred with the 2002 Durango fire, and probably with the much greater Peshtigo Fire. The greater draft of a firestorm draws in greater quantities of oxygen, which significantly increases combustion, thereby also substantially increasing the production of heat. The intense heat of a firestorm manifests largely as radiated heat (infrared radiation), which may ignite flammable material at a distance ahead of the fire itself.[failed verification] This also serves to expand the area and the intensity of the firestorm. Violent, erratic wind drafts suck movables into the fire and as is observed with all intense conflagrations, radiated heat from the fire can melt asphalt, some metals, and glass, and turn street tarmac into flammable hot liquid. The very high temperatures ignite anything that might possibly burn, until the firestorm runs low on fuel.

A firestorm does not appreciably ignite material at a distance ahead of itself; more accurately, the heat desiccates those materials and makes them more vulnerable to ignition by embers or firebrands, increasing the rate of fire spotting. During the formation of a firestorm many fires merge to form a single convective column of hot gases rising from the burning area and strong, fire-induced, radial (inwardly directed) winds are associated with the convective column. Thus the fire front is essentially stationary and the outward spread of fire is prevented by the in-rushing wind.

Characterization of a Firestorm

A firestorm is characterized by strong to gale-force winds blowing toward the fire, everywhere around the fire perimeter, an effect which is caused by the buoyancy of the rising column of hot gases over the intense mass fire, drawing in cool air from the periphery. These winds from the perimeter blow the fire brands into the burning area and tend to cool the unignited fuel outside the fire area so that ignition of material outside the periphery by radiated heat and fire embers is more difficult, thus limiting fire spread. At Hiroshima, this inrushing to feed the fire is said to have prevented the firestorm perimeter from expanding, and thus the firestorm was confined to the area of the city damaged by the blast.

In 2002 various sensing instruments detected 17 distinct pyrocumulonimbus cloud events in North America alone.

Large wildfire conflagrations are distinct from firestorms if they have moving fire fronts which are driven by the ambient wind and do not develop their own wind system like true firestorms. (This does not mean that a firestorm must be stationary; as with any other convective storm, the circulation may follow surrounding pressure gradients and winds, if those lead it onto fresh fuel sources.) Furthermore, non-firestorm conflagrations can develop from a single ignition, whereas firestorms have only been observed where large numbers of fires are burning simultaneously over a relatively large area, with the important caveat that the density of simultaneously burning fires needs to be above a critical threshold for a firestorm to form (a notable example of large numbers of fires burning simultaneously over a large area without a firestorm developing was the Kuwaiti oil fires of 1991, where the distance between individual fires was too large).

The high temperatures within the firestorm zone ignite most everything that might possibly burn, until a tipping point is reached, that is, upon running low on fuel, which occurs after the firestorm has consumed so much of the available fuel within the firestorm zone that the necessary fuel density required to keep the firestorm's wind system active drops below the threshold level, at which time the firestorm breaks up into isolated conflagrations.

In Australia, the prevalence of eucalyptus trees that have oil in their leaves results in forest fires that are noted for their extremely tall and intense flame front. Hence the bush fires appear more as a firestorm than a simple forest fire. Sometimes, emission of combustible gases from swamps (e.g., methane) has a similar effect. For instance, methane explosions enforced the Peshtigo Fire.

Weather and Climate Effects

Firestorms will produce hot buoyant smoke clouds of primarily water vapor that will form condensation clouds as it enters the cooler upper atmosphere, generating what is known as pyrocumulus clouds ("fire clouds") or, if large enough, pyrocumulonimbus ("fire storm") clouds. For example, the black rain that began to fall approximately 20 minutes after the atomic bombing of Hiroshima produced in total 5–10 cm of black soot-filled rain in a 1–3 hour period. Moreover, if the conditions are right, a large pyrocumulus can grow into a pyrocumulonimbus and produce lightning, which could potentially set off further fires. Apart from city and forest fires, pyrocumulus clouds can also be produced by volcanic eruptions due to the comparable amounts of hot buoyant material formed.

On a more continental and global extent, away from the direct vicinity of the fire, wildfire firestorms which produce pyrocumulonimbus cloud events have been found to "surprisingly frequently" generate minor "nuclear winter" effects. These are analogous to minor volcanic winters, with each mass addition of volcanic gases additive in increasing the depth of the "winter" cooling, from near-imperceptible to "year without a summer" levels.

Pyro-Cumulonimbus and Atmospheric Effects (In Wildfires)

A very important but poorly understood aspect of wildfire behavior are pyrocumulonimbus (pyroCb) firestorm dynamics and their atmospheric impact. These are well illustrated in the Black Saturday case study below. The "pyroCb" is a fire-started or fire-augmented thunderstorm that in its most extreme manifestation injects huge abundances of smoke and other biomass-burning emissions into the lower stratosphere. The observed hemispheric spread of smoke and other biomass-burning emissions has known important climate consequences. Direct attribution of the stratospheric aerosols to pyroCbs only occurred in the last decade. Such an extreme injection by thunderstorms was previously judged to be unlikely because the extratopical tropopause is considered to be a strong barrier to convection. Two recurring themes have developed as pyroCb research unfolds. First, puzzling stratospheric aerosol-layer observations— and other layers reported as volcanic aerosol can now be explained in terms of pyroconvection. Second, pyroCb events occur surprisingly frequently, and they are likely a relevant aspect of several historic wildfires.

On an intraseasonal level it is established that pyroCbs occur with surprising frequency. In 2002, at least 17 pyroCbs erupted in North America alone. Still to be determined is how often this process occurred in the boreal forests of Asia in 2002. However, it is now established that this most extreme form of pyroconvection, along with more frequent pyrocumulus convection, was widespread and persisted for at least 2 months. The characteristic injection height of pyroCb emissions is the upper troposphere, and a subset of these storms pollutes the lower stratosphere. Thus, a new appreciation for the role of extreme wildfire behavior and its atmospheric ramifications is now coming into focus.

City Firestorms

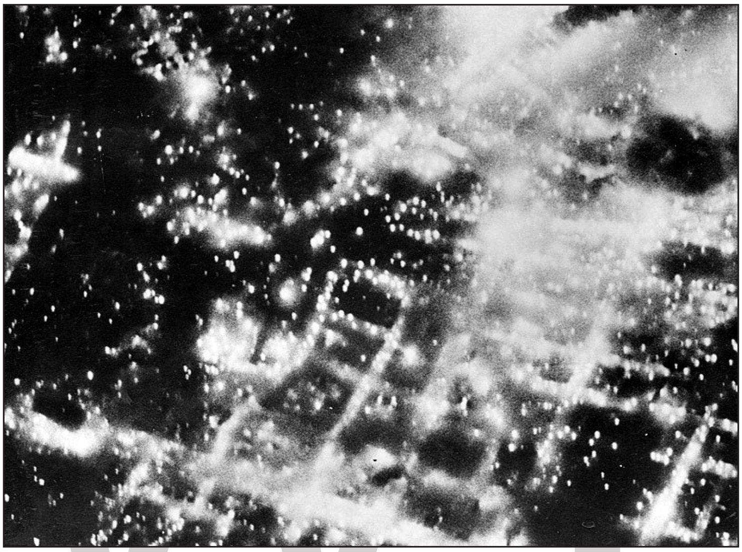
Joseph Pennell's 1918 prophetic Liberty bond poster calls up the pictorial image of a bombed New York City, totally engulfed in a firestorm. At the time, the armaments available to the world's various air forceswere not powerful enough to produce such a result.

The same underlying combustion physics can also apply to man-made structures such as cities during war or natural disaster.

Firestorms are thought to have been part of the mechanism of large urban fires, such as accompanied the 1755 Lisbon earthquake, the 1906 San Francisco earthquake and the 1923 Great Kantō earthquake. Genuine firestorms are occurring more frequently in California wildfires, such as the 1991 wildfire disaster in Oakland, California, and the October 2017 Tubbs Fire in Santa Rosa, California. During the July–August 2018 Carr Fire, a deadly fire vortex equivalent in size and strength to an EF-3 tornado spawned during the firestorm in Redding, California and caused tornado-like wind damage. Firestorms were also created by the firebombing raids of World War II in cities like Hamburg and Dresden. Of the two nuclear weapons used in combat, only Hiroshima resulted in a firestorm.

In contrast, experts suggest that due to the nature of modern U.S. city design and construction, a firestorm is unlikely after a nuclear detonation.

Firebombing



Braunschweig burning after aerial firebombing attack in 1944. Notice that a firestorm event has yetto develop in this picture, as single isolated fires are seen burning, and not the single large mass firethat is the identifying characteristic of a firestorm.

Firebombing is a technique designed to damage a target, generally an urban area, through the use of fire, caused by incendiary devices, rather than from the blast effect of large bombs. Such raids often employ both incendiary devices and high explosives. The high explosive destroys roofs, making it easier for the incendiary devices to penetrate the structures and cause fires. The high explosives also disrupt the ability of firefighters to douse the fires.

Although incendiary bombs have been used to destroy buildings since the start of gunpowder warfare, World War II saw the first use of strategic bombing from the air to destroy the ability of the enemy to wage war. London, Coventry, and many other British cities were firebombed during the Blitz. Most large German cities were extensively firebombed starting in 1942, and almost all large Japanese cities were firebombed during the last six months of World War II. As Sir Arthur Harris, the officer commanding RAF Bomber Command from 1942 through to the end of the war in Europe, pointed out in his post-war analysis, although many attempts were made to create deliberate man-made firestorms during World War II, few attempts succeeded:

The Germans again and again missed their chance, of setting our cities ablaze by a concentrated attack. Coventry was adequately concentrated in point of space, but all the same there was little concentration in point of time, and nothing like the fire tornadoes of Hamburg or Dresden ever occurred in this country. But they did do us enough damage to teach us the principle of concentration, the principle of starting so many fires at the same time that no fire fighting services, however efficiently and quickly they were reinforced by the fire brigades of other towns could get them under control.

According to physicist David Hafemeister, firestorms occurred after about 5% of all fire-bombing raids during World War II (but he does not explain if this is a percentage based on both Allied and Axis raids, or combined Allied raids, or U.S. raids alone). In 2005, the American National Fire Protection Association stated in a report that three major firestorms resulted from Allied conventional bombing campaigns during World War II: Hamburg, Dresden, and Tokyo. They do not include the comparatively minor firestorms at Kassel, Darmstadt or even Ube into their major firestorm category. Despite later quoting and corroborating Glasstone and Dolan and data collected from these smaller firestorms:

> "Based on World War II experience with mass fires resulting from air raids on Germany and Japan, the minimum requirements for a firestorm to develop are considered by some authorities to be the following: (1) at least 8 pounds of combustibles per square foot of fire area (40 kg per square meter), (2) at least half of the structures in the area on fire simultaneously, (3) a wind of less than 8 miles per hour at the time, and (4) a minimum burning area of about half a square mile."

Nuclear Weapons in Comparison to Conventional Weapons

The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same overall result with respect to destruction of life and property can be achieved by the use of conventional incendiary and high-explosive bombs. It has been estimated, for example, that the same fire ferocity and damage produced at Hiroshima by one 16-kiloton nuclear bomb from a single B-29 could have instead been produced by about 1,200 tons/1.2 kilotons of incendiary bombs from 220 B-29s distributed over the city; for Nagasaki, a single 21 kiloton nuclear bomb dropped on the city could have been estimated to be caused by 1,200 tons of incendiary bombs from 125 B-29s.

It may seem counterintuitive that the same amount of fire damage caused by a nuclear weapon could have instead been produced by smaller total yield of thousands of incendiary bombs; however, World War II experience supports this assertion. For example, although not a perfect clone of the city of Hiroshima in 1945, in the conventional bombing of Dresden, the combined Royal Air Force (RAF) and United States Army Air Forces (USAAF) dropped a total of 3441.3 tons (approximately 3.4 kilotons) of ordnance (about half of which was incendiary bombs) on the night of 13–14 February 1945, and this resulted in "more than" 2.5 square miles (6.5 km^2) of the city being destroyed by fire and firestorm effects according to one authoritative source, or approximately 8 square miles (21 km^2) by another. In total about 4.5 kilotons of conventional ordnance was dropped on the city over a number of months during 1945 and this resulted in approximately 15 square miles (39 km^2) of the city being destroyed by blast and fire effects. During the Operation MeetingHouse firebombing of Tokyo on 9–10 March 1945, 279 of the 334 B-29s dropped 1,665 tons of incendiary and high-explosive bombs on the city, resulting in the destruction of over 10,000 acres of buildings — 16 square miles (41 km^2), a quarter of the city. In contrast to these raids, when a single 16-kiloton nuclear bomb was dropped on Hiroshima, 4.5 square miles (12 km^2) of the city was destroyed by blast, fire, and firestorm effects. Similarly, Major Cortez F. Enloe, a surgeon in the USAAF who worked with the United States Strategic Bombing Survey (USSBS), said that the 21-kiloton nuclear bomb dropped on Nagasaki did not do as much fire damage as the extended conventional airstrikes on Hamburg.

Hiroshima after the bombing and firestorm. No known aerial photography of the firestorm exists.

This Tokyo residential section was virtually destroyed. All that remained standing were concrete buildings in this photograph.

American historian Gabriel Kolko also echoed this sentiment:

During November 1944 American B-29's began their first incendiary bomb raids on Tokyo, and on 9 March 1945, wave upon wave dropped masses of small incendiaries containing an early version of napalm on the city's population. Soon small fires spread, connected, grew into a vast firestorm that sucked the oxygen out of the lower atmosphere. The bomb raid was a 'success' for the Americans; they killed 125,000 Japanese in one attack. The Allies bombed Hamburg and Dresden in the same manner, and Nagoya, Osaka, Kobe, and Tokyo again on May 24. in fact the atomic bomb used against Hiroshima was less lethal than massive fire bombing. Only its technique was novel—nothing more. There was another difficulty posed by mass conventional bombing, and that was its very success, a success that made the two modes of human destruction qualitatively identical in fact and in the minds of the American military. "We was a little fearful", [Secretary of War] Stimson told [President] Truman, "that before we could get ready the Air Force might have Japan so thoroughly bombed out that the new weapon would not have a fair background to show its strength." To this the President "laughed and said he understood."

This break from the linear expectation of more fire damage to occur after greater explosive yield is dropped can be easily explained by two major factors. First, the order of blast and thermal events during a nuclear explosion is not ideal for the creation of fires. In an incendiary bombing raid, incendiary weapons followed after high-explosive blast weapons were dropped, in a manner designed to create the greatest probability of fires from a limited quantity of explosive and incendiary weapons. The so-called two-ton "cookies", also known as "blockbusters", were dropped first and were intended to rupture water mains, as well as to blow off roofs, doors, and windows, creating an air flow that would feed the fires caused by the incendiaries that would then follow and be dropped, ideally, into holes created by the prior blast weapons, such into attic and roof spaces. On the other hand, nuclear weapons produce effects that are in the reverse order, with thermal effects and "flash" occurring first, which are then followed by the slower blast wave. It is for this reason that conventional incendiary bombing raids are considered to be a great deal more efficient at causing mass fires than nuclear weapons of comparable yield. It is likely this led the nuclear weapon effects experts Franklin D'Olier, Samuel Glasstone and Philip J. Dolan to state that the same fire damage suffered at Hiroshima could have instead been produced by about 1 kiloton/1,000 tons of incendiary bombs.

The second factor explaining the non-intuitive break in the expected results of greater explosive yield producing greater city fire damage is that city fire damage is largely dependent not on the yield of the weapons used, but on the conditions in and around the city itself, with the fuel loading per square meter value of the city being one of the major factors. A few hundred strategically placed incendiary devices would be sufficient to start a firestorm in a city if the conditions for a firestorm, namely high fuel loading, are already inherent to the city. The Great Fire of London in 1666, although not forming a firestorm due to the single point of ignition, serves as an example that, given a densely packed and predominately wooden and thatch building construction in the urban area, a mass fire is conceivable from the mere incendiary power of no more than a domestic fireplace. On the other hand, the largest nuclear weapon conceivable will be incapable of igniting a city into a firestorm if the city's properties, namely its fuel density, are not conducive to one developing.

Despite the disadvantage of nuclear weapons when compared to conventional weapons of lower or comparable yield in terms of effectiveness at starting fires, for the reasons, nuclear weapons also do not add any fuel to a city, and fires are entirely dependent on what was contained in the city prior to bombing, in direct contrast to the incendiary device effect of conventional raids. One undeniable advantage of nuclear weapons over conventional weapons when it comes to creating fires is that nuclear weapons undoubtedly produce all their thermal and explosive effects in a very short period of time; that is, to use Arthur Harris's terminology, they are the epitome of an air raid guaranteed to be concentrated in "point in time". In contrast, early in World War II, the ability to achieve conventional air raids concentrated in "point of time" depended largely upon the skill of pilots to remain in formation, and their ability to hit the target whilst at times also being under heavy fire from anti-aircraft fire from the cities below. Nuclear weapons largely remove these uncertain variables. Therefore, nuclear weapons reduce the question of whether a city will firestorm or not to a smaller number of variables, to the point of becoming entirely reliant on the intrinsic properties of the city, such as fuel loading, and predictable atmospheric conditions, such as wind speed, in and around the city, and less reliant on the unpredictable possibility of hundreds of bomber crews acting together successfully as a single unit.

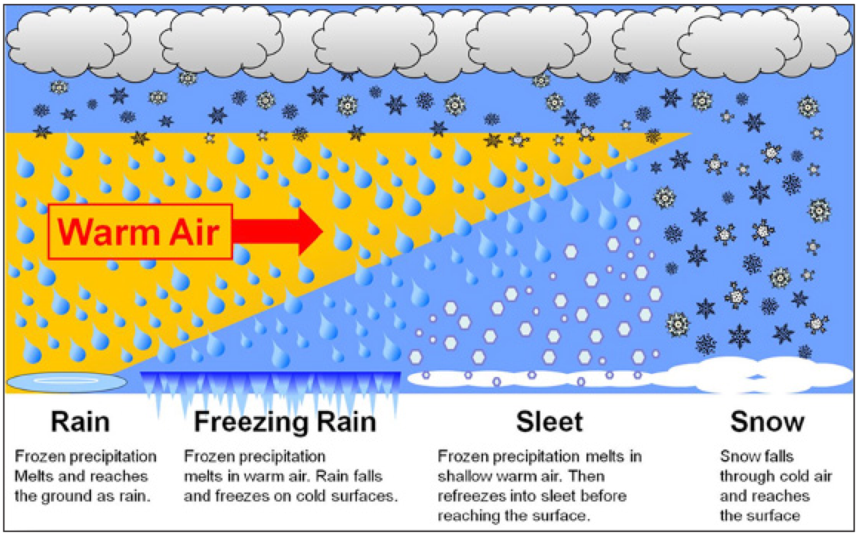
ICE STORM

Ice storms are weather phenomena caused by freezing rain. The falling rain comes into contact with surfaces and turns into a thin sheet of ice. Ice storms cause accidents, take power lines down and cause serious damage.

The U.S. National Weather Service defines an ice storm as a storm which results in the accumulation of at least 0.25-inch (6.4 mm) of ice on exposed surfaces. From 1982 to 1994, ice storms were more common than blizzards and averaged 16 per year. They are generally not violent storms but instead are commonly perceived as gentle rains occurring at temperatures just below freezing.

After 2013 Ice Storm in Guelph, Ontario, Canada

Formation



A graph showing the formation of different kinds of precipitation.

It starts with a layer of warmer (not freezing) air above a layer of sub-freezing temperatures lower down. Frozen precipitation melts to rain while falling into the warm air layer, and then begins to refreeze in the cold layer below.

1. If the precipitate refreezes while still in the air, it will land on the ground as sleet.
2. Or, the liquid droplets continue to fall without freezing. They pass through the cold air just above the surface. This thin layer of air cools the rain to a temperature below freezing (0 °C or 32 °F), but the drops themselves do not freeze. This is a phenomenon called super-cooling.

When the supercooled drops strike ground or anything else below 0 °C (32 °F) (e.g. power lines, tree branches, aircraft), a layer of ice builds up, hence “freezing rain”.

Effect

Power lines sagging after an ice storm. Besides disrupting transportation, ice storms can disrupt utilities by snapping lines and poles.

Devastation caused by an ice storm.

The freezing rain from an ice storm covers everything with heavy, smooth glaze ice. In addition to hazardous driving or walking conditions, branches or even whole trees may break from the weight of ice. Falling branches can block roads, tear down power and telephone lines, and cause other damage. Even without falling trees and tree branches, the weight of the ice itself can easily snap power lines and also break and bring down power/utility poles; even electricity pylons with steel frames. This can leave people without power for anywhere from several days to a month. According to most meteorologists, just one quarter of an inch of ice accumulation can add about 500 pounds (230 kg) of weight per line span. Damage from ice storms is easily capable of shutting down entire metropolitan areas.

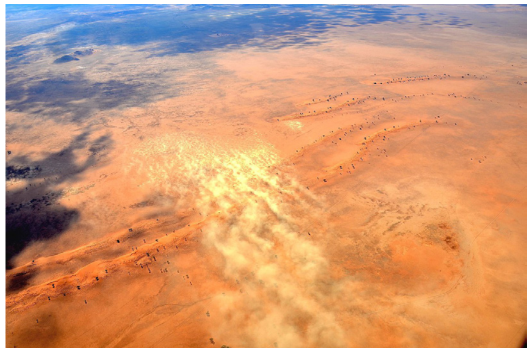
DUST STORM

A dust storm, also called sandstorm, is a meteorological phenomenon common in arid and semi-arid regions. Dust storms arise when a gust front or other strong wind blows loose sand and dirt from a dry surface. Fine particles are transported by saltation and suspension, a process that moves soil from one place and deposits it in another.

Drylands around North Africa and the Arabian peninsula are the main terrestrial sources of airborne dust. It has been argued that poor management of the Earth's drylands, such as neglecting the fallow system, are increasing dust storms size and frequency from desert margins and changing both the local and global climate, and also impacting local economies.

The term sandstorm is used most often in the context of desert dust storms, especially in the Sahara Desert, or places where sand is a more prevalent soil type than dirt or rock, when, in addition to fine particles obscuring visibility, a considerable amount of larger sand particles are blown closer to the surface. The term dust storm is more likely to be used when finer particles are blown long distances, especially when the dust storm affects urban areas.

A sandstorm approaching Al Asad, Iraq, just before nightfall. Effect May cause coughing and spread dust.



A sandstorm might not look as strong as it really is. Namib Desert 25°20′07″S 016°03′05″E.

Causes

As the force of wind passing over loosely held particles increases, particles of sand first start to vibrate, then to saltate ("leaps"). As they repeatedly strike the ground, they loosen and break off smaller particles of dust which then begin to travel in suspension. At wind speeds above that which causes the smallest to suspend, there will be a population of dust grains moving by a range of mechanisms: suspension, saltation and creep.

A study from 2008 finds that the initial saltation of sand particles induces a static electric field by friction. Saltating sand acquires a negative charge relative to the ground which in turn loosens more sand particles which then begin saltating. This process has been found to double the number of particles predicted by previous theories.

Particles become loosely held mainly due to a prolonged drought or arid conditions, and high wind speeds. Gust fronts may be produced by the outflow of rain-cooled air from an intense thunderstorm. Or, the wind gusts may be produced by a dry cold front, that is, a cold front that is moving into a dry air mass and is producing no precipitation—the type of dust storm which was common during the Dust Bowl years in the U.S. Following the passage of a dry cold front, convective instability resulting from cooler air riding over heated ground can maintain the dust storm initiated at the front.

In desert areas, dust and sand storms are most commonly caused by either thunderstorm outflows, or by strong pressure gradients which cause an increase in wind velocity over a wide area. The vertical extent of the dust or sand that is raised is largely determined by the stability of the atmosphere above the ground as well as by the weight of the particulates. In some cases, dust and sand may be confined to a relatively shallow layer by a low-lying temperature inversion. In other instances, dust (but not sand) may be lifted as high as 20,000 feet (6,100 m) high.

Drought and wind contribute to the emergence of dust storms, as do poor farming and grazing practices by exposing the dust and sand to the wind.

One poor farming practice which contributes to dust storms is dryland farming. Particularly poor dryland farming techniques are intensive tillage or not having established crops or cover crops when storms strike at particularly vulnerable times prior to revegetation. In a semi-arid climate, these practices increase susceptibility to dust storms. However, soil conservation practices may be implemented to control wind erosion.

Physical and Environmental Effects

Sydney shrouded in dust during the 2009 Australian dust storm.

A sandstorm can transport and carry large volumes of sand unexpectedly. Dust storms can carry large amounts of dust, with the leading edge being composed of a wall of thick dust as much as 1.6 km (0.99 mi) high. Dust and sand storms which come off the Sahara Desert are locally known as a simoom or simoon. The haboob is a sandstorm prevalent in the region of Sudan around Khartoum, with occurrences being most common in the summer.

The Sahara desert is a key source of dust storms, particularly the Bodélé Depression and an area covering the confluence of Mauritania, Mali, and Algeria. Sahara dust is frequently emitted into the Mediterranean atmosphere and transported by the winds sometimes as far north as central Europe and Great Britain.

Saharan dust storms have increased approximately 10-fold during the half-century since the 1950s, causing topsoil loss in Niger, Chad, northern Nigeria, and Burkina Faso.In Mauritania there were just two dust storms a year in the early 1960s, but there are about 80 a year today, according to Andrew Goudie, a professor of geography at Oxford University. Levels of Saharan dust coming off the east coast of Africa in June 2007 were five times those observed in June 2006, and were the highest observed since at least 1999, which may have cooled Atlantic waters enough to slightly reduce hurricane activity in late 2007.

Dust storms have also been shown to increase the spread of disease across the globe. Virus spores in the ground are blown into the atmosphere by the storms with the minute particles and interact with urban air pollution.

Short-term effects of exposure to desert dust include immediate increased symptoms and worsening of the lung function in individuals with asthma, increased mortality and morbidity from long-transported dust from both Saharan and Asian dust storms suggesting that long-transported dust storm particles adversely affects the circulatory system. Dust pneumonia is the result of large amounts of dust being inhaled.

Prolonged and unprotected exposure of the respiratory system in a dust storm can also cause silicosis, which, if left untreated, will lead to asphyxiation; silicosis is an incurable condition that may also lead to lung cancer. There is also the danger of keratoconjunctivitis sicca (“dry eyes”) which, in severe cases without immediate and proper treatment, can lead to blindness.

Economic Impact

Dust storms cause soil loss from the dry lands, and worse, they preferentially remove organic matter and the nutrient-rich lightest particles, thereby reducing agricultural productivity. Also, the abrasive effect of the storm damages young crop plants. Dust storms also reduced visibility affecting aircraft and road transportation. In addition dust storms also create problems due to complications of breathing in dust.

Dust can also have beneficial effects where it deposits: Central and South American rain forests get most of their mineral nutrients from the Sahara; iron-poor ocean regions get iron; and dust in Hawaii increases plantain growth. In northern China as well as the mid-western U.S., ancient dust storm deposits known as loess are highly fertile soils, but they are also a significant source of contemporary dust storms when soil-securing vegetation is disturbed.

Extraterrestrial Dust Storms

Dust storms are not limited to Earth and have been known to form on other planets such as Mars. These dust storms can extend over larger areas than those on Earth, sometimes encircling the planet, with wind speeds as high as 60 miles per hour (97 km/h). However, given Mars' much lower atmospheric pressure (roughly 1% that of Earth's), the intensity of Mars storms could never reach the kind of hurricane-force winds that are experienced on Earth. Martian dust storms are formed when solar heating warms the Martian atmosphere and causes the air to move, lifting dust off the ground. The chance for storms is increased when there are great temperature variations like those seen at the equator during the Martian summer.

CLOUDBURST

Cloudburst is a sudden, very heavy rainfall, usually local in nature and of brief duration. Most so-called cloudbursts occur in connection with thunderstorms. In these storms there are violent up-rushes of air, which at times prevent the condensing raindrops from falling to the ground. A large amount of water may thus accumulate at high levels, and if the upward currents are weakened the whole of this water falls at one time.

Cloudbursts are especially common in mountainous areas. This is probably because the warm air currents of a thunderstorm tend to follow the upward slope of a mountain. The effects of heavy rain are especially striking on mountain slopes because the falling water is concentrated in valleys and gulleys. Mountain cloudbursts cause sudden and destructive floods. The intensity of rainfall in the most severe cloudbursts can only be conjectured. A rainfall of 2.47 inches (63 mm) in 3 minutes was registered by an automatic rain gauge at Porto Bello, Panama, on November 29, 1911, and one of 1.50 inches (38 mm) in 1 minute was registered at the Barot rain gauge near Les Abymes, Guadeloupe, on November 26, 1970. There have been cases, however, in which the excavations made in the ground by the falling water of a cloudburst appear to indicate an even greater intensity of rainfall.

CYCLONE

A cyclone is caused by atmospheric disturbances around a low-pressure area and is usually accompanied by violent storms and severe weather conditions. Intense tropical storms are called Hurricanes over the Atlantic Ocean and Typhoons over the Pacific Ocean.

Origination and Strength of Cyclones

Cyclones originate over the sea and travel about 300 to 500 km a day, drawing heat energy from the ocean waters. A fully matured cyclone releases energy equivalent to few hydrogen bombs. The diameter of a cyclone varies from 150 to 1000 kilometres but their effects dominate thousands of square kilometres of the ocean surface.

Classification of Tropical Cyclones

Cyclones are classified into five different categories on the basis of wind speed, from Category 1 to Category 5. The wind speed varies according to the category of the cyclone, from 60 kilometers an hour to about 220 kmph and above.

Once the winds around the low pressure area reach upto 62 kmph, it is termed as a tropical cyclone and is assigned a name. As and when the wind speed settles between 89 and 118 kmph, it turns into a Severe Cyclonic Storm. Thereafter, the storm intensifies into a Very Severe Cyclonic Storm when the wind blows at a speed of about 119 to 221 kmph. When the wind speed exceeds 221 kmph, the cyclone is called a Super Cyclonic Storm.

Eye of a Cyclone

A fully matured cyclone develops a calm centre called Eye with a ring of hurricane winds around it, possessing the following characteristics:

A fully matured cyclone develops a calm centre called Eye with a ring of hurricane winds around it, possessing the following characteristics:

1. Eye forms at the centre of Central Dense Overcast (CDO) region of storm.
2. Diameter of the Eye of a storm is about 10-50 km.

3. Eye is the cloud-free zone, surrounded by thick cloud walls.
4. Eye is surrounded by a 10-15 km thick wall of convective clouds, a zone of maximum wind.
5. Eye is the calm region with practically no rains.
6. Eye is warmer than the surrounding region.
7. Lowest surface pressure is observed at the Eye.
8. Eye is an indicative of very strong winds spiralling around the centre.
9. All cyclonic storms may not develop an Eye.
10. Sometimes, double Eye is also seen, which is indicative of very high intensity.
11. Eye wall is the most dangerous part of the storm.
12. Storm surge, torrential rains and high velocity winds are the associated features of Eye wall.

Tropical Cyclone

A tropical cyclone is a rapidly rotating storm system characterized by a low-pressure center, a closed low-level atmospheric circulation, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain. Depending on its location and strength, a tropical cyclone is referred to by different names, including hurricane, typhoon, tropical storm, cyclonic storm, tropical depression, and simply cyclone. A hurricane is a tropical cyclone that occurs in the Atlantic Ocean and northeastern Pacific Ocean, and a typhoon occurs in the northwestern Pacific Ocean; in the south Pacific or Indian Ocean, comparable storms are referred to simply as "tropical cyclones" or "severe cyclonic storms".

"Tropical" refers to the geographical origin of these systems, which form almost exclusively over tropical seas. "Cyclone" refers to their winds moving in a circle, whirling round their central clear eye, with their winds blowing counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The opposite direction of circulation is due to the Coriolis effect. Tropical cyclones typically form over large bodies of relatively warm water. They derive their energy through the evaporation of water from the ocean surface, which ultimately recondenses into clouds and rain when moist air rises and cools to saturation. This energy source differs from that of mid-latitude cyclonic storms, such as nor'easters and European windstorms, which are fueled primarily by horizontal temperature contrasts. Tropical cyclones are typically between 100 and 2,000 km (62 and 1,243 mi) in diameter.

The strong rotating winds of a tropical cyclone are a result of the conservation of angular momentum imparted by the Earth's rotation as air flows inwards toward the axis of rotation. As a result, they rarely form within 5° of the equator. Tropical cyclones are almost unknown in the South Atlantic due to a consistently strong wind shear and a weak Intertropical Convergence Zone. Also, the African easterly jet and areas of atmospheric instability which give rise to cyclones in the Atlantic Ocean and Caribbean Sea, along with the Asian monsoon and Western Pacific Warm Pool, are features of the Northern Hemisphere and Australia.

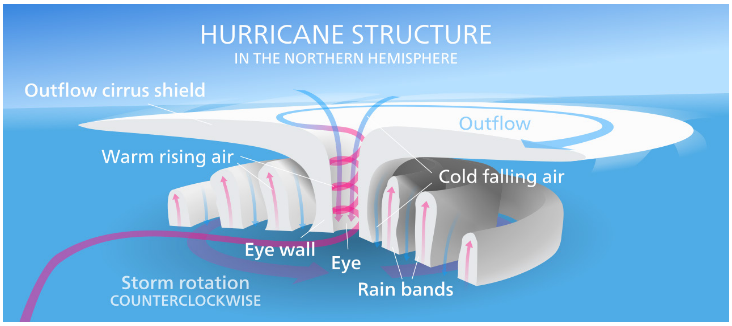
Coastal regions are particularly vulnerable to the impact of a tropical cyclone, compared to inland regions. The primary energy source for these storms is warm ocean waters, therefore these forms are typically strongest when over or near water, and weaken quite rapidly over land. Coastal damage may be caused by strong winds and rain, high waves (due to winds), storm surges (due to wind and severe pressure changes), and the potential of spawning tornadoes. Tropical cyclones also draw in air from a large area—which can be a vast area for the most severe cyclones—and concentrate the precipitation of the water content in that air (made up from atmospheric moisture and moisture evaporated from water) into a much smaller area. This continual replacement of moisture-bearing air by new moisture-bearing air after its moisture has fallen as rain, which may cause extremely heavy rain and river flooding up to 40 kilometres (25 mi) from the coastline, far beyond the amount of water that the local atmosphere holds at any one time.

Though their effects on human populations are often devastating, tropical cyclones can relieve drought conditions. They also carry heat energy away from the tropics and transport it toward temperate latitudes, which may play an important role in modulating regional and global climate.

Hurricane Isabel as seen from orbit during Expedition 7 of the International Space Station.The eye, eyewall, and surrounding rainbands, characteristics of tropical cyclones in the narrow sense,are clearly visible in this view from space.

Physical Structure

Northern Hemisphere Hurricane



Tropical cyclones are areas of relatively low pressure in the troposphere, with the largest pressure perturbations occurring at low altitudes near the surface. On Earth, the pressures recorded at the centers of tropical cyclones are among the lowest ever observed at sea level. The environment near the center of tropical cyclones is warmer than the surroundings at all altitudes, thus they are characterized as "warm core" systems.

Wind Field

The near-surface wind field of a tropical cyclone is characterized by air rotating rapidly around a center of circulation while also flowing radially inwards. At the outer edge of the storm, air may be nearly calm; however, due to the Earth's rotation, the air has non-zero absolute angular momentum. As air flows radially inward, it begins to rotate cyclonically (counter-clockwise in the Northern Hemisphere, and clockwise in the Southern Hemisphere) in order to conserve angular momentum. At an inner radius, air begins to ascend to the top of the troposphere. This radius is typically coincident with the inner radius of the eyewall, and has the strongest near-surface winds of the storm; consequently, it is known as the radius of maximum winds. Once aloft, air flows away from the storm's center, producing a shield of cirrus clouds.

The previously mentioned processes result in a wind field that is nearly axisymmetric: Wind speeds are low at the center, increase rapidly moving outwards to the radius of maximum winds, and then decay more gradually with radius to large radii. However, the wind field often exhibits additional spatial and temporal variability due to the effects of localized processes, such as thunderstorm activity and horizontal flow instabilities. In the vertical direction, winds are strongest near the surface and decay with height within the troposphere.

Eye and Center

Thunderstorm activity in the eyewall of Cyclone Bansi as seen from the International Space Station.

At the center of a mature tropical cyclone, air sinks rather than rises. For a sufficiently strong storm, air may sink over a layer deep enough to suppress cloud formation, thereby creating a clear "eye". Weather in the eye is normally calm and free of clouds, although the sea may be extremely violent. The eye is normally circular in shape, and is typically 30–65 km (19–40 mi) in diameter, though eyes as small as 3 km (1.9 mi) and as large as 370 km (230 mi) have been observed.

The cloudy outer edge of the eye is called the "eyewall". The eyewall typically expands outward with height, resembling an arena football stadium; this phenomenon is sometimes referred to as the "stadium effect". The eyewall is where the greatest wind speeds are found, air rises most rapidly, clouds reach to their highest altitude, and precipitation is the heaviest. The heaviest wind damage occurs where a tropical cyclone's eyewall passes over land.

In a weaker storm, the eye may be obscured by the central dense overcast, which is the upper-level cirrus shield that is associated with a concentrated area of strong thunderstorm activity near the center of a tropical cyclone.

The eyewall may vary over time in the form of eyewall replacement cycles, particularly in intense tropical cyclones. Outer rainbands can organize into an outer ring of thunderstorms that slowly moves inward, which is believed to rob the primary eyewall of moisture and angular momentum. When the primary eyewall weakens, the tropical cyclone weakens temporarily. The outer eyewall eventually replaces the primary one at the end of the cycle, at which time the storm may return to its original intensity.

Rapid Intensification

On occasion, tropical cyclones may undergo a process known as rapid intensification, a period in which the maximum sustained winds of a tropical cyclone increase by 30 knots within a 24-hour period. In order for rapid intensification to occur, several conditions must be in place. Water temperatures must be extremely high (near or above 30 °C, 86 °F), and water of this temperature must be sufficiently deep such that waves do not upwell cooler waters to the surface. Wind shear must be low; when wind shear is high, the convection and circulation in the cyclone will be disrupted. Usually, an anticyclone in the upper layers of the troposphere above the storm must be present as well—for extremely low surface pressures to develop, air must be rising very rapidly in the eyewall of the storm, and an upper-level anticyclone helps channel this air away from the cyclone efficiently.

Size

There are a variety of metrics commonly used to measure storm size. The most common metrics include the radius of maximum wind, the radius of 34-knot wind (i.e. gale force), the radius of outermost closed isobar (ROCI), and the radius of vanishing wind. An additional metric is the radius at which the cyclone's relative vorticity field decreases to $1\times10^{-5}\ s^{-1}$.

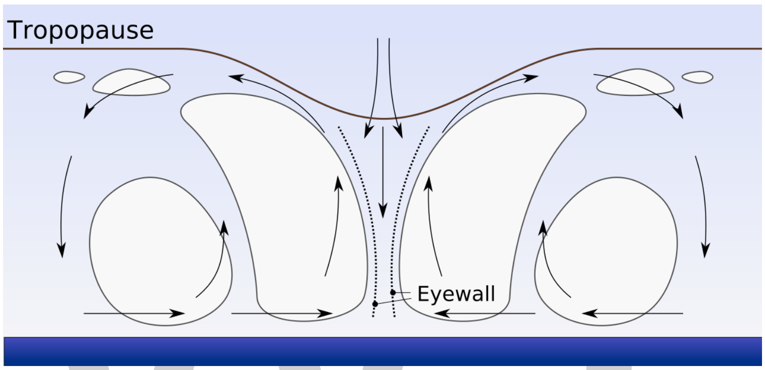
On Earth, tropical cyclones span a large range of sizes, from 100–2,000 kilometres (62–1,243 mi) as measured by the radius of vanishing wind. They are largest on average in the northwest Pacific Ocean basin and smallest in the northeastern Pacific Ocean basin. If the radius of outermost closed isobar is less than two degrees of latitude (222 km (138 mi)), then the cyclone is "very small" or a "midget". A radius of 3–6 latitude degrees (333–670 km (207–416 mi)) is considered "average sized". "Very large" tropical cyclones have a radius of greater than 8 degrees (888 km (552 mi)). Observations indicate that size is only weakly correlated to variables such as storm intensity (i.e. maximum wind speed), radius of maximum wind, latitude, and maximum potential intensity.

Size plays an important role in modulating damage caused by a storm. All else equal, a larger storm will impact a larger area for a longer period of time. Additionally, a larger near-surface wind field can generate higher storm surge due to the combination of longer wind fetch, longer duration, and enhanced wave setup.

The upper circulation of strong hurricanes extends into the tropopause of the atmosphere, which at low latitudes is 15,000–18,000 metres (50,000–60,000 ft).

Size descriptions of tropical cyclones	
ROCI (Diameter)	Type
Less than 2 degrees latitude	Very small/minor
2 to 3 degrees of latitude	Small
3 to 6 degrees of latitude	Medium/Average/Normal
6 to 8 degrees of latitude	Large
Over 8 degrees of latitude	Very large

Physics and Energetics



Tropical cyclones exhibit an overturning circulation where air inflows at low levels near the surface, rises in thunderstorm clouds, and outflows at high levels near the tropopause.

The three-dimensional wind field in a tropical cyclone can be separated into two components: a "primary circulation" and a "secondary circulation". The primary circulation is the rotational part of the flow; it is purely circular. The secondary circulation is the overturning (in-up-out-down) part of the flow; it is in the radial and vertical directions. The primary circulation is larger in magnitude, dominating the surface wind field, and is responsible for the majority of the damage a storm causes, while the secondary circulation is slower but governs the energetics of the storm.

Secondary Circulation: A Carnot Heat Engine

A tropical cyclone's primary energy source is heat from the evaporation of water from the surface of a warm ocean, previously heated by sunshine. The energetics of the system may be idealized as an atmospheric Carnot heat engine. First, inflowing air near the surface acquires heat primarily via evaporation of water (i.e. latent heat) at the temperature of the warm ocean surface (during evaporation, the ocean cools and the air warms). Second, the warmed air rises and cools within the eyewall while conserving total heat content (latent heat is simply converted to sensible heat during condensation). Third, air outflows and loses heat via infrared radiation to space at the temperature of the cold tropopause. Finally, air subsides and warms at the outer edge of the storm while conserving total heat content. The first and third legs are nearly isothermal, while the second and fourth legs are nearly isentropic. This in-up-out-down overturning flow is known as the secondary circulation. The Carnot perspective provides an upper bound on the maximum wind speed that a storm can attain.

Scientists estimate that a tropical cyclone releases heat energy at the rate of 50 to 200 exajoules (1018 J) per day, equivalent to about 1 PW (1015 watt). This rate of energy release is equivalent to 70 times the world energy consumption of humans and 200 times the worldwide electrical generating capacity, or to exploding a 10-megaton nuclear bomb every 20 minutes.

Primary Circulation: Rotating Winds

The primary rotating flow in a tropical cyclone results from the conservation of angular momentum by the secondary circulation. Absolute angular momentum on a rotating planet M is given by:

$$M = \frac{1}{2} fr^2 + vr$$

where f is the Coriolis parameter, v is the azimuthal (i.e. rotating) wind speed, and r is the radius to the axis of rotation. The first term on the right hand side is the component of planetary angular momentum that projects onto the local vertical (i.e. the axis of rotation). The second term on the right hand side is the relative angular momentum of the circulation itself with respect to the axis of rotation. Because the planetary angular momentum term vanishes at the equator (where $f = 0$), tropical cyclones rarely form within 5° of the equator.

As air flows radially inward at low levels, it begins to rotate cyclonically in order to conserve angular momentum. Similarly, as rapidly rotating air flows radially outward near the tropopause, its cyclonic rotation decreases and ultimately changes sign at large enough radius, resulting in an upper-level anti-cyclone. The result is a vertical structure characterized by a strong cyclone at low levels and a strong anti-cyclone near the tropopause; from thermal wind balance, this corresponds to a system that is warmer at its center than in the surrounding environment at all altitudes (i.e. "warm-core"). From hydrostatic balance, the warm core translates to lower pressure at the center at all altitudes, with the maximum pressure drop located at the surface.

Maximum Potential Intensity

Due to surface friction, the inflow only partially conserves angular momentum. Thus, the sea surface lower boundary acts as both a source (evaporation) and sink (friction) of energy for the system. This fact leads to the existence of a theoretical upper bound on the strongest wind speed that a tropical cyclone can attain. Because evaporation increases linearly with wind speed (just as climbing out of a pool feels much colder on a windy day), there is a positive feedback on energy input into the system known as the Wind-Induced Surface Heat Exchange (WISHE) feedback. This feedback is offset when frictional dissipation, which increases with the cube of the wind speed, becomes sufficiently large. This upper bound is called the "maximum potential intensity", v_p, and is given by:

$$v_p^2 = \frac{C_k}{C_d} \frac{T_s - T_o}{T_o} \Delta k$$

where T_s is the temperature of the sea surface, T_o is the temperature of the outflow ([K]), Δk is the enthalpy difference between the surface and the overlying air ([J/kg]), and C_k and C_d are the surface exchange coefficients (dimensionless) of enthalpy and momentum, respectively. The surface-air enthalpy difference is taken as $\Delta k = k_s^* - k$, where k_s^* is the saturation enthalpy of air at sea surface temperature and sea-level pressure and k is the enthalpy of boundary layer air overlying the surface.

The maximum potential intensity is predominantly a function of the background environment alone (i.e. without a tropical cyclone), and thus this quantity can be used to determine which regions on Earth can support tropical cyclones of a given intensity, and how these regions may evolve in time. Specifically, the maximum potential intensity has three components, but its variability in space and time is due predominantly to the variability in the surface-air enthalpy difference component Δk.

Derivation

A tropical cyclone may be viewed as a heat engine that converts input heat energy from the surface into mechanical energy that can be used to do mechanical work against surface friction. At equilibrium, the rate of net energy production in the system must equal the rate of energy loss due to frictional dissipation at the surface, i.e.

$$W_{in} = W_{out}$$

The rate of energy loss per unit surface area from surface friction, W_{out}, is given by:

$$W_{out} = C_{d\rho} |u|^3$$

where ρ is the density of near-surface air ([kg/m^3]) and | u | is the near surface wind speed ([m/s]).

The rate of energy production per unit surface area, W_{in} is given by:

$$W_{in} = \in Q_{in}$$

where ϵ is the heat engine efficiency and Q_{in} is the total rate of heat input into the system per unit surface area. Given that a tropical cyclone may be idealized as a Carnot heat engine, the Carnot heat engine efficiency is given by:

$$\epsilon = \frac{T_s - T_o}{T_s}$$

Heat (enthalpy) per unit mass is given by:

$$k = C_p T + L_v q$$

where C_p is the heat capacity of air, T is air temperature, L_v is the latent heat of vaporization, and q is the concentration of water vapor. The first component corresponds to sensible heat and the second to latent heat.

There are two sources of heat input. The dominant source is the input of heat at the surface, primarily due to evaporation. The bulk aerodynamic formula for the rate of heat input per unit area at the surface, $Q_{in:k}$, is given by:

$$Q_{in:k} = C_k \rho |u| \Delta k$$

where $\Delta k = k_s^* - k$ represents the enthalpy difference between the ocean surface and the overlying air. The second source is the internal sensible heat generated from frictional dissipation (equal to W_{out}), which occurs near the surface within the tropical cyclone and is recycled to the system.

$$Q_{in:friction} = C_{d\rho} |u|^3$$

Thus, the total rate of net energy production per unit surface area is given by:

$$W_{in} = \frac{T_s - T_o}{T_s}\left(C_{k\rho}|u|\Delta k + C_{d\rho}|u|^3\right)$$

Setting $W_{in} = W_{out}$ and taking $|\mathbf{u}| \approx v$ (i.e. the rotational wind speed is dominant) leads to the solution for v_p given above. This derivation assumes that total energy input and loss within the system can be approximated by their values at the radius of maximum wind. The inclusion of $Q_{in:friction}$ acts to multiply the total heat input rate by the factor $\frac{T_s}{T_o}$. Mathematically, this has the effect of replacing T_s with T_o in the denominator of the Carnot efficiency.

An alternative definition for the maximum potential intensity, which is mathematically equivalent to the above formulation is:

$$v_p = \sqrt{\frac{T_s}{T_o}\frac{C_k}{C_d}\left(CAPE_s^* - CAPE_b\right)\Big|_m}$$

where CAPE stands for the Convective Available Potential Energy, $CAPE_s^*$ is the CAPE of an air parcel lifted from saturation at sea level in reference to the environmental sounding, $CAPE_b$ is the CAPE of the boundary layer air, and both quantities are calculated at the radius of maximum wind.

Characteristic Values and Variability on Earth

On Earth, a characteristic temperature for T_s is 300 K and for T_o is 200 K, corresponding to a Carnot efficiency of $\epsilon = 1/3$. The ratio of the surface exchange coefficients, C_k / C_d, is typically taken to be 1. However, observations suggest that the drag coefficient C_d varies with wind speed and may decrease at high wind speeds within the boundary layer of a mature hurricane. Additionally, C_k may vary at high wind speeds due to the effect of sea spray on evaporation within the boundary layer.

A characteristic value of the maximum potential intensity, v_p, is 80 metres per second (180 mph; 290 km/h). However, this quantity varies significantly across space and time, particularly within the seasonal cycle, spanning a range of 0 to 100 metres per second (0 to 224 mph; 0 to 360 km/h). This variability is primarily due to variability in the surface enthalpy disequilibrium (Δk) as well as in the thermodynamic structure of the troposphere, which are controlled by the large-scale dynamics of the tropical climate. These processes are modulated by factors including the sea surface temperature (and underlying ocean dynamics), background near-surface wind speed, and the vertical structure of atmospheric radiative heating. The nature of this modulation is complex, particularly on climate time-scales (decades or longer). On shorter time-scales, variability in the maximum potential intensity is commonly linked to sea surface temperature perturbations from the tropical mean, as regions with relatively warm water have thermodynamic states much more capable of sustaining a tropical cyclone than regions with relatively cold water. However, this relationship is indirect via the large-scale dynamics of the tropics; the direct influence of the absolute sea surface temperature on v_p is weak in comparison.

Interaction with the Upper Ocean

The passage of a tropical cyclone over the ocean causes the upper layers of the ocean to cool substantially, which can influence subsequent cyclone development. This cooling is primarily caused by wind-driven mixing of cold water from deeper in the ocean with the warm surface waters. This effect results in a negative feedback process that can inhibit further development or lead to weakening. Additional cooling may come in the form of cold water from falling raindrops (this is because the atmosphere is cooler at higher altitudes). Cloud cover may also play a role in cooling the ocean, by shielding the ocean surface from direct sunlight before and slightly after the storm passage. All these effects can combine to produce a dramatic drop in sea surface temperature over a large area in just a few days. Coversely, the mixing of the sea can result in heat being inserted in deeper waters, with potential effects on global climate.

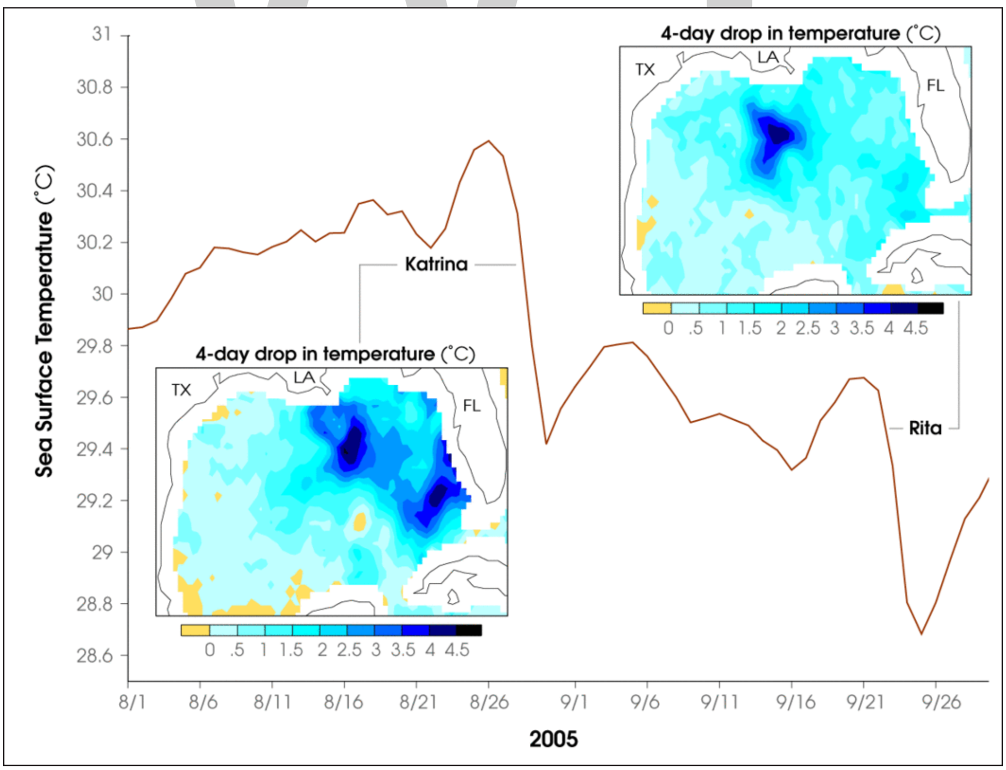
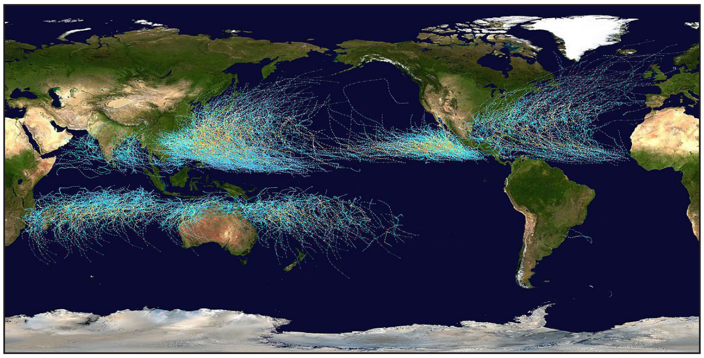
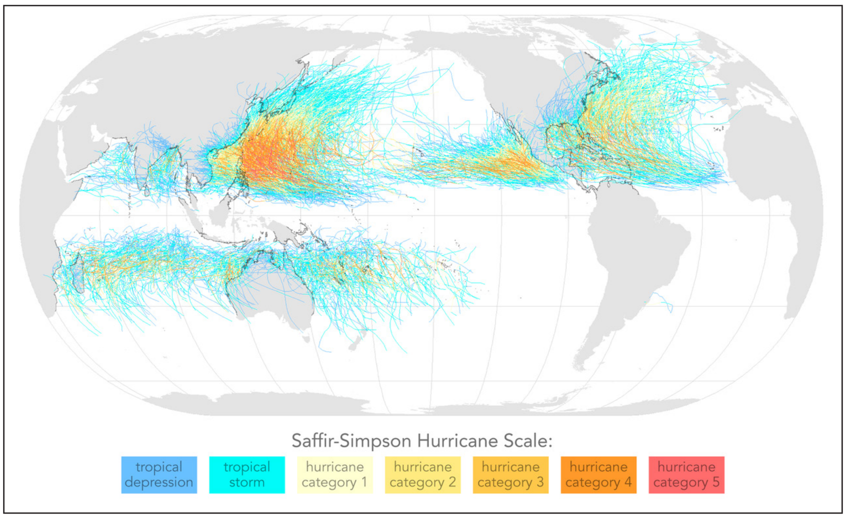


Chart displaying the drop in surface temperature in the Gulf of Mexico as HurricanesKatrina and Rita passed over.

Formation



Map of the cumulative tracks of all tropical cyclones during the 1985–2005 time period. The Pacific Ocean west of the International Date Line sees more tropical cyclones than any other basin, while there is almost no activity in the southern hemisphere between Africa and 160°W.



Map of all tropical cyclone tracks from 1945 to 2006. Equal-area projection.

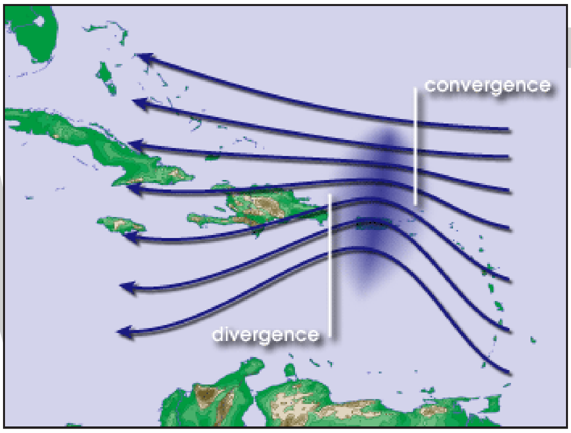
Worldwide, tropical cyclone activity peaks in late summer, when the difference between temperatures aloft and sea surface temperatures is the greatest. However, each particular basin has its own seasonal patterns. On a worldwide scale, May is the least active month, while September is the most active month. November is the only month in which all the tropical cyclone basins are in season.

Times

In the Northern Atlantic Ocean, a distinct cyclone season occurs from June 1 to November 30, sharply peaking from late August through September. The statistical peak of the Atlantic hurricane season is September 10. The Northeast Pacific Ocean has a broader period of activity, but in a similar time frame to the Atlantic. The Northwest Pacific sees tropical cyclones year-round, with a minimum in February and March and a peak in early September. In the North Indian ba-sin, storms are most common from April to December, with peaks in May and November. In the Southern Hemisphere, the tropical cyclone year begins on July 1 and runs all year-round encom passing the tropical cyclone seasons, which run from November 1 until the end of April, with peaks in mid-February to early March.

Season lengths and averages			
Basin	Season start	Season end	Tropical cyclones
North Atlantic	June 1	November 30	12.1
Eastern Pacific	May 15	November 30	16.6
Western Pacific	January 1	December 31	26.0
North Indian	January 1	December 31	4.8
South-West Indian	July 1	June 30	9.3
Australian region	November 1	April 30	11.0
Southern Pacific	November 1	April 30	7.1
Total:			86.9

Factors



Waves in the trade winds in the Atlantic Ocean—areas of converging winds that move along the same track as the prevailing wind—create instabilities in the atmosphere that may lead to the formation of hurricanes.

The formation of tropical cyclones is the topic of extensive ongoing research and is still not fully understood. While six factors appear to be generally necessary, tropical cyclones may occasionally form without meeting all of the following conditions. In most situations, water temperatures of at least 26.5 °C (79.7 °F) are needed down to a depth of at least 50 m (160 ft); waters of this temperature cause the overlying atmosphere to be unstable enough to sustain convection and thunderstorms. For tropical transitioning cyclones (i.e. Hurricane Ophelia (2017)) a water temperature of at least 22.5 °C (72.5 °F) has been suggested.

Another factor is rapid cooling with height, which allows the release of the heat of condensation that powers a tropical cyclone. High humidity is needed, especially in the lower-to-mid troposphere; when there is a great deal of moisture in the atmosphere, conditions are more favorable for disturbances to develop. Low amounts of wind shear are needed, as high shear is disruptive to the storm's circulation. Tropical cyclones generally need to form more than 555 km (345 mi) or five degrees of latitude away from the equator, allowing the Coriolis effect to deflect winds blowing towards the low pressure center and creating a circulation. Lastly, a formative tropical cyclone needs a preexisting system of disturbed weather. Tropical cyclones will not form spontaneously. Low-latitude and low-level westerly wind bursts associated with the Madden–Julian oscillation can create favorable conditions for tropical cyclogenesis by initiating tropical disturbances.

Locations

Most tropical cyclones form in a worldwide band of thunderstorm activity near the equator, referred to as the Intertropical Front (ITF), the Intertropical Convergence Zone (ITCZ), or the monsoon trough. Another important source of atmospheric instability is found in tropical waves, which contribute to the development of about 85% of intense tropical cyclones in the Atlantic Ocean and become most of the tropical cyclones in the Eastern Pacific. The majority forms between 10 and 30 degrees of latitude away of the equator, and 87% forms no farther away than 20 degrees north or south. Because the Coriolis effect initiates and maintains their rotation, tropical cyclones rarely form or move within 5 degrees of the equator, where the effect is weakest. However, it is still possible for tropical systems to form within this boundary as Tropical Storm Vamei and Cyclone Agni did in 2001 and 2004, respectively.

Movement

The movement of a tropical cyclone (i.e. its "track") is typically approximated as the sum of two terms: "steering" by the background environmental wind and "beta drift".

Environmental Steering

Environmental steering is the dominant term. Conceptually, it represents the movement of the storm due to prevailing winds and other wider environmental conditions, similar to "leaves carried along by a stream". Physically, the winds, or flow field, in the vicinity of a tropical cyclone may be treated as having two parts: the flow associated with the storm itself, and the large-scale background flow of the environment in which the storm takes place. In this way, tropical cyclone motion may be represented to first-order simply as advection of the storm by the local environmental flow. This environmental flow is termed the "steering flow".

Climatologically, tropical cyclones are steered primarily westward by the east-to-west trade winds on the equatorial side of the subtropical ridge—a persistent high-pressure area over the world's subtropical oceans. In the tropical North Atlantic and Northeast Pacific oceans, the trade winds steer tropical easterly waves westward from the African coast toward the Caribbean Sea, North America, and ultimately into the central Pacific Ocean before the waves dampen out. These waves are the precursors to many tropical cyclones within this region. In contrast, in the Indian Ocean and Western Pacific in both hemispheres, tropical cyclogenesis is influenced less by tropical easterly waves and more by the seasonal movement of the Inter-tropical Convergence Zone and the monsoon trough. Additionally, tropical cyclone motion can be influenced by transient weather systems, such as extratropical cyclones.

Beta Drift

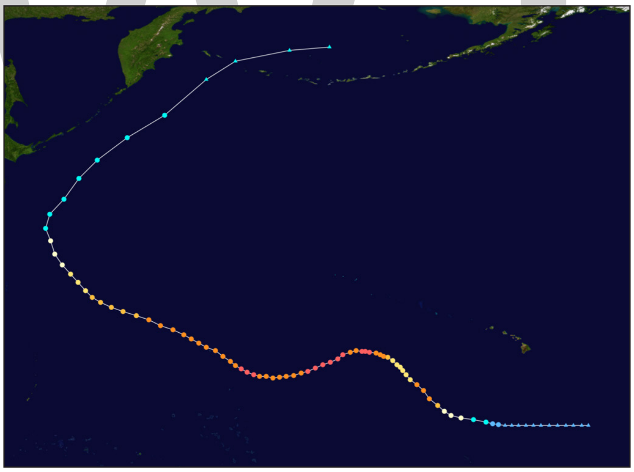
In addition to environmental steering, a tropical cyclone will tend to drift slowly poleward and westward, a motion known as "beta drift". This motion is due to the superposition of a vortex, such as a tropical cyclone, onto an environment in which the Coriolis force varies with latitude, such as on a sphere or beta plane. It is induced indirectly by the storm itself, the result of a feedback between the cyclonic flow of the storm and its environment.

Physically, the cyclonic circulation of the storm advects environmental air poleward east of center and equatorial west of center. Because air must conserve its angular momentum, this flow configuration induces a cyclonic gyre equatorward and westward of the storm center and an anticyclonic gyre poleward and eastward of the storm center. The combined flow of these gyres acts to advect the storm slowly poleward and westward. This effect occurs even if there is zero environmental flow.

Multiple Storm Interaction

A third component of motion that occurs relatively infrequently involves the interaction of multiple tropical cyclones. When two cyclones approach one another, their centers will begin orbiting cyclonically about a point between the two systems. Depending on their separation distance and strength, the two vortices may simply orbit around one another or else may spiral into the center point and merge. When the two vortices are of unequal size, the larger vortex will tend to dominate the interaction, and the smaller vortex will orbit around it. This phenomenon is called the Fujiwhara effect, after Sakuhei Fujiwhara.

Interaction with the Mid-Latitude Westerlies



Storm track of Typhoon Ioke, showing recurvature off the Japanese coast in 2006.

Though a tropical cyclone typically moves from east to west in the tropics, its track may shift poleward and eastward either as it moves west of the subtropical ridge axis or else if it interacts with the mid-latitude flow, such as the jet stream or an extratropical cyclone. This motion, termed "recurvature", commonly occurs near the western edge of the major ocean basins, where the jet stream typically has a poleward component and extratropical cyclones are common. An example of tropical cyclone recurvature was Typhoon Ioke in 2006.

Landfall

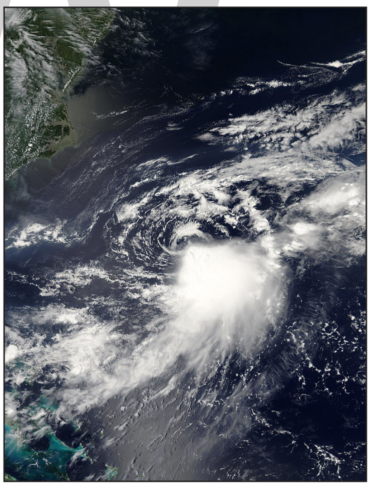
The landfall of a tropical cyclone occurs when a storm's surface center moves over a coastline. Storm conditions may be experienced on the coast and inland hours before landfall; in fact, a tropical cyclone can launch its strongest winds over land, yet not make landfall. NOAA uses the term "direct hit" to describe when a location (on the left side of the eye) falls within the radius of maximum winds (or twice that radius if on the right side), whether or not the hurricane's eye made landfall.

Changes Caused by El Niño–Southern Oscillation

Most tropical cyclones form on the side of the subtropical ridge closer to the equator, then move poleward past the ridge axis before recurving into the main belt of the Westerlies. When the subtropical ridge position shifts due to El Niño, so will the preferred tropical cyclone tracks. Areas west of Japan and Korea tend to experience much fewer September–November tropical cyclone impacts during El Niño and neutral years. During El Niño years, the break in the subtropical ridge tends to lie near 130°E which would favor the Japanese archipelago. During El Niño years, Guam's chance of a tropical cyclone impact is one-third more likely than of the long-term average. The tropical Atlantic Ocean experiences depressed activity due to increased vertical wind shear across the region during El Niño years. During La Niña years, the formation of tropical cyclones, along with the subtropical ridge position, shifts westward across the western Pacific Ocean, which increases the landfall threat to China and much greater intensity in the Philippines.

Dissipation

Factors



Tropical Storm Franklin, an example of a strongly sheared tropical cyclone in the NorthAtlantic hurricane basin during 2005.

A tropical cyclone can cease to have tropical characteristics in several different ways. One such way is if it moves over land, thus depriving it of the warm water it needs to power itself, quickly losing strength. Most strong storms lose their strength very rapidly after landfall and become disorganized areas of low pressure within a day or two, or evolve into extratropical cyclones. There is a chance a tropical cyclone could regenerate if it managed to get back over open warm water, such as with Hurricane Ivan. If it remains over mountains for even a short time, weakening will accelerate. Many storm fatalities occur in mountainous terrain, when diminishing cyclones unleash their moisture as torrential rainfall. This rainfall may lead to deadly floods and mudslides, as was the case with Hurricane Mitch around Honduras in October 1998. Without warm surface water, the storm cannot survive.

A tropical cyclone can dissipate when it moves over waters significantly below 26.5 °C (79.7 °F). This will cause the storm to lose its tropical characteristics, such as a warm core with thunderstorms near the center, and become a remnant low-pressure area. These remnant systems may persist for up to several days before losing their identity. This dissipation mechanism is most common in the eastern North Pacific. Weakening or dissipation can occur if it experiences vertical wind shear, causing the convection and heat engine to move away from the center; this normally ceases development of a tropical cyclone. In addition, its interaction with the main belt of the Westerlies, by means of merging with a nearby frontal zone, can cause tropical cyclones to evolve into extratropical cyclones. This transition can take 1–3 days. Even after a tropical cyclone is said to be extratropical or dissipated, it can still have tropical storm force (or occasionally hurricane/typhoon force) winds and drop several inches of rainfall. In the Pacific Ocean and Atlantic Ocean, such tropical-derived cyclones of higher latitudes can be violent and may occasionally remain at hurricane or typhoon-force wind speeds when they reach the west coast of North America. These phenomena can also affect Europe, where they are known as European windstorms; Hurricane Iris's extratropical remnants are an example of such a windstorm from 1995. A cyclone can also merge with another area of low pressure, becoming a larger area of low pressure. This can strengthen the resultant system, although it may no longer be a tropical cyclone. Studies in the 2000s have given rise to the hypothesis that large amounts of dust reduce the strength of tropical cyclones.

Effects

The aftermath of Hurricane Katrina in Gulfport, Mississippi.

Tropical cyclones out at sea cause large waves, heavy rain, flood and high winds, disrupting international shipping and, at times, causing shipwrecks. Tropical cyclones stir up water, leaving a cool wake behind them, which causes the region to be less favorable for subsequent tropical cyclones. On land, strong winds can damage or destroy vehicles, buildings, bridges, and other outside objects, turning loose debris into deadly flying projectiles. The storm surge, or the increase in sea level due to the cyclone, is typically the worst effect from landfalling tropical cyclones, historically resulting in 90% of tropical cyclone deaths. The broad rotation of a landfalling tropical cyclone, and vertical wind shear at its periphery, spawns tornadoes. Tornadoes can also be spawned as a result of eyewall mesovortices, which persist until landfall.

Over the past two centuries, tropical cyclones have been responsible for the deaths of about 1.9 million people worldwide. Large areas of standing water caused by flooding lead to infection, as well as contributing to mosquito-borne illnesses. Crowded evacuees in shelters increase the risk of disease propagation. Tropical cyclones significantly interrupt infrastructure, leading to power outages, bridge destruction, and the hampering of reconstruction efforts. On average, the Gulf and east coasts of the United States suffer approximately US$5 billion (1995 US $) in cyclone damage every year. The majority (83%) of tropical cyclone damage is caused by severe hurricanes, category 3 or greater. However, category 3 or greater hurricanes only account for about one-fifth of cyclones that make landfall every year.

Although cyclones take an enormous toll in lives and personal property, they may be important factors in the precipitation regimes of places they impact, as they may bring much-needed precipitation to otherwise dry regions. Tropical cyclones also help maintain the global heat balance by moving warm, moist tropical air to the middle latitudes and polar regions, and by regulating the thermohaline circulation through upwelling. The storm surge and winds of hurricanes may be destructive to human-made structures, but they also stir up the waters of coastal estuaries, which are typically important fish breeding locales. Tropical cyclone destruction spurs redevelopment, greatly increasing local property values.

When hurricanes surge upon shore from the ocean, salt is introduced to many freshwater areas and raises the salinity levels too high for some habitats to withstand. Some are able to cope with the salt and recycle it back into the ocean, but others can not release the extra surface water quickly enough or do not have a large enough freshwater source to replace it. Because of this, some species of plants and vegetation die due to the excess salt. In addition, hurricanes can carry toxins and acids onto shore when they make landfall. The flood water can pick up the toxins from different spills and contaminate the land that it passes over. The toxins are very harmful to the people and animals in the area, as well as the environment around them. The flooding water can also spark many dangerous oil spills.

Preparedness and Response

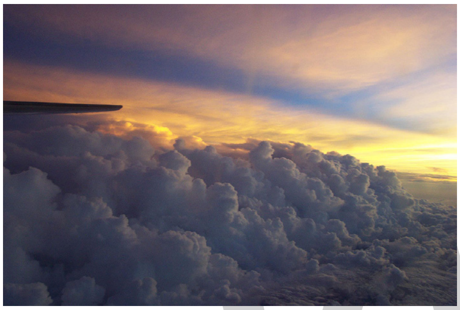
Hurricane preparedness encompasses the actions and planning taken before a tropical cyclone strikes to mitigate damage and injury from the storm. Knowledge of tropical cyclone impacts on an area help plan for future possibilities. Preparedness may involve preparations made by individuals as well as centralized efforts by governments or other organizations. Tracking storms during the tropical cyclone season helps individuals know current threats. Regional Specialized Meteorological Centers and Tropical Cyclone Warning Centers provide current information and forecasts to help individuals make the best decision possible.

Hurricane response is the disaster response after a hurricane. Activities performed by hurricane responders include assessment, restoration, and demolition of buildings; removal of debris and waste; repairs to land-based and maritime infrastructure; and public health services including search and rescue operations. Hurricane response requires coordination between federal, tribal, state, local, and private entities. According to the National Voluntary Organizations Active in Disaster, potential response volunteers should affiliate with established organizations and should not self-deploy, so that proper training and support can be provided to mitigate the danger and stress of response work.

Hurricane responders face many hazards. Hurricane responders may be exposed to chemical and biological contaminants including stored chemicals, sewage, human remains, and mold growth encouraged by flooding, as well as asbestos and lead that may be present in older buildings. Common injuries arise from falls from heights, such as from a ladder or from level surfaces; from electrocution in flooded areas, including from backfeed from portable generators; or from motor vehicle accidents. Long and irregular shifts may lead to sleep deprivation and fatigue, increasing the risk of injuries, and workers may experience mental stress associated with a traumatic incident. Additionally, heat stress is a concern as workers are often exposed to hot and humid temperatures, wear protective clothing and equipment, and have physically difficult tasks.

Observation and Forecasting

Observation



Sunset view of Hurricane Isidore's rainbands photographed at 7,000 feet (2,100 m).

"Hurricane Hunter" – WP-3D Orion is used to go into the eye of a hurricane for data collection and measurements purposes.

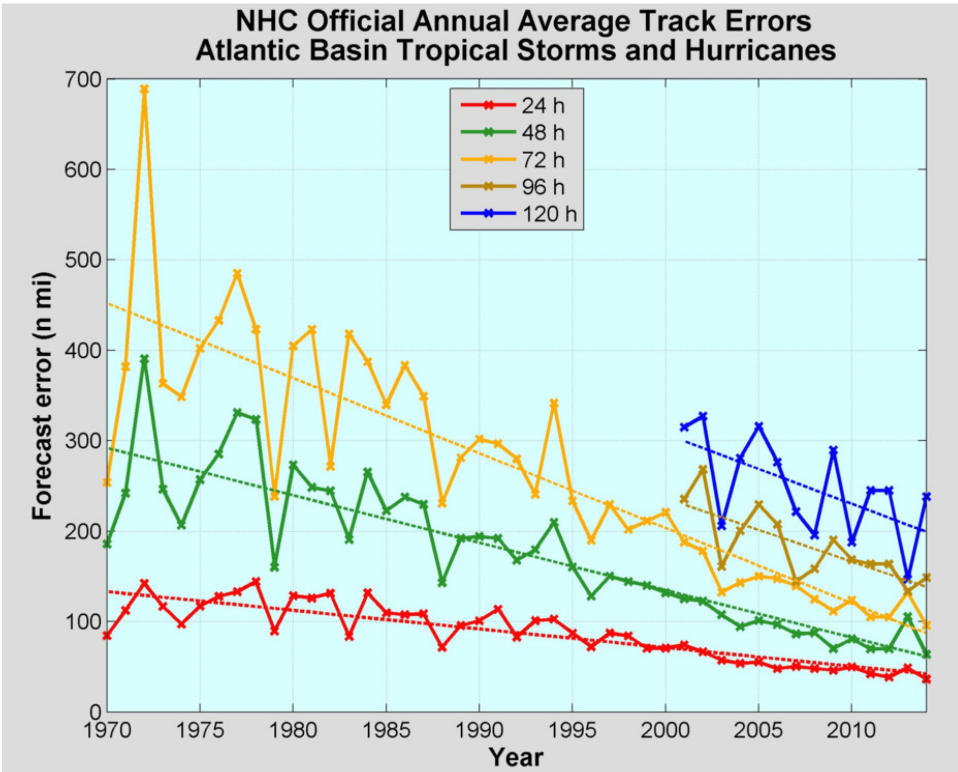
Intense tropical cyclones pose a particular observation challenge, as they are a dangerous oceanic phenomenon, and weather stations, being relatively sparse, are rarely available on the site of the storm itself. In general, surface observations are available only if the storm is passing over an island or a coastal area, or if there is a nearby ship. Real-time measurements are usually taken in the periphery of the cyclone, where conditions are less catastrophic and its true strength cannot be evaluated. For this reason, there are teams of meteorologists that move into the path of tropical cyclones to help evaluate their strength at the point of landfall.

Tropical cyclones far from land are tracked by weather satellites capturing visible and infrared images from space, usually at half-hour to quarter-hour intervals. As a storm approaches land, it can be observed by land-based Doppler weather radar. Radar plays a crucial role around landfall by showing a storm's location and intensity every several minutes.

In situ measurements, in real-time, can be taken by sending specially equipped reconnaissance flights into the cyclone. In the Atlantic basin, these flights are regularly flown by United States government hurricane hunters. The aircraft used are WC-130 Hercules and WP-3D Orions, both four-engine turboprop cargo aircraft. These aircraft fly directly into the cyclone and take direct and remote-sensing measurements. The aircraft also launch GPS dropsondes inside the cyclone. These sondes measure temperature, humidity, pressure, and especially winds between flight level and the ocean's surface. A new era in hurricane observation began when a remotely piloted Aerosonde, a small drone aircraft, was flown through Tropical Storm Ophelia as it passed Virginia's Eastern

Shore during the 2005 hurricane season. A similar mission was also completed successfully in the western Pacific Ocean. This demonstrated a new way to probe the storms at low altitudes that human pilots seldom dare.

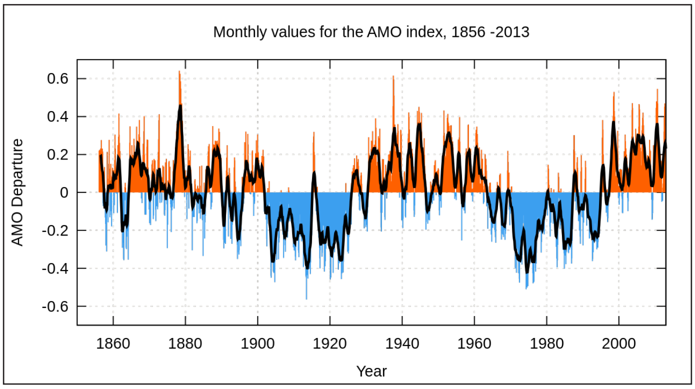
Forecasting



A general decrease in error trends in tropical cyclone path prediction is evident since the 1970s.

Because of the forces that affect tropical cyclone tracks, accurate track predictions depend on determining the position and strength of high- and low-pressure areas, and predicting how those areas will change during the life of a tropical system. The deep layer mean flow, or average wind through the depth of the troposphere, is considered the best tool in determining track direction and speed. If storms are significantly sheared, use of wind speed measurements at a lower altitude, such as at the 70 kPa pressure surface (3,000 metres or 9,800 feet above sea level) will produce better predictions. Tropical forecasters also consider smoothing out short-term wobbles of the storm as it allows them to determine a more accurate long-term trajectory. High-speed computers and sophisticated simulation software allow forecasters to produce computer models that predict tropical cyclone tracks based on the future position and strength of high- and low-pressure systems. Combining forecast models with increased understanding of the forces that act on tropical cyclones, as well as with a wealth of data from Earth-orbiting satellites and other sensors, scientists have increased the accuracy of track forecasts over recent decades. However, scientists are not as skillful at predicting the intensity of tropical cyclones. The lack of improvement in intensity forecasting is attributed to the complexity of tropical systems and an incomplete understanding of factors that affect their development. New tropical cyclone position and forecast information is available at least every six hours from the various warning centers.

Long-Term Activity Trends



Atlantic Multidecadal Oscillation Timeseries, 1856–2013.

While the number of storms in the Atlantic has increased since 1995, there is no obvious global trend; the annual number of tropical cyclones worldwide remains about 87 ± 10 (Between 77 and 97 tropical cyclones annually). However, the ability of climatologists to make long-term data analysis in certain basins is limited by the lack of reliable historical data in some basins, primarily in the Southern Hemisphere, while noting that a significant downward trend in tropical cyclone numbers has been identified for the region near Australia (based on high quality data and accounting for the influence of the El Niño-Southern Oscillation). In spite of that, there is some evidence that the intensity of hurricanes is increasing. Kerry Emanuel stated, "Records of hurricane activity worldwide show an upswing of both the maximum wind speed in and the duration of hurricanes. The energy released by the average hurricane (again considering all hurricanes worldwide) seems to have increased by around 70% in the past 30 years or so, corresponding to about a 15% increase in the maximum wind speed and a 60% increase in storm lifetime."

Atlantic storms are becoming more destructive financially, as evidenced by the fact that five of the ten most expensive storms in United States history have occurred since 1990. According to the World Meteorological Organization, "recent increase in societal impact from tropical cyclones has been caused largely by rising concentrations of population and infrastructure in coastal regions." Political scientist Pielke et al. normalized mainland US hurricane damage from 1900–2005 to 2005 values and found no remaining trend of increasing absolute damage. The 1970s and 1980s were notable because of the extremely low amounts of damage compared to other decades. The decade 1996–2005 was the second most damaging among the past 11 decades, with only the decade 1926–1935 surpassing its costs.

Often in part because of the threat of hurricanes, many coastal regions had sparse population between major ports until the advent of automobile tourism; therefore, the most severe portions of hurricanes striking the coast may have gone unmeasured in some instances. The combined effects of ship destruction and remote landfall severely limit the number of intense hurricanes in the official record before the era of hurricane reconnaissance aircraft and satellite meteorology. Although the record shows a distinct increase in the number and strength of intense hurricanes, therefore, experts regard the early data as suspect.

The number and strength of Atlantic hurricanes may undergo a 50–70 year cycle, also known as the Atlantic Multidecadal Oscillation. Nyberg et al. reconstructed Atlantic major hurricane activity back to the early 18th century and found five periods averaging 3–5 major hurricanes per year and lasting 40–60 years, and six other averaging 1.5–2.5 major hurricanes per year and lasting 10–20 years. These periods are associated with the Atlantic multidecadal oscillation. Throughout, a decadal oscillation related to solar irradiance was responsible for enhancing/dampening the number of major hurricanes by 1–2 per year.

Although more common since 1995, few above-normal hurricane seasons occurred during 1970–94. Destructive hurricanes struck frequently from 1926 to 1960, including many major New England hurricanes. Twenty-one Atlantic tropical storms formed in 1933, a record only recently exceeded in 2005, which saw 28 storms. Tropical hurricanes occurred infrequently during the seasons of 1900–25; however, many intense storms formed during 1870–99. During the 1887 season, 19 tropical storms formed, of which a record 4 occurred after November 1 and 11 strengthened into hurricanes. Few hurricanes occurred in the 1840s to 1860s; however, many struck in the early 19th century, including an 1821 storm that made a direct hit on New York City. Some historical weather experts say these storms may have been as high as Category 4 in strength.

These active hurricane seasons predated satellite coverage of the Atlantic basin. Before the satellite era began in 1960, tropical storms or hurricanes went undetected unless a reconnaissance aircraft encountered one, a ship reported a voyage through the storm, or a storm hit land in a populated area.

Proxy records based on paleotempestological research have revealed that major hurricane activity along the Gulf of Mexico coast varies on timescales of centuries to millennia. Few major hurricanes struck the Gulf coast during 3000–1400 BC and again during the most recent millennium. These quiescent intervals were separated by a hyperactive period during 1400 BC and 1000 AD, when the Gulf coast was struck frequently by catastrophic hurricanes and their landfall probabilities increased by 3–5 times. This millennial-scale variability has been attributed to long-term shifts in the position of the Azores High, which may also be linked to changes in the strength of the North Atlantic oscillation.

According to the Azores High hypothesis, an anti-phase pattern is expected to exist between the Gulf of Mexico coast and the Atlantic coast. During the quiescent periods, a more northeasterly position of the Azores High would result in more hurricanes being steered towards the Atlantic coast. During the hyperactive period, more hurricanes were steered towards the Gulf coast as the Azores High was shifted to a more southwesterly position near the Caribbean. Such a displacement of the Azores High is consistent with paleoclimatic evidence that shows an abrupt onset of a drier climate in Haiti around 3200 14C years BP, and a change towards more humid conditions in the Great Plains during the late-Holocene as more moisture was pumped up the Mississippi Valley through the Gulf coast. Preliminary data from the northern Atlantic coast seem to support the Azores High hypothesis. A 3000-year proxy record from a coastal lake in Cape Cod suggests that hurricane activity increased significantly during the past 500–1000 years, just as the Gulf coast was amid a quiescent period of the last millennium.

Tropical Cyclogenesis

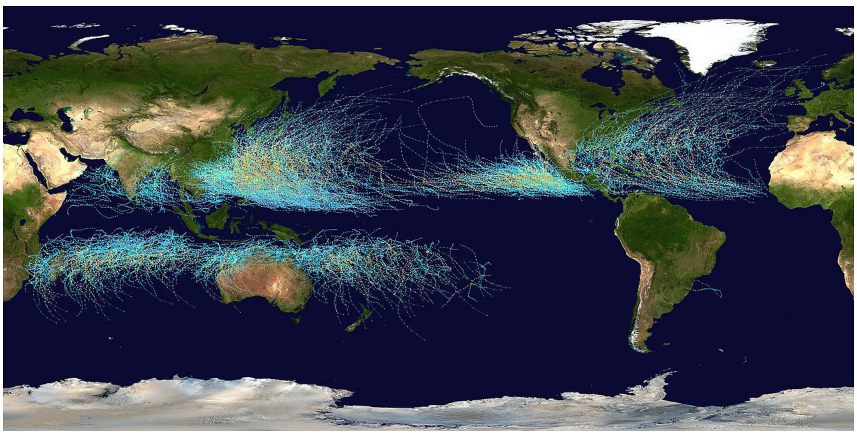
Tropical cyclogenesis is the development and strengthening of a tropical cyclone in the atmosphere.

The mechanisms through which tropical cyclogenesis occurs are distinctly different from those through which temperate cyclogenesis occurs. Tropical cyclogenesis involves the development of a warm-core cyclone, due to significant convection in a favorable atmospheric environment.

Tropical cyclogenesis requires six main factors: sufficiently warm sea surface temperatures (at least 26.5 °C (79.7 °F)), atmospheric instability, high humidity in the lower to middle levels of the troposphere, enough Coriolis force to develop a low-pressure center, a pre-existing low-level focus or disturbance, and low vertical wind shear.

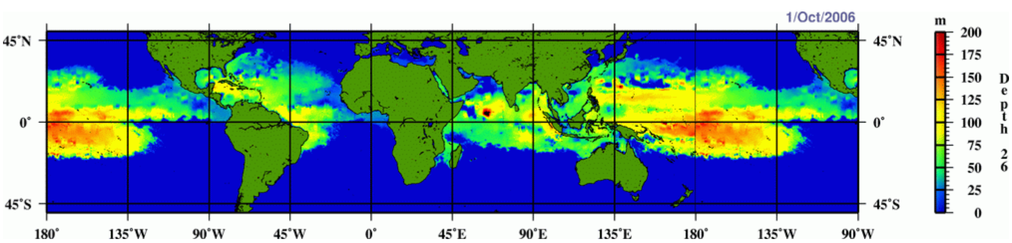
Tropical cyclones tend to develop during the summer, but have been noted in nearly every month in most basins. Climate cycles such as ENSO and the Madden–Julian oscillation modulate the timing and frequency of tropical cyclone development. There is a limit on tropical cyclone intensity which is strongly related to the water temperatures along its path.

An average of 86 tropical cyclones of tropical storm intensity form annually worldwide. Of those, 47 reach hurricane/typhoon strength, and 20 become intense tropical cyclones (at least Category 3 intensity on the Saffir–Simpson Hurricane Scale).



Global tropical cyclone tracks between 1985 and 2005, indicating the areas where tropicalcyclones usually develop.

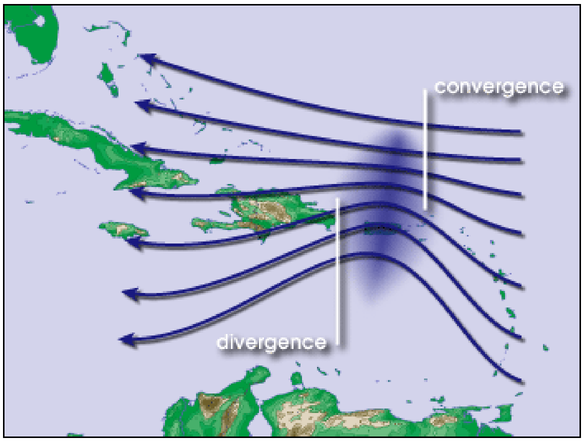
Requirements for Tropical Cyclone Formation



Depth of 26 °C isotherm on October 1, 2006.

There are six main requirements for tropical cyclogenesis: sufficiently warm sea surface temperatures, atmospheric instability, high humidity in the lower to middle levels of the troposphere, enough Coriolis force to sustain a low pressure center, a preexisting low level focus or disturbance, and low vertical wind shear. While these conditions are necessary for tropical cyclone formation, they do not guarantee that a tropical cyclone will form.

Warm Waters, Instability, and Mid-Level Moisture



Waves in the trade winds in the Atlantic Ocean—areas of converging winds that move slowly along thesame track as the prevailing wind—create instabilities in the atmosphere that may lead to theformation of hurricanes.

Normally, an ocean temperature of 26.5 °C (79.7 °F) spanning through at least a 50-metre depth is considered the minimum to maintain a tropical cyclone. These warm waters are needed to maintain the warm core that fuels tropical systems. This value is well above 16.1 °C (60.9 °F), the global average surface temperature of the oceans.

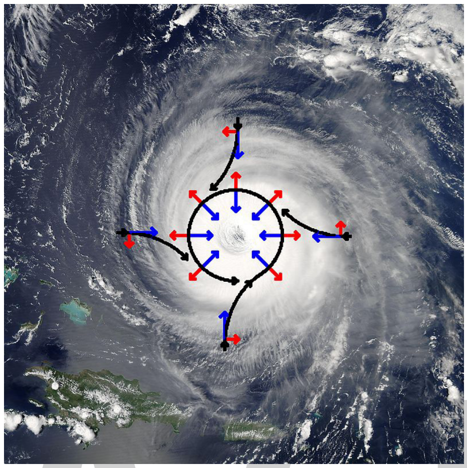
Tropical cyclones are known to form even when normal conditions are not met. For example, cooler air temperatures at a higher altitude (e.g., at the 500 hPa level, or 5.9 km) can lead to tropical cyclogenesis at lower water temperatures, as a certain lapse rate is required to force the atmosphere to be unstable enough for convection. In a moist atmosphere, this lapse rate is 6.5 °C/km, while in an atmosphere with less than 100% relative humidity, the required lapse rate is 9.8 °C/km.

At the 500 hPa level, the air temperature averages −7 °C (18 °F) within the tropics, but air in the tropics is normally dry at this level, giving the air room to wet-bulb, or cool as it moistens, to a more favorable temperature that can then support convection. A wetbulb temperature at 500 hPa in a tropical atmosphere of −13.2 °C is required to initiate convection if the water temperature is 26.5 °C, and this temperature requirement increases or decreases proportionally by 1 °C in the sea surface temperature for each 1 °C change at 500 hpa. Under a cold cyclone, 500 hPa temperatures can fall as low as −30 °C, which can initiate convection even in the driest atmospheres. This also explains why moisture in the mid-levels of the troposphere, roughly at the 500 hPa level, is normally a requirement for development. However, when dry air is found at the same height, temperatures at 500 hPa need to be even colder as dry atmospheres require a greater lapse rate for instability than moist atmospheres. At heights near the tropopause, the 30-year average temperature (as measured in the period encompassing 1961 through 1990) was −77 °C (−105 °F). A recent example of a tropical cyclone that maintained itself over cooler waters was Epsilon of the 2005 Atlantic hurricane season.

Role of Maximum Potential Intensity (MPI)

Kerry Emanuel created a mathematical model around 1988 to compute the upper limit of tropical cyclone intensity based on sea surface temperature and atmospheric profiles from the latest global model runs. Emanuel's model is called the maximum potential intensity, or MPI. Maps created from this equation show regions where tropical storm and hurricane formation is possible, based upon the thermodynamics of the atmosphere at the time of the last model run. This does not take into account vertical wind shear.

Coriolis Force



Schematic representation of flow around a low-pressure area (in this case, Hurricane Isabel) in the Northernhemisphere. The pressure gradient force is represented by blue arrows, the Coriolis acceleration(always perpendicular to the velocity) by red arrows.

A minimum distance of 500 km (310 mi) from the equator (about 4.5 degrees from the equator) is normally needed for tropical cyclogenesis. The Coriolis force imparts rotation on the flow and arises as winds begin to flow in toward the lower pressure created by the pre-existing disturbance. In areas with a very small or non-existent Coriolis force (e.g. near the Equator), the only significant atmospheric forces in play are the pressure gradient force (the pressure difference that causes winds to blow from high to low pressure) and a smaller friction force; these two alone would not cause the large-scale rotation required for tropical cyclogenesis. The existence of a significant Coriolis force allows the developing vortex to achieve gradient wind balance. This is a balance condition found in mature tropical cyclones that allows latent heat to concentrate near the storm core; this results in the maintenance or intensification of the vortex if other development factors are neutral.

Low Level Disturbance

Whether it be a depression in the intertropical covergence zone (ITCZ), a tropical wave, a broad surface front, or an outflow boundary, a low level feature with sufficient vorticity and convergence is required to begin tropical cyclogenesis. Even with perfect upper level conditions and the required atmospheric instability, the lack of a surface focus will prevent the development of organized convection and a surface low. Tropical cyclones can form when smaller circulations within the Intertropical Convergence Zone merge.

Weak Vertical Wind Shear

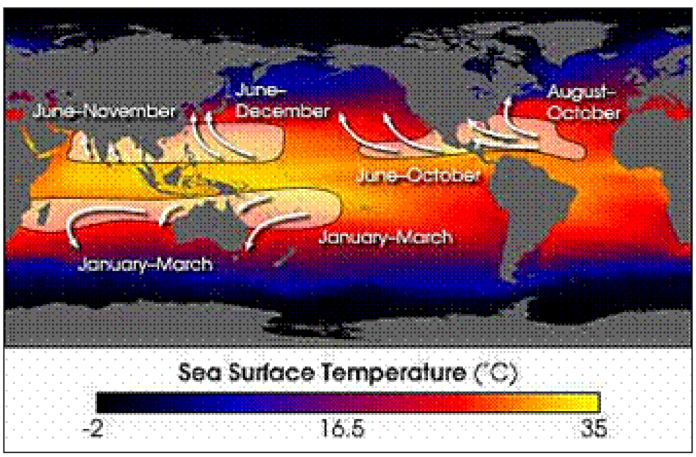
Vertical wind shear of less than 10 m/s (20 kt, 22 mph) between the surface and the tropopause is favored for tropical cyclone development. A weaker vertical shear makes the storm grow faster vertically into the air, which helps the storm develop and become stronger. If the vertical shear is too strong, the storm cannot rise to its full potential and its energy becomes spread out over too large of an area for the storm to strengthen. Strong wind shear can "blow" the tropical cyclone apart, as it displaces the mid-level warm core from the surface circulation and dries out the mid-levels of the troposphere, halting development. In smaller systems, the development of a significant mesoscale convective complex in a sheared environment can send out a large enough outflow boundary to destroy the surface cyclone. Moderate wind shear can lead to the initial development of the convective complex and surface low similar to the mid-latitudes, but it must relax to allow tropical cyclogenesis to continue.

Favorable Trough Interactions

Limited vertical wind shear can be positive for tropical cyclone formation. When an upper-level trough or upper-level low is roughly the same scale as the tropical disturbance, the system can be steered by the upper level system into an area with better diffluence aloft, which can cause further development. Weaker upper cyclones are better candidates for a favorable interaction. There is evidence that weakly sheared tropical cyclones initially develop more rapidly than non-sheared tropical cyclones, although this comes at the cost of a peak in intensity with much weaker wind speeds and higher minimum pressure. This process is also known as baroclinic initiation of a tropical cyclone. Trailing upper cyclones and upper troughs can cause additional outflow channels and aid in the intensification process. Developing tropical disturbances can help create or deepen upper troughs or upper lows in their wake due to the outflow jet emanating from the developing tropical disturbance/cyclone.

There are cases where large, mid-latitude troughs can help with tropical cyclogenesis when an upper-level jet stream passes to the northwest of the developing system, which will aid divergence aloft and inflow at the surface, spinning up the cyclone. This type of interaction is more often associated with disturbances already in the process of recurvature.

Times of Formation



Peaks of activity worldwide.

Worldwide, tropical cyclone activity peaks in late summer when water temperatures are warmest. Each basin, however, has its own seasonal patterns. On a worldwide scale, May is the least active month, while September is the most active.

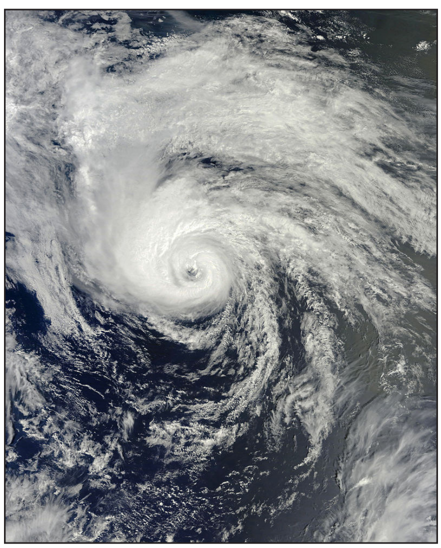
In the North Atlantic, a distinct hurricane season occurs from June 1 through November 30, sharply peaking from late August through October. The statistical peak of the North Atlantic hurricane season is September 10. The Northeast Pacific has a broader period of activity, but in a similar time frame to the Atlantic. The Northwest Pacific sees tropical cyclones year-round, with a minimum in February and a peak in early September. In the North Indian basin, storms are most common from April to December, with peaks in May and November.

In the Southern Hemisphere, tropical cyclone activity generally begins in early November and generally ends on April 30. Southern Hemisphere activity peaks in mid-February to early March. Virtually all the Southern Hemisphere activity is seen from the southern African coast eastward, toward South America. Tropical cyclones are rare events across the south Atlantic Ocean and the far southeastern Pacific Ocean.

Season lengths and averages			
Basin	Season start	Season end	Tropical cyclones
North Atlantic	June 1	November 30	12.1
Eastern Pacific	May 15	November 30	16.6
Western Pacific	January 1	December 31	26.0
North Indian	January 1	December 31	4.8
South-West Indian	July 1	June 30	9.3
Australian region	November 1	April 30	11.0
Southern Pacific	November 1	April 30	7.1
Total:			86.9

Unusual Areas of Formation

Middle Latitudes



Hurricane Chris formed in the temperate subtropics during the 2012 Atlantic season.

Areas farther than 30 degrees from the equator (except in the vicinity of a warm current) are not normally conducive to tropical cyclone formation or strengthening, and areas more than 40 degrees from the equator are often very hostile to such development. The primary limiting factor is water temperatures, although higher shear at increasing latitudes is also a factor. These areas are sometimes frequented by cyclones moving poleward from tropical latitudes. On rare occasions, such as Alex in 2004, Alberto in 1988, and the 1975 Pacific Northwest hurricane, storms may form or strengthen in this region. Typically, tropical cyclones will undergo extratropical transition after recurving polewards, and typically become fully extratropical after reaching 45–50˚ of latitude. The majority of extratropical cyclones tend to restrengthen after completing the transition period.

Near the Equator

Areas within approximately ten degrees latitude of the equator do not experience a significant Coriolis Force, a vital ingredient in tropical cyclone formation. However, a few tropical cyclones have been observed forming within five degrees of the equator.

South Atlantic

A combination of wind shear and a lack of tropical disturbances from the Intertropical Convergence Zone (ITCZ) makes it very difficult for the South Atlantic to support tropical activity. Over four tropical cyclones have been observed here such as— a weak tropical storm in 1991 off the coast of Africa near Angola, Hurricane Catarina, which made landfall in Brazil in 2004 at Category 2 strength, and a smaller storm in January 2004, east of Salvador, Brazil. The January storm is thought to have reached tropical storm intensity based on scatterometer wind measurements.

Mediterranean and Black Seas

Storms that appear similar to tropical cyclones in structure sometimes occur in the Mediterranean basin. Examples of these "Mediterranean tropical cyclones" formed in September 1947, September 1969, September 1973, August 1976, January 1982, September 1983, December 1984, December 1985, October 1994, January 1995, October 1996, September 1997, December 2005, September 2006, November 2011, November 2014, November 2017 and September 2018. However, there is debate on whether these storms were tropical in nature.

The Black Sea has, on occasion, produced or fueled storms that begin cyclonic rotation, and that appear to be similar to tropical-like cyclones observed in the Mediterranean.

Elsewhere

Tropical cyclogenesis is extremely rare in the far southeastern Pacific Ocean, due to the cold sea-surface temperatures generated by the Humboldt Current, and also due to unfavorable wind shear; as such, there are no records of a tropical cyclone impacting western South America. But in mid-2015, a rare subtropical cyclone was identified in early May relatively close to Chile. This system was unofficially dubbed Katie by researchers. Another subtropical cyclone was identified at 77.8 degrees longitude in May 2018, just off the coast of Chile.

Vortices have been reported off the coast of Morocco in the past. However, it is debatable if they are truly tropical in character.

Tropical activity is also extremely rare in the Great Lakes. However, a storm system that appeared similar to a subtropical or tropical cyclone formed in 1996 on Lake Huron. The system developed an eye-like structure in its center, and it may have briefly been a subtropical or tropical cyclone.

Influence of Large-Scale Climate Cycles

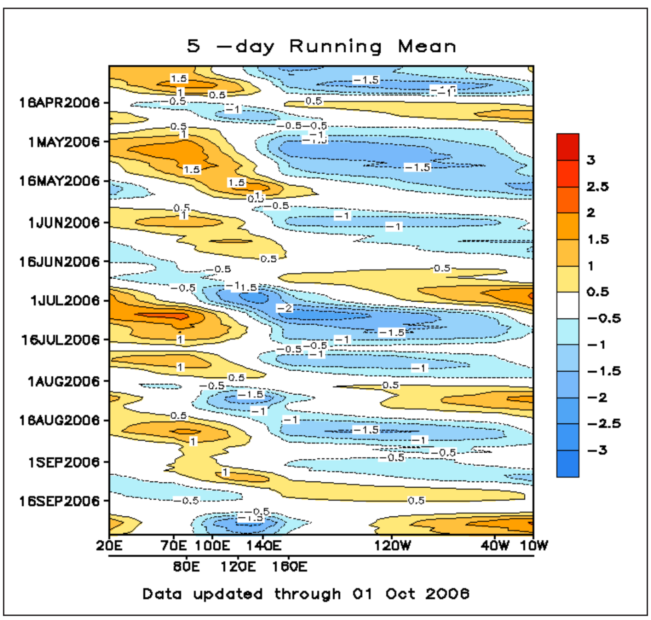
Influence of ENSO

El Niño (ENSO) shifts the region (warmer water, up and down welling at different locations, due to winds) in the Pacific and Atlantic where more storms form, resulting in nearly constant Accumulated Cyclone Energy (ACE) values in any one basin. The El Niño event typically decreases hurricane formation in the Atlantic, and far western Pacific and Australian regions, but instead increases the odds in the central North and South Pacific and particular in the western North Pacific typhoon region.

Tropical cyclones in the northeastern Pacific and north Atlantic basins are both generated in large part by tropical waves from the same wave train.

In the Northwestern Pacific, El Niño shifts the formation of tropical cyclones eastward. During El Niño episodes, tropical cyclones tend to form in the eastern part of the basin, between 150°E and the International Date Line (IDL). Coupled with an increase in activity in the North-Central Pacific (IDL to 140°W) and the South-Central Pacific (east of 160°E), there is a net increase in tropical cyclone development near the International Date Line on both sides of the equator. While there is no linear relationship between the strength of an El Niño and tropical cyclone formation in the Northwestern Pacific, typhoons forming during El Niño years tend to have a longer duration and higher intensities. Tropical cyclogenesis in the Northwestern Pacific is suppressed west of 150°E in the year following an El Niño event.

Influence of the MJO



5-day running mean of MJO. Note how it moves eastward with time.

In general, westerly wind increases associated with the Madden–Julian oscillation lead to increased tropical cyclogenesis in all basins. As the oscillation propagates from west to east, it leads to an eastward march in tropical cyclogenesis with time during that hemisphere's summer season. There is an inverse relationship between tropical cyclone activity in the western Pacific basin and the north Atlantic basin, however. When one basin is active, the other is normally quiet, and vice versa. The main cause appears to be the phase of the Madden–Julian oscillation, or MJO, which is normally in opposite modes between the two basins at any given time.

Influence of Equatorial Rossby Waves

Research has shown that trapped equatorial Rossby wave packets can increase the likelihood of tropical cyclogenesis in the Pacific Ocean, as they increase the low-level westerly winds within that region, which then leads to greater low-level vorticity. The individual waves can move at approximately 1.8 m/s (4 mph) each, though the group tends to remain stationary.

Subtropical Cyclone

A subtropical cyclone is a weather system that has some characteristics of a tropical and an extratropical cyclone.

As early as the 1950s, meteorologists were uncertain whether they should be characterized as tropical or extratropical cyclones. They were officially recognized by the National Hurricane Center in 1972. Beginning in 2002, subtropical cyclones received names from the official tropical cyclone lists in the North Atlantic, South-west Indian Ocean, and South Atlantic basins.

There are two definitions currently used for subtropical cyclones. Across the north Atlantic and southwest Indian Ocean, they require central convection fairly near the center and a warming core in the mid-levels of the troposphere. Across the eastern half of the northern Pacific, they require a mid-tropospheric cyclone to be cut off from the main belt of the westerlies and only a weak surface circulation. Subtropical cyclones have broad wind patterns with maximum sustained winds located farther from the center than typical tropical cyclones, and have no weather fronts linked into their center.

Subtropical Storm Leslie in September 2018.

Since they form from initially extratropical cyclones which have colder temperatures aloft than normally found in the tropics, the sea surface temperatures required for their formation are lower than the tropical cyclone threshold by 3°C (5°F), lying around 23 °C (73 °F). This also means that subtropical cyclones are more likely to form outside the traditional bounds of the North Atlantic hurricane season. Subtropical cyclones are also observed to form in the South Atlantic; South Atlantic subtropical cyclones are observed in all months.

Throughout the 1950s and 1960s, the term semi-tropical and quasi-tropical were used for what would become known as subtropical cyclones. The term subtropical cyclone merely referred to any cyclone located in the subtropical belt near and just north of the horse latitudes. Intense debate ensued in the late 1960s, after a number of hybrid cyclones formed in the Atlantic Basin. In 1972, the National Hurricane Center (NHC) finally designated these storms as subtropical cyclones in real-time, and updated the hurricane database to include subtropical cyclones from 1968 through 1971.

The term "neutercane" began to be used for small subtropical cyclones which formed from mesoscale features, and the NHC began issuing public statements during the 1972 Atlantic hurricane season employing that classification. This name was not noted as controversial in contemporary news reports, but it was dropped less than a year later.

Naming

Subtropical Storm Gustav in 2002, the first system to be given a name as a subtropical cyclone

In the North Atlantic basin, subtropical cyclones were initially named from the NATO phonetic alphabet list in the early to mid-1970s. In the intervening years of 1975–2001, subtropical storms were either named from the traditional list and considered tropical in real-time, or used a separate numbering system. Between 1992 and 2001, two different numbers were given to subtropical depressions or subtropical storms, one for public use, the other one for NRL and NHC reference. For example, Hurricane Karen in 2001 was initially known as Subtropical Storm One as well as AL1301 (or 13L for short). In 2002, the NHC began giving numbers to subtropical depressions and names to subtropical storms from the same sequence as tropical cyclones. From 2002 onward, Subtropical Depression 13L would be known as Subtropical Depression Thirteen instead. Hurricane Gustav of 2002 was the first Subtropical Storm to receive a name but became tropical shortly after naming. Subtropical Storm Nicole, from the 2004 Atlantic hurricane season was the first subtropical storm that did not become tropical since the policy change. A subtropical storm from the 2005 Atlantic hurricane season also did not become tropical, but was not named since it was not recognized until post-season analysis.

In the southern Indian Ocean, subtropical cyclones are also named once winds reach tropical storm, or gale, force.

Since 2011, subtropical storms in the western South Atlantic Ocean are named by the Brazilian Navy Hydrographic Center.

Formation

Subtropical cyclones form in a wide band of latitude, mainly south of the 50th parallel in the northern hemisphere. Due to the increased frequency of cyclones which cut off from the main belt of the westerlies during the summer and fall, subtropical cyclones are significantly more frequent across the North Atlantic than the northwestern Pacific Ocean. In the eastern half of the north Pacific Ocean and north Indian Ocean, the older subtropical cyclone definition term is still used, which requires a weak circulation forming underneath a mid to upper-tropospheric low which has cut off from the main belt of the westerlies during the cold season (winter). In the case of the north Indian Ocean, the formation of this type of vortex leads to the onset of monsoon rains during the wet season. In the southern hemisphere, subtropical cyclones are regularly observed across southern portions of the Mozambique Channel.

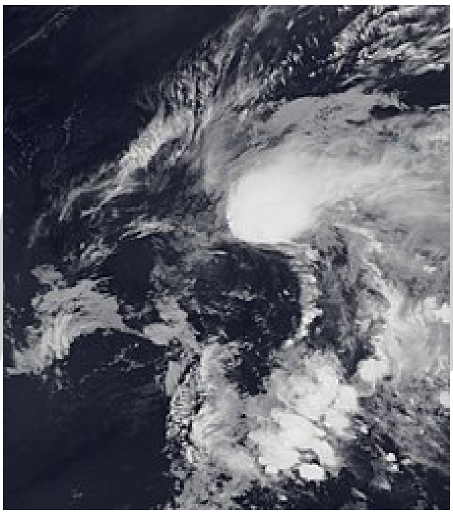
Most subtropical cyclones form when a deep cold-core extratropical cyclone drops down into the subtropics. The system becomes blocked by a high latitude ridge, and eventually sheds its frontal boundaries as its source of cool and dry air from the high latitudes diverts away from the system. Temperature differences between the 500 hPa pressure level, or 5,900 meters (19,400 ft) above ground level, and the sea surface temperatures initially exceed the dry adiabatic lapse rate, which causes an initial round of thunderstorms to form at a distance east of the center. Due to the initial cold temperatures aloft, sea surface temperatures usually need to reach at least 20 °C (68 °F) for this initial round of thunderstorms. The initial thunderstorm activity moistens up the environment around the low, which destabilizes the atmosphere by reducing the lapse rate needed for convection. When the next shortwave or upper level jet streak (wind maximum within the jet stream) moves nearby, convection reignites closer to the center and the system develops into a true subtropical cyclone. The average sea surface temperature that helps lead to subtropical cyclogenesis is 24 °C (75 °F). If the thunderstorm activity becomes deep and persistent, allowing its initial low level warm core to deepen, tropical cyclogenesis is possible. The locus of formation for North Atlantic subtropical cyclones is out in the open ocean; the island of Bermuda is regularly impacted by these systems.

The South Atlantic environment for formation of subtropical cyclones has both stronger vertical wind shear and lower sea surface temperatures, yet subtropical cyclogenesis is regularly observed in the open ocean in the South Atlantic. A second mechanism for formation has been diagnosed for South Atlantic subtropical cyclones: lee cyclogenesis in the region of the Brazil Current.

Transition from Extratropical

By gaining tropical characteristics, an extratropical low may transit into a subtropical depression or storm. A subtropical depression/storm may further gain tropical characteristics to become a pure tropical depression or storm, which may eventually develop into a hurricane, and there are at least ten cases of tropical cyclones transforming into a subtropical cyclone (Tropical Storm Gilda in 1973, Subtropical Storm Four in 1974, Tropical Storm Jose in 1981, Hurricane Klaus in 1984, Tropical Storm Allison in 2001, Tropical Storm Lee in 2011, Hurricane Humberto in 2013, Tropical Storm Ian in 2016, Typhoon Jelawat in 2018, and Tropical Storm Gaemi in 2018). There have also been two recorded cases of a storm transitioning from tropical to extratropical to a subtropical cyclone; as seen with Hurricane Georges in 1980 and Hurricane Beryl in 2018. Generally, a tropical storm or tropical depression is not called subtropical while it is becoming extratropical, after hitting either land or colder waters. This transition normally requires significant instability through the atmosphere, with temperature differences between the underlying ocean and the mid-levels of the troposphere requiring over 20 °C, or 72 °F, of contrast in this roughly 5,900 meters (19,400 ft) layer of the lower atmosphere. The mode of the sea surface temperatures that subtropical cyclones form over is 23 °C (73 °F). Transition from subtropical cyclones into tropical cyclones occurs only in very rare cases over the South Atlantic Ocean, such as Hurricane Catarina in 2004.

Characteristics



Subtropical Storm Andrea peaking as a weak subtropical cyclone on May 20, 2019.

These storms can have maximum winds extending farther from the center than in a purely tropical cyclone and have no weather fronts linking directly to the center of circulation. In the Atlantic Basin, the United States NOAA classifies subtropical cyclones similarly to their tropical cousins, based on maximum sustained surface winds. Those with winds below 18 m/s, (65 km/h, 35 knots, or 39 mph) are called subtropical depressions, while those at or above this speed are referred to as subtropical storms.

Subtropical cyclones with hurricane-force winds of 33 m/s, (119 km/h, 64 knots, or 74 mph) or greater are not officially recognized by the National Hurricane Center. Once a subtropical storm intensifies enough to have hurricane-force winds, it is then automatically assumed to have become a fully tropical hurricane. Despite this, however, prior to the start of modern policies, two subtropical cyclones in the Atlantic hurricane database attained hurricane-force winds; a subtropical storm in 1968, and a subtropical storm in 1979.

Subtropical cyclones are also more likely than tropical cyclones to form outside of a region's designated hurricane season. Recent North Atlantic examples of this include the following storms:

- Subtropical Storm Ana (which became Tropical Storm Ana) in late-April of the 2003 hurricane season.
- Subtropical Storm Andrea in early-May of the 2007 hurricane season.
- Subtropical Storm Olga (which became Tropical Storm Olga) in mid-December of the 2007 hurricane season.
- Subtropical Storm Beryl (which became Tropical Storm Beryl) in late-May of the 2012 hurricane season.
- An unnamed subtropical storm in early-December of the 2013 hurricane season.
- Subtropical Storm Ana (which became Tropical Storm Ana) in early-May of the 2015 hurricane season.
- Subtropical Storm Alex (which became Hurricane Alex) in mid-January of the 2016 hurricane season.
- Subtropical Depression One (which became Tropical Storm Arlene) in mid-April of the 2017 hurricane season.
- Subtropical Storm Alberto (which became Tropical Storm Alberto) in late-May of the 2018 Atlantic hurricane season.
- Subtropical Storm Andrea in late-May of the 2019 Atlantic hurricane season.

Diagrams which depict a cyclone's phase depict subtropical cyclones with a shallow warm core and as asymmetric systems, similar to tropical cyclones which have begun the transition to an extratropical cyclone.

Types

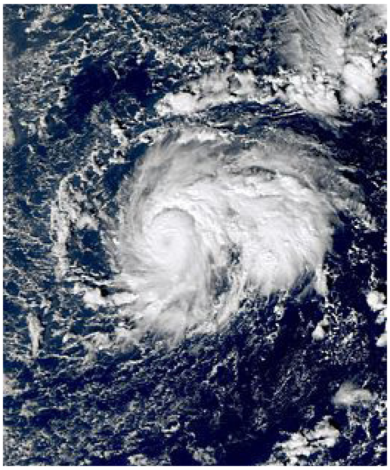
Upper-Level Low

The most common type of subtropical storm is an upper-level cold low with circulation extending to the surface layer and maximum sustained winds generally occurring at a radius of about 160 kilometers (99 mi) or more from the center. In comparison to tropical cyclones, such systems have a relatively broad zone of maximum winds that is located farther from the center, and typically have a less symmetric wind field and distribution of convection.

Mesoscale Low

A second type of subtropical cyclone is a mesoscale low originating in or near a frontolyzing zone of horizontal wind shear, also known as a dying frontal zone, with radius of maximum sustained winds generally less than 50 kilometers (31 mi). The entire circulation may initially have a diameter of less than 160 kilometers (99 mi). These generally short-lived systems may be either cold core or warm core, and in 1972 this type of subtropical cyclone was referred to as a "neutercane".

Kona Storm



A subtropical storm in December 2010, originally a Kona storm.

Kona storms (or Kona lows) are deep cyclones that form during the cool season of the central Pacific Ocean. A definition change in the term during the early 1970s makes categorization of the systems more complex, as many kona lows are extratropical cyclones, complete with their own weather fronts. Those across the northeast Pacific Ocean consider them subtropical cyclones as long as a weak surface circulation is present. Kona is a Hawaiian term for leeward, which explains the change in wind direction for the Hawaiian Islands from easterly to southerly when this type of cyclone is present

Australian East Coast Lows

An Australian East Coast Low in June 2013.

Australian east coast lows (known locally as east coast lows and sometimes as east coast cyclones) are extratropical cyclones, the most intense of these systems have many of the characteristics of subtropical cyclones. They develop between 25° south and 40° south and within 5° of the Australian coastline, typically during the winter months. Each year there are about ten "significant impact" maritime lows. Explosive cyclogenesis is seen on average just once per year, but these storms cause significant wind and flood damage when they occur. Australian east coast cyclones vary in size from mesoscale (approximately 10 km to 100 km) to synoptic scale (approximately 100 km to 1,000 km). These storms which mostly affect the south east coast should not be confused with Australian region tropical cyclones which typically affect the northern half of the continent.

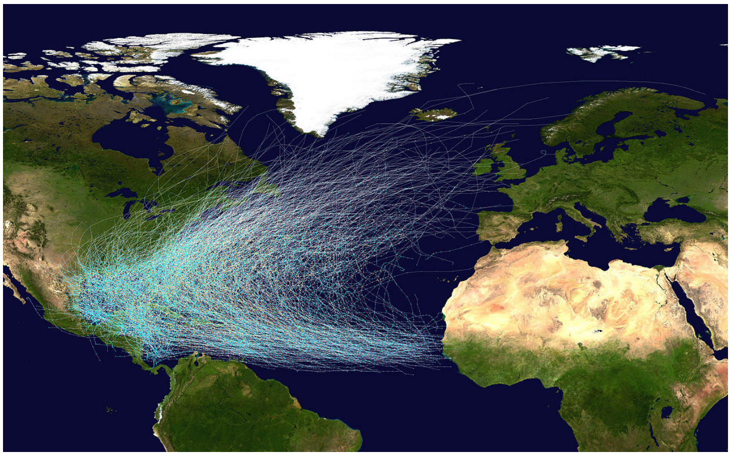
ATLANTIC HURRICANE

An Atlantic hurricane or tropical storm is a tropical cyclone that forms in the Atlantic Ocean, usually between the months of June and November. A hurricane differs from a cyclone or typhoon only on the basis of location. A hurricane is a storm that occurs in the Atlantic Ocean and northeastern Pacific Ocean, a typhoon occurs in the northwestern Pacific Ocean, and a cyclone occurs in the south Pacific or Indian Ocean.

Tropical cyclones can be categorized by intensity. Tropical storms have one-minute maximum sustained winds of at least 39 mph (34 knots, 17 m/s, 63 km/h), while hurricanes have one-minute maximum sustained winds exceeding 74 mph (64 knots, 33 m/s, 119 km/h). Most North Atlantic tropical storms and hurricanes form between June 1 and November 30. The United States National Hurricane Center monitors the basin and issues reports, watches, and warnings about tropical weather systems for the North Atlantic Basin as one of the Regional Specialized Meteorological Centers for tropical cyclones, as defined by the World Meteorological Organization.

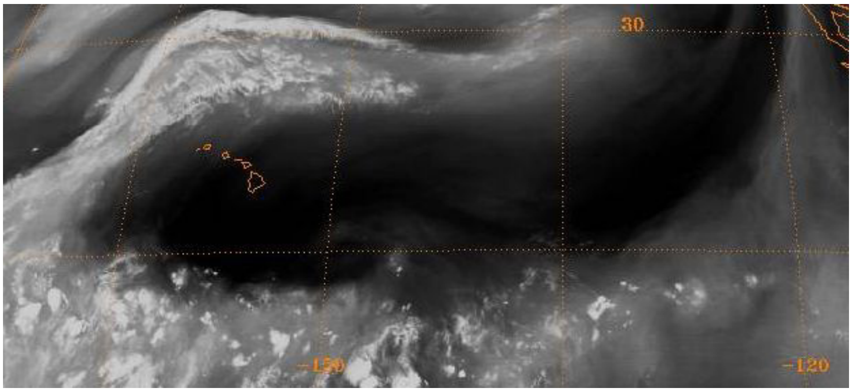
In recent times, tropical disturbances that reach tropical storm intensity are named from a predetermined list. Hurricanes that result in significant damage or casualties may have their names retired from the list at the request of the affected nations in order to prevent confusion should a subsequent storm be given the same name. On average, in the North Atlantic basin (from 1966 to 2009) 11.3 named storms occur each season, with an average of 6.2 becoming hurricanes and 2.3 becoming major hurricanes (Category 3 or greater). The climatological peak of activity is around September 10 each season.

In March 2004, Catarina was the first hurricane-intensity tropical cyclone ever recorded in the Southern Atlantic Ocean. Since 2011, the Brazilian Navy Hydrographic Center has started to use the same scale of the North Atlantic Ocean for tropical cyclones in the South Atlantic Ocean and assign names to those which reach 35 kn (65 km/h; 40 mph).



Tracks of North Atlantic tropical cyclones.

Steering Factors



The subtropical ridge (in the Pacific) shows up as a large area of black (dryness) on this water vapor satellite image from September 2000.

Tropical cyclones are steered by the surrounding flow throughout the depth of the troposphere (the atmosphere from the surface to about eight miles (12 km) high). Neil Frank, former director of the United States National Hurricane Center, used the analogies such as “a leaf carried along in a stream” or a “brick moving through a river of air” to describe the way atmospheric flow affects the path of a hurricane across the ocean. Specifically, air flow around high pressure systems and toward low pressure areas influences hurricane tracks.

In the tropical latitudes, tropical storms and hurricanes generally move westward with a slight tendency toward the north, under the influence of the subtropical ridge, a high pressure system that usually extends east-west across the subtropics. South of the subtropical ridge, surface easterly winds (blowing from east to west) prevail. If the subtropical ridge is weakened by an upper trough, a tropical cyclone may turn poleward and then recurve, or curve back toward the northeast into the main belt of the Westerlies. Poleward (north) of the subtropical ridge, westerly winds prevail and generally steer tropical cyclones that reach northern latitudes toward the east. The westerlies also steer extratropical cyclones with their cold and warm fronts from west to east.

Intensity

Generally speaking, the intensity of a tropical cyclone is determined by either the storm’s maximum sustained winds or lowest barometric pressure. The following table lists the most intense Atlantic hurricanes in terms of their lowest barometric pressure. In terms of wind speed, Hurricane Allen (in 1980) was the strongest Atlantic tropical cyclone on record, with maximum sustained winds of 190 mph (305 km/h). However, these measurements are suspect since instrumentation used to document wind speeds at the time would likely succumb to winds of such intensity. Nonetheless, their central pressures are low enough to rank them among the strongest recorded Atlantic hurricanes.

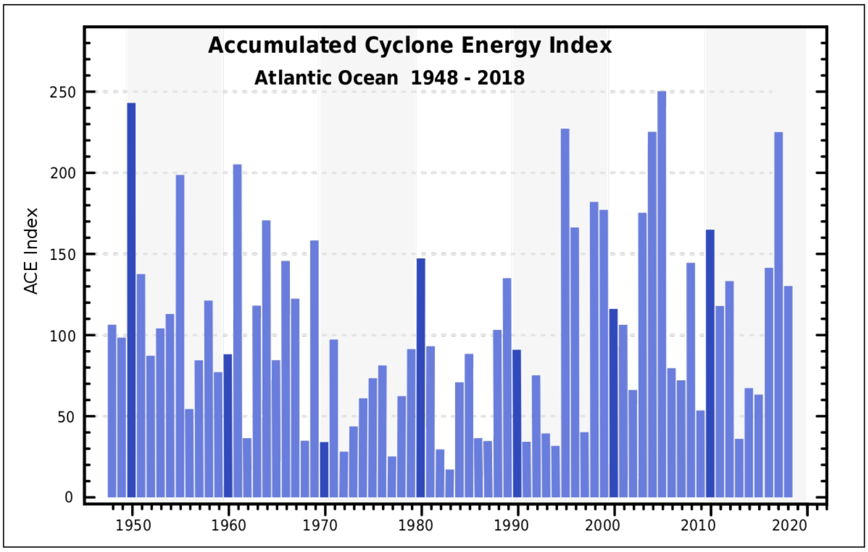
Owing to their intensity, the strongest Atlantic hurricanes have all attained Category 5 classification. Hurricane Opal, the strongest Category 4 hurricane recorded, intensified to reach a minimum pressure of 916 mbar (hPa; 27.05 inHg), a pressure typical of Category 5 hurricanes. Nonetheless, the pressure remains too high to list Opal as one of the ten strongest Atlantic tropical cyclones. Presently, Hurricane Wilma is the strongest Atlantic hurricane ever recorded, after reaching an intensity of 882 mbar (hPa; 26.05 inHg) in October 2005; this also made Wilma the strongest tropical cyclone worldwide outside of the West Pacific, where seven tropical cyclones have been recorded to intensify to lower pressures. However, this was later superseded by Hurricane Patricia in 2015 in the east Pacific, which had a pressure reading of 872 mbar. Preceding Wilma is Hurricane Gilbert, which had also held the record for most intense Atlantic hurricane for 17 years. The 1935 Labor Day hurricane, with a pressure of 892 mbar (hPa; 26.34 inHg), is the third strongest Atlantic hurricane and the strongest documented tropical cyclone prior to 1950. Since the measurements taken during Wilma and Gilbert were documented using dropsonde, this pressure remains the lowest measured over land.

Hurricane Rita is the fourth strongest Atlantic hurricane in terms of barometric pressure and one of three tropical cyclones from 2005 on the list, with the others being Wilma and Katrina at first and seventh respectively. However, with a barometric pressure of 895 mbar (hPa; 26.43 inHg), Rita is the strongest tropical cyclone ever recorded in the Gulf of Mexico. Mitch and Dean share intensities for the eighth strongest Atlantic hurricane at 905 mbar (hPa; 26.73 inHg). The tenth place for most intense Atlantic tropical cyclone is Hurricane Maria listed to have deepened to a pressure as low as 908 mbar (hPa; 26.81 inHg).

Many of the strongest recorded tropical cyclones weakened prior to their eventual landfall or demise. However, three of the storms remained intense enough at landfall to be considered some of the strongest landfalling hurricanes – three of the eleven hurricanes on the list constitute the three most intense Atlantic landfalls in recorded history. The 1935 Labor Day hurricane made landfall at peak intensity, making it the most intense Atlantic landfall. Though it weakened slightly before its eventual landfall on the Yucatán Peninsula, Hurricane Gilbert maintained a pressure of 900 mbar (hPa; 26.58 inHg) at landfall, as did Camille, making their landfalls tied as the second strongest. Similarly, Hurricane Dean made landfall on the peninsula, though it did so at peak intensity and with a higher barometric pressure; its landfall marked the fourth strongest in Atlantic hurricane history.

Most intense Atlantic hurricanes				
Rank	Hurricane	Season	Pressure	
			hPa	inHg
1	Wilma	2005	882	26.05
2	Gilbert	1988	888	26.23
3	"Labor Day"	1935	892	26.34
4	Rita	2005	895	26.43
5	Allen	1980	899	26.55
6	Camille	1969	900	26.58
7	Katrina	2005	902	26.64
8	Mitch	1998	905	26.73
	Dean	2007		
10	Maria	2017	908	26.81

Trends



Atlantic Accumulated Cyclone Energy (ACE) index from NOAA.

While the number of storms in the Atlantic has increased since 1995, there is no obvious global trend. The annual number of tropical cyclones worldwide remains about 87 ± 10. However, the ability of climatologists to make long-term data analysis in certain basins is limited by the lack of reliable historical data in some basins, primarily in the Southern Hemisphere. In spite of that, there is some evidence that the intensity of hurricanes is increasing. In 2006, Kerry Emanuel stated, "Records of hurricane activity worldwide show an upswing of both the maximum wind speed in and the duration of hurricanes. The energy released by the average hurricane (again considering all hurricanes worldwide) seems to have increased by around 70% in the past 30 years or so, corresponding to about a 15% increase in the maximum wind speed and a 60% increase in storm lifetime." At the time, Emanuel theorized that increased heat from global warming was driving this trend, however, some argue that Emanuel's own research in 2008 refuted this theory. Others contend that the trend does not exist at all, but instead is a figment created by faulty readings from primitive 1970s-era measurement equipment. Vecchi and Knutson (2008) found a weakly positive, although not statistically-significant trend in the number of North Atlantic tropical cyclones for 1878–2006, but also a surprisingly strong decrease in cyclone duration over this period.

On May 15, 2014, the journal Nature published a peer-reviewed submission from October 2013 by James P. Kossin, Kerry A. Emanuel, and Gabriel A. Vecchi that suggests that a poleward migration exists for the paths of maximum intensity of tropical cyclone activity in the Atlantic. The focus of the report is on the latitude at which recent tropical cyclones in the Atlantic are reaching maximum intensity. Their data indicates that during the past thirty years, the peak intensity of these storms has shifted poleward in both hemispheres at a rate of approximately 60 km per decade, amounting to approximately one degree of latitude per decade.

Atlantic storms are becoming more destructive financially, since five of the ten most expensive storms in United States history have occurred since 1990. According to the World Meteorological Organization, "recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions." Pielke et al. normalized mainland U.S. hurricane damage from 1900–2005 to 2005 values and found no remaining trend of increasing absolute damage. The 1970s and 1980s were notable because of the extremely low amounts of damage compared to other decades. The decade 1996–2005 has the second most damage among the past 11 decades, with only the decade 1926–1935 surpassing its costs. The most damaging single storm is the 1926 Miami hurricane, with $157 billion of normalized damage.

Often in part because of the threat of hurricanes, many coastal regions had sparse population between major ports until the advent of automobile tourism; therefore, the most severe portions of hurricanes striking the coast may have gone unmeasured in some instances. The combined effects of ship destruction and remote landfall severely limit the number of intense hurricanes in the official record before the era of hurricane reconnaissance aircraft and satellite meteorology. Although the record shows a distinct increase in the number and strength of intense hurricanes, therefore, experts regard the early data as suspect. Christopher Landsea et al. estimated an undercount bias of zero to six tropical cyclones per year between 1851 and 1885 and zero to four per year between 1886 and 1910. These undercounts roughly take into account the typical size of tropical cyclones, the density of shipping tracks over the Atlantic basin, and the amount of populated coastline.

The number and strength of Atlantic hurricanes may undergo a 50–70 year cycle, also known as the Atlantic Multidecadal Oscillation. Nyberg et al. reconstructed Atlantic major hurricane activity back to the early eighteenth century and found five periods averaging 3–5 major hurricanes per year and lasting 40–60 years, and six other averaging 1.5–2.5 major hurricanes per year and lasting 10–20 years. These periods are associated with the Atlantic multidecadal oscillation. Throughout, a decadal oscillation related to solar irradiance was responsible for enhancing/dampening the number of major hurricanes by 1–2 per year.

Although more uncommon since 1995, few above-normal hurricane seasons occurred during 1970–94. Destructive hurricanes struck frequently from 1926–60, including many major New England hurricanes. Twenty-one Atlantic tropical storms formed in 1933, a record only recently exceeded in 2005, which saw 28 storms. Tropical hurricanes occurred infrequently during the seasons of 1900–25; however, many intense storms formed during 1870–99. During the 1887 season, 19 tropical storms formed, of which a record 4 occurred after November 1 and 11 strengthened into hurricanes. Few hurricanes occurred in the 1840s to 1860s; however, many struck in the early 19th century, including an 1821 storm that made a direct hit on New York City. Some historical weather experts say these storms may have been as high as Category 4 in strength.

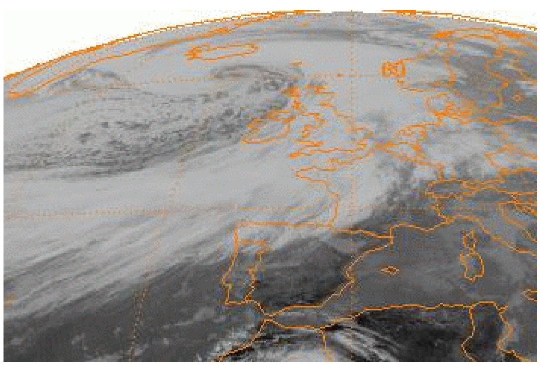
These active hurricane seasons predated satellite coverage of the Atlantic basin. Before the satellite era began in 1960, tropical storms or hurricanes went undetected unless a reconnaissance aircraft encountered one, a ship reported a voyage through the storm, or a storm landed in a populated area. The official record, therefore, could miss storms in which no ship experienced gale-force winds, recognized it as a tropical storm (as opposed to a high-latitude extra-tropical cyclone, a tropical wave, or a brief squall), returned to port, and reported the experience.

Proxy records based on paleotempestological research have revealed that major hurricane activity along the Gulf of Mexico coast varies on timescales of centuries to millennia. Few major hurricanes struck the Gulf coast during 3000–1400 BC and again during the most recent millennium. These quiescent intervals were separated by a hyperactive period during 1400 BC and 1000 AD, when the Gulf coast was struck frequently by catastrophic hurricanes and their landfall probabilities increased by 3–5 times. This millennial-scale variability has been attributed to long-term shifts in the position of the Azores High, which may also be linked to changes in the strength of the North Atlantic Oscillation.

According to the Azores High hypothesis, an anti-phase pattern is expected to exist between the Gulf of Mexico coast and the Atlantic coast. During the quiescent periods, a more northeasterly position of the Azores High would result in more hurricanes being steered towards the Atlantic coast. During the hyperactive period, more hurricanes were steered towards the Gulf coast as the Azores High was shifted to a more southwesterly position near the Caribbean. Such a displacement of the Azores High is consistent with paleoclimatic evidence that shows an abrupt onset of a drier climate in Haiti around 3200 14C years BP, and a change towards more humid conditions in the Great Plains during the late-Holocene as more moisture was pumped up the Mississippi Valley through the Gulf coast. Preliminary data from the northern Atlantic coast seem to support the Azores High hypothesis. A 3,000-year proxy record from a coastal lake in Cape Cod suggests that hurricane activity increased significantly during the past 500–1000 years, just as the Gulf Coast was amid a quiescent period during the last millennium. Evidence also shows that the average latitude of hurricane impacts has been steadily shifting northward, towards the Eastern Seaboard over the past few centuries. This change has been sped up in modern times due to the Arctic Ocean heating up especially much from fossil fuel-caused global warming.

EXPLOSIVE CYCLOGENESIS

Explosive cyclogenesis (also referred to as a weather bomb, meteorological bomb, explosive development, bomb cyclone or bombogenesis) is the rapid deepening of an extratropical cyclonic low-pressure area. The change in pressure needed to classify something as explosive cyclogenesis is latitude dependent. For example, at 60° latitude, explosive cyclogenesis occurs if the central pressure decreases by 24 mbar (hPa) or more in 24 hours. This is a predominantly maritime, winter event, but also occurs in continental settings, even in the summer. This process is the extra-tropical equivalent of the tropical rapid deepening. Although their cyclogenesis is totally different from that of tropical cyclones, bombs can produce winds of 74–95 mph, the same order as the first categories of the Saffir-Simpson scale and give heavy precipitation. Even though only a minority of the bombs become so strong, some have caused significant damage.

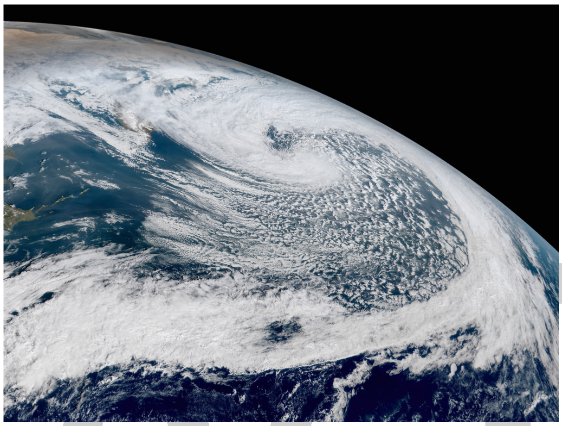


The Braer Storm of January 1993 explosively deepened to a record low of 914 mbar (hPa).

Formation

Baroclinic instability has been cited as one of the principal mechanisms for the development of most explosively deepening cyclones. However, the relative roles of baroclinic and diabatic processes in explosive deepening of extratropical cyclones have been subject to debate (citing case studies) for a long time. Other factors include the relative position of a 500-hPa trough and thickness patterns, deep tropospheric frontogenetic processes which happen both upstream and downstream of the surface low, the influence of air–sea interaction, and latent heat release.

Regions and Motion



Absorbing the remnants of a powerful tropical cyclone can trigger explosive cyclogenesis.

The four most active regions where extratropical explosive cyclogenesis occurs in the world are the Northwest Pacific, the North Atlantic, the Southwest Pacific, and the South Atlantic.

In the Northern Hemisphere the maximum frequency of explosively deepening cyclones is found within or to the north of the Atlantic Gulf Stream and Kuroshio Current in the western Pacific, and in the Southern Hemisphere it is found with Australian east coast lows above the East Australian Current, which shows the importance of air-sea interaction in initiating and rapidly developing extratropical cyclones.

Explosively deepening cyclones south of 50°S often show equator-ward movement, in contrast with the poleward motion of most Northern Hemisphere bombs. Over the year, 45 cyclones on average in the Northern Hemisphere and 26 in the Southern Hemisphere develop explosively, mostly in the respective hemisphere's winter time. Less seasonality has been noticed in bomb cyclogenesis occurrences in the Southern Hemisphere.

DROUGHT

Drought is an extended period of unusually dry weather when there is not enough rain. The lack of precipitation can cause a variety of problems for local communities, including damage to crops and a shortage of drinking water. These effects can lead to devastating economic and social disasters, such as famine, forced migration away from drought-stricken areas, and conflict over remaining resources.

Because the full effects of a drought can develop slowly over time, impacts can be underestimated. However, drought can have drastic and long-term effects on vegetation, animals, and people. Since 1900, more than 11 million people have died and more than 2 billion people have been affected by drought. Drought is also one of the costliest weather-related disasters. Since 2014 California has lost at least 2 billion-dollars a year, due to drought.

Drought is a complicated phenomenon, and can be hard to define. One difficulty is that drought means different things in different regions. A drought is defined depending on the average amount of precipitation that an area is accustomed to receiving.

For example, in Atlanta, Georgia, the average rainfall is about 127 centimeters (50 inches) a year. If significantly less rain falls, there may be water shortages and a drought may be declared. However, some arid regions, such as the deserts of the American Southwest, may receive less than about 25 centimeters (10 inches) of rainfall in a non-drought year. A drought in Atlanta could be a very wet period in Phoenix, Arizona.

Determining the start of a drought can be tricky. Unlike many natural hazards that bring about sudden and dramatic results—such as earthquakes, tornadoes, and hurricanes—the onset of a drought can be gradual and subtle. It can take weeks, months, or even years for the full effects of long-term inadequate rainfall to become apparent.

The end of a drought can also be difficult to determine. While a single rainstorm will provide short-term relief from a drought, it might take weeks or months before levels of precipitation return to normal. The start and end of a drought are often only clear in hindsight.

Causes of Drought

Most droughts occur when regular weather patterns are interrupted, causing disruption to the water cycle. Changes in atmospheric circulation patterns can cause storm tracks to be stalled for months or years. This disruption can dramatically impact amounts of precipitation that a region normally receives. Changes in wind patterns can also be disruptive to how moisture is absorbed in various regions.

Scientists have found a link between certain climate patterns and drought. El Niño is a weather event where the surface water in the Pacific Ocean along the central South American coast rises in temperature. These warmer waters alter storm patterns and are associated with droughts in Indonesia, Australia, and northeastern South America. El Nino events keep climate scientists guessing, by occurring every two to seven years.

La Niña is the counterpart to El Niño, when the surface water in the Pacific Ocean along the coast of South America decreases in temperature. The cooler waters affect storm patterns by contributing to drier-than-normal conditions in parts of North and South America. El Niño and La Niña both usually last about a year. The effects of La Niña on weather patterns are often more complex than El Niño. Two of the most devastating droughts in the history of the United States—the 1930s Dust Bowl and the 1988 drought in the Midwest—are associated with the effects of La Niña.

There is still a lot of debate about the connection between drought and global warming, the current period of climate change. A 2013 NASA study predicts warmer worldwide temperatures will mean increased rainfall in some parts of the world and decreased rainfall in others, leading to both more flooding and more droughts worldwide. Other scientists question the prediction that there will be more droughts and believe global warming will create a wetter climate around the world.

Impacts of Drought

Trees and other plants have adapted to withstand the effects of drought through various survival methods. Some plants (such as grasses) will slow their growth or turn brown to conserve water. Trees can drop their leaves earlier in the season to prevent losing water through the leaf surface. However, if drought conditions persist, much vegetation will die.

Certain plants have adapted so they can withstand long periods without water. Yuccas, for instance, have deep root systems that can seek out water with incredible efficiency. Cacti have spiny, hairy spines, spikes, or leaves that limit how much water they lose to evaporation. Mosses can withstand complete dehydration. Juniper trees can self-prune by steering water only toward the branches required for survival. Other plants only grow when there is enough water to support them. In periods of drought, their seeds can survive under the soil for years until conditions are favorable again.

However, many organisms cannot adapt to drought conditions, and the environmental effects of extended, unusual periods of low precipitation can be severe. Negative impacts include damage to habitats, loss of biodiversity, soil erosion, and an increased risk from wildfires. During the U.S. drought of 1988, rainfall in many states was 50 to 85 percent below normal. Summer thunderstorms produced lightning without rain and ignited fires in dry trees. In Yellowstone National Park 36 percent of the park was destroyed by fire.

Drought can also create significant economic and social problems. The lack of rain can result in crop loss, a decrease in land prices, and unemployment due to declines in production. As water levels in rivers and lakes fall, water-supply problems can develop. These can bring about other social problems. Many of these problems are health-related, such as lack of water, poor nutrition, and famine. Other problems include conflicts over water usage and food, and forced migration away from drought-stricken areas.

While drought is a naturally occurring part of the weather cycle and cannot be prevented, human activity can influence the effects that drought has on a region. Many modern agricultural practices may make land more vulnerable to drought. While new irrigation techniques have increased the amount of land that can be used for farming, they have also increased farmers' dependence on water.

Traditional agricultural techniques allow land to "rest" by rotating crops each season and alternating areas where livestock graze. Now, with many areas in the world struggling with overpopulation and a shortage of farmland, there is often not enough arable land to support sustainable practices. Over-farming and overgrazing can lead to soil being compacted and unable to hold water. As the soil becomes drier, it is vulnerable to erosion. This process can lead to fertile land becoming desert-like, a process known as desertification. The desertification of the Sahel in North Africa is partly blamed on a prolonged drought whose effects were intensified by farming practices that result in overgrazing.

Increased drought conditions in Kenya have been attributed to deforestation and other human activities. Trees help bring precipitation into the ground and prevent soil erosion. But in 2009, it was reported that one-quarter of a protected forest reserve had been cleared for farming and logging, leading to drought conditions affecting 10 million people around the country.

Forecasting and Measuring Drought

Even though scientists are unable to predict how long a drought will last or how severe it will be, early warning systems and monitoring tools can minimize some of drought's damaging impacts. There are a number of tools used to monitor drought across the U.S. Due to the limitations of each system, data from different sources are often compiled to create a more comprehensive forecast.

The Palmer Drought Severity Index (PDSI), developed in 1965 by the National Weather Service, is the most commonly used drought monitor. It is a complex measurement system and an effective way to forecast long-term drought. Its limitations are that it does not provide early warnings for drought and is not as accurate for use in mountainous areas because it does not account for snow (only rain) as precipitation. The PDSI is often used by the U.S. Department of Agriculture to determine when to begin providing drought relief.

Information from the Standardized Precipitation Index (SPI) is often used to supplement the PDSI data. The SPI, developed in 1993, is less complex than the PDSI and only measures precipitation—not evaporation or water runoff. Many scientists prefer using the SPI because the time period being analyzed can easily be customized. The SPI can also identify droughts many months earlier than the PDSI. The National Drought Mitigation Center uses the SPI to monitor drought conditions around the U.S.

The U.S. Drought Monitor, started in 1999, is a joint effort between three U.S. government agencies—the Department of Agriculture, the Department of Commerce, and the National Oceanic and Atmospheric Administration (NOAA). The Monitor synthesizes data from academic and federal scientists into a weekly map indicating levels of dryness around the country. It is designed to be a blend of science and art that can be used as a general summary of drought conditions around the country. It is not meant to be used as a drought predictor or for detailed information about specific areas.

The Famine Early Warning System Network (FEWS NET) monitors satellite data of crops and rainfall across Africa and some parts of Central America, the Middle East, and Central Asia. Analysis of the data allows for early intervention to try to prevent drought-induced famine.

Preparing for Drought

People and governments need to adopt new practices and policies to prepare as much as possible for inevitable future droughts. Emergency spending once a crisis has begun is less effective than money spent in preparation. The Federal Emergency Management Agency (FEMA) estimates that every $1 spent in planning for a natural hazard will save $4 in the long term.

Many areas are extremely vulnerable to drought as people continue to be dependent on a steady supply of water. The U.S. Department of Agriculture recommends a series of conservation practices to help farmers prepare for drought. Some preventative measures include installing an efficient irrigation system that reduces the amount of water lost to evaporation, storing water in ditches along fields, regularly monitoring soil moisture, planting crops that are more drought-resistant, and rotating crops to allow water in the soil to increase.

In urban areas, many cities are promoting water conservation by addressing water usage habits. Some enforce water restrictions, such as limiting days when lawns and plants can be watered, and offering free high-efficiency toilets and kitchen faucets.

A cracked, parched landscape is often an effect of drought.

Some drought-ravaged cities are taking even more extreme measures to prepare for future droughts. In Australia, the city of Perth is planning for a massive wastewater-recycling program that will eventually provide up to a quarter of the city's water demands by 2060. Perth has been dealing with a decline in rainfall since the mid 1970s. The city, which is on the edge of a huge desert, is also struggling with its history of over-consumption of water. Water-hungry traditions such as planting large, lush lawns and parks will need to be addressed through conservation measures.

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Geologic Hazards

3 CHAPTER

Geologic hazards refer to the geologic conditions which can cause loss of life and property. Such hazards include avalanche, earthquake, volcanic eruptions, landslides, etc. The topics elaborated in this chapter will help in gaining a better perspective of such geologic hazards.

AVALANCHE

On any slope, the snow is piled up and supported by a snow-pack. It keeps the snow from tumbling down all the time. Avalanches occur when the snow-pack starts to weaken and allows the buildup of snow to be released. Small avalanches are generally made up of ice, snow and air. The larger ones comprise of rocks, trees, debris and even mud that is resting on the lower slopes. Contrary to belief, these snow slides are not random events that occur without any warning signs. Winter season is when they are most common, often brought on after a large storm in the area. Rainfall and sleet also tend to be responsible for avalanches in the summer and monsoon season.

Types of Avalanches

To help in understanding of avalanches, they have been classified into four types:

1. Loose Snow Avalanches: First of these are the Loose Snow Avalanches. They are common on steep slopes and are seen after a fresh snowfall. Since the snow does not have time to settle down fully or has been made loose by sunlight, the snow-pack is not very solid. Such avalanches have a single point of origin, from where they widen as they travel down the slope.

2. Slab Avalanches: Loose Snow Avalanches in turn could cause a Slab Avalanche, which are characterized by a the fall of a large block of ice down the slopes. Thin slabs cause fairly small amounts of damage, while the thick ones are responsible for many fatalities.

3. Powder Snow Avalanches: Powder Snow Avalanches are a mix of the other forms, Loose Snow and Slab. The bottom half of this avalanche consists of a slab or a dense concentration of snow, ice and air. Above this is a cloud of powdered snow, which can snowball into a larger avalanche as it progresses down the slope. The speed attained by this avalanche can cross 190 miles per hour and they can cross large distances.

4. Wet Snow Avalanches: Finally, there are Wet Snow Avalanches. These are quite dangerous as they travel slowly due to friction, which collects debris from the path fairly easily. The avalanche comprises of water and snow at the beginning, but understanding of avalanches has showed us that it can pick up speed with ease.

Causes of Avalanches

There is no one reason behind the development of avalanches. It was believed for long that the echo of a human voice in the mountains could dislodge enough snow to start one. Similarly, a person's weight can cause a avalanche too. The sudden addition of weight can fracture a weak area of snow. However, scientific understanding of avalanches shows us that there are many environmental factors at work.

1. Snowstorm and Wind Direction: Heavy snowstorms are more likely to cause Avalanches. The 24 hours after a storm are considered to be the most critical. Wind normally blows from one side of the slope of mountain to another side. While blowing up, it will scour snow off the surface which can overhang a mountain.

2. Heavy snowfall: Heavy snowfall is the first, since it deposits snow in unstable areas and puts pressure on the snow-pack. Precipitation during the summer months is the leading cause of wet snow avalanches.

3. Human Activity: Humans have contributed to the start of many avalanches in recent years. Winter sports that require steep slopes often put pressure on the snow-pack which it cannot deal. Combined with the heavy deforestation and soil erosion in mountain regions, it gives the snow little stability in the winter months. Further natural causes include earthquakes and tremors, since they can often create cracks in the snow-pack.

4. Vibration or Movement: The use of All Terrain Vehicles and Snowmobiles creates vibrations within the snow that it cannot withstand. Coupled with the gravitational pull, it is one of the quickest ways to cause an avalanche. The other is construction work done with explosives, which tend to weaken the entire surrounding area.

5. Layers of Snow: There are conditions where snow is already on the mountains and has turned into ice. Then, fresh snow falls on top which can easily slide down.
6. Steep Slopes: Layers of snow build up and and slide down the mountain at a faster rate as steep slopes can increase the speed of snow. A rock or piece of huge ice can shake the snow and cause it to come down.
7. Warm Temperature: Warm temperatures that can last several hours a day can weaken some of the upper layers of snow and cause it to slide down.

Effects of Avalanches

As such, there is little damage to the overall ecological system due to avalanches. They are a part of nature and have been happening for thousands of years. However, they are a major natural hazard for the local human population.

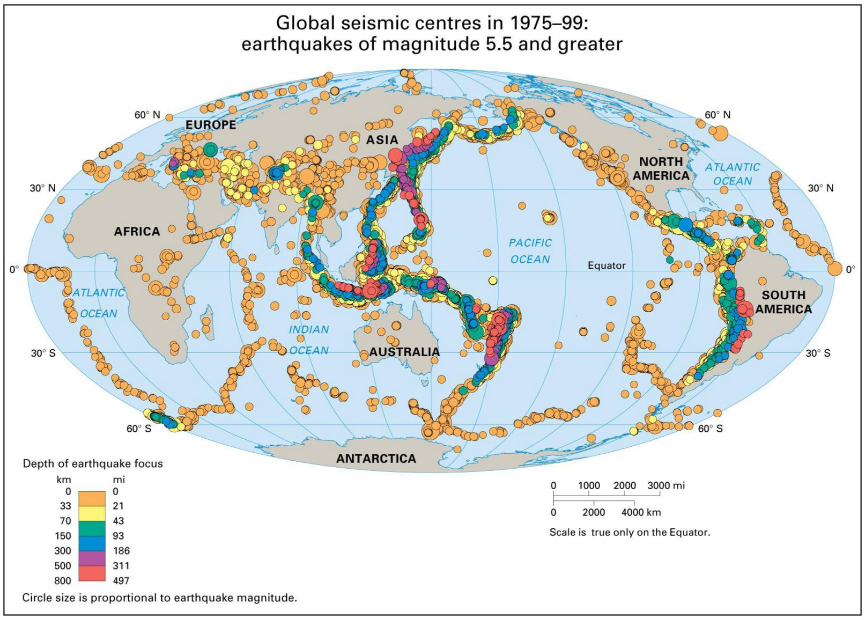
1. Damage to Life and Property: A large number of casualties takes place after avalanches hit heavily populated areas. Infrastructure is damaged and the blockage caused, impacts the livelihood of many. People who enjoy skiing, snowboarding and snowmobiling are at a greater risk of losing their lives. A powerful avalanche can even destroy buildings and power supplies can be cut off.
2. Flash floods: When an avalanche occurs, it brings down all the debris with it and can cause havoc in low lying areas. Flash floods are seen to happen after avalanches, which is a long term problem many villagers and townspeople have to deal with. They can also change weather patterns and cause crop failure in farms present on the lower fields.
3. Economic Impact: An avalanche can block anything in its path and even restrict the normal movement of traffic. Various ski resorts depend on tourists to run their business successfully. Ski resorts and other businesses are forced to close until the avalanche decreases and weather conditions become suitable.

EARTHQUAKE

Residents of an earthquake-damaged neighbourhood of Port-au-Prince, Haiti, seeking safety in a sports field,Jan. 13, 2010. The magnitude-7.0 earthquake struck the region the day before.

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.

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 in 1906.

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

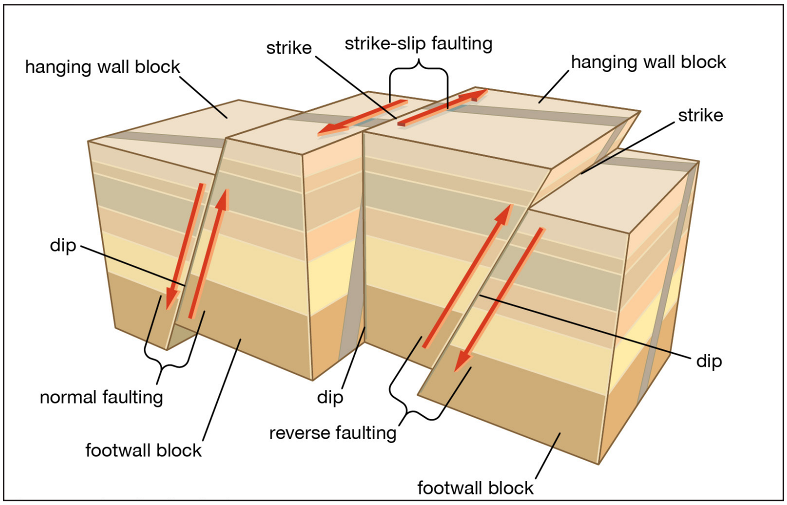
Earthquakes are caused by the sudden release of energy within some limited region of the rocks of the Earth. The energy can be released by elastic strain, gravity, chemical reactions, or even the motion of massive bodies. Of all these the release of elastic strain is the most important cause, because 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 earthquakes.

In normal and reverse faulting, rock masses slip vertically past each other. In strike-slip faulting, the rocks slip past each other horizontally.

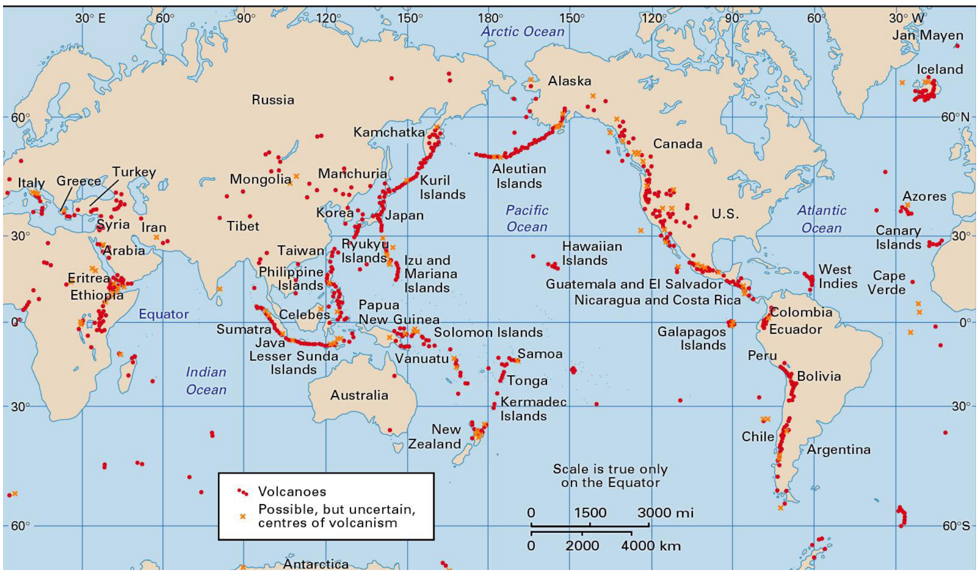
All known faults are assumed to have been the seat of one or more earthquakes in the past, though tectonic movements along faults are often slow, and most geologically ancient faults are now aseismic (that is, they no longer cause earthquakes). The actual faulting associated with an earthquake may be 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 in India (1967), the evidence favours strike-slip faulting motion. At both the Kremasta Dam in Greece (1965) and the Kariba Dam in Zimbabwe-Zambia (1961), 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).

Effects of Earthquakes

Earthquakes have varied effects, including changes in geologic features, damage to man-made structures, and impact on human and animal life. Most of these effects occur on solid ground, but, since most earthquake foci are actually located under the ocean bottom, severe effects are often observed along the margins of oceans.

Surface Phenomena

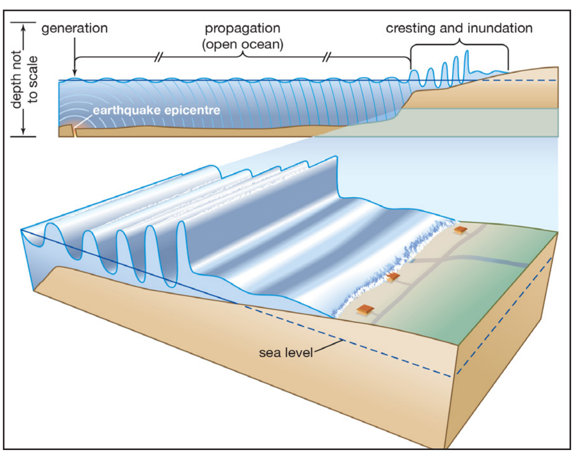
Earthquakes often cause dramatic geomorphological changes, including ground movements—either vertical or horizontal—along geologic fault traces; rising, dropping, and tilting of the ground surface; changes in the flow of groundwater; liquefaction of sandy ground; landslides; and mudflows. The investigation of topographic changes is aided by geodetic measurements, which are made systematically in a number of countries seriously affected by earthquakes.

Earthquakes can do significant damage to buildings, bridges, pipelines, railways, embankments, and other structures. The type and extent of damage inflicted are related to the strength of the ground motions and to the behaviour of the foundation soils. In the most intensely damaged region, called the meizoseismal area, the effects of a severe earthquake are usually complicated and depend on the topography and the nature of the surface materials. They are often more severe on soft alluvium and unconsolidated sediments than on hard rock. At distances of more than 100 km (60 miles) from the source, the main damage is caused by seismic waves traveling along the surface. In mines there is frequently little damage below depths of a few hundred metres even though the ground surface immediately above is considerably affected.

Earthquakes are frequently associated with reports of distinctive sounds and lights. The sounds are generally low-pitched and have been likened to the noise of an underground train passing through a station. The occurrence of such sounds is consistent with the passage of high-frequency seismic waves through the ground. Occasionally, luminous flashes, streamers, and bright balls have been reported in the night sky during earthquakes. These lights have been attributed to electric induction in the air along the earthquake source.

Tsunamis

Following certain earthquakes, very long-wavelength water waves in oceans or seas sweep inshore. More properly called seismic sea waves or tsunamis (tsunami is a Japanese word for "harbour wave"), they are commonly referred to as tidal waves, although the attractions of the Moon and Sun play no role in their formation. They sometimes come ashore to great heights—tens of metres above mean tide level—and may be extremely destructive.



Tsunami, After being generated by an undersea earthquake or landslide, a tsunami may propagate unnoticed over vastreaches of open ocean before cresting in shallow water and inundating a coastline.

The usual immediate cause of a tsunami is sudden displacement in a seabed sufficient to cause the sudden raising or lowering of a large body of water. This deformation may be the fault source of an earthquake, or it may be a submarine landslide arising from an earthquake. Large volcanic eruptions along shorelines, such as those of Thera (c. 1580 BCE) and Krakatoa (1883 CE), have also produced notable tsunamis. The most destructive tsunami ever recorded occurred on December 26, 2004, after an earthquake displaced the seabed off the coast of Sumatra, Indonesia. More than 200,000 people were killed by a series of waves that flooded coasts from Indonesia to Sri Lanka and even washed ashore on the Horn of Africa.

Following the initial disturbance to the sea surface, water waves spread in all directions. Their speed of travel in deep water is given by the formula $\left(\sqrt{gh}\right)$, where h is the sea depth and g is the acceleration of gravity. This speed may be considerable—100 metres per second (225 miles per hour) when h is 1,000 metres (3,300 feet). However, the amplitude (that is, the height of disturbance) at the water surface does not exceed a few metres in deep water, and the principal wavelength may be on the order of hundreds of kilometres; correspondingly, the principal wave period—that is, the time interval between arrival of successive crests—may be on the order of tens of minutes. Because of these features, tsunami waves are not noticed by ships far out at sea.

When tsunamis approach shallow water, however, the wave amplitude increases. The waves may occasionally reach a height of 20 to 30 metres above mean sea level in U- and V-shaped harbours and inlets. They characteristically do a great deal of damage in low-lying ground around such inlets. Frequently, the wave front in the inlet is nearly vertical, as in a tidal bore, and the speed of onrush may be on the order of 10 metres per second. In some cases there are several great waves separated by intervals of several minutes or more. The first of these waves is often preceded by an extraordinary recession of water from the shore, which may commence several minutes or even half an hour beforehand.

Organizations, notably in Japan, Siberia, Alaska, and Hawaii, have been set up to provide tsunami warnings. A key development is the Seismic Sea Wave Warning System, an internationally supported system designed to reduce loss of life in the Pacific Ocean. Centred in Honolulu, it issues alerts based on reports of earthquakes from circum-Pacific seismographic stations.

Seiches

Seiches are rhythmic motions of water in nearly landlocked bays or lakes that are sometimes induced by earthquakes and tsunamis. Oscillations of this sort may last for hours or even for a day or two.

The great Lisbon earthquake of 1755 caused the waters of canals and lakes in regions as far away as Scotland and Sweden to go into observable oscillations. Seiche surges in lakes in Texas, in the southwestern United States, commenced between 30 and 40 minutes after the 1964 Alaska earthquake, produced by seismic surface waves passing through the area.

A related effect is the result of seismic waves from an earthquake passing through the seawater following their refraction through the seafloor. The speed of these waves is about 1.5 km (0.9 mile) per second, the speed of sound in water. If such waves meet a ship with sufficient intensity, they give the impression that the ship has struck a submerged object. This phenomenon is called a seaquake.

Intensity and Magnitude of Earthquakes

Intensity Scales

The violence of seismic shaking varies considerably over a single affected area. Because the entire range of observed effects is not capable of simple quantitative definition, the strength of the shaking is commonly estimated by reference to intensity scales that describe the effects in qualitative terms. Intensity scales date from the late 19th and early 20th centuries, before seismographs capable of accurate measurement of ground motion were developed. Since that time, the divisions in these scales have been associated with measurable accelerations of the local ground shaking. Intensity depends, however, in a complicated way not only on ground accelerations but also on the periods and other features of seismic waves, the distance of the measuring point from the source, and the local geologic structure. Furthermore, earthquake intensity, or strength, is distinct from earthquake magnitude, which is a measure of the amplitude, or size, of seismic waves as specified by a seismograph reading.

A number of different intensity scales have been set up during the past century and applied to both current and ancient destructive earthquakes. For many years the most widely used was a 10-point scale devised in 1878 by Michele Stefano de Rossi and Francois-Alphonse Forel. The scale now generally employed in North America is the Mercalli scale, as modified by Harry O. Wood and Frank Neumann in 1931, in which intensity is considered to be more suitably graded. A 12-point abridged form of the modified Mercalli scale is provided below. Modified Mercalli intensity VIII is roughly correlated with peak accelerations of about one-quarter that of gravity (g = 9.8 metres, or 32.2 feet, per second squared) and ground velocities of 20 cm (8 inches) per second. Alternative scales have been developed in both Japan and Europe for local conditions. The European (MSK) scale of 12 grades is similar to the abridged version of the Mercalli.

Modified Mercalli scale of earthquake intensity:

- Not felt: Marginal and long-period effects of large earthquakes.
- Felt by persons at rest, on upper floors, or otherwise favourably placed to sense tremors.
- Felt indoors: Hanging objects swing. Vibrations are similar to those caused by the passing of light trucks. Duration can be estimated.
- Vibrations are similar to those caused by the passing of heavy trucks (or a jolt similar to that caused by a heavy ball striking the walls). Standing automobiles rock. Windows, dishes, doors rattle. Glasses clink, crockery clashes. In the upper range of grade IV, wooden walls and frames creak.
- Felt outdoors: Direction may be estimated. Sleepers awaken. Liquids are disturbed, some spilled. Small objects are displaced or upset. Doors swing, open, close. Pendulum clocks stop, start, change rate.
- Felt by all: Many are frightened and run outdoors. Persons walk unsteadily. Pictures fall off walls. Furniture moves or overturns. Weak plaster and masonry cracks. Small bells ring (church, school). Trees, bushes shake.

- Difficult to stand: Noticed by drivers of automobiles. Hanging objects quivering. Furniture broken. Damage to weak masonry. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices. Waves on ponds; water turbid with mud. Small slides and caving along sand or gravel banks. Large bells ringing. Concrete irrigation ditches damaged.

- Steering of automobiles affected: Damage to masonry; partial collapse. Some damage to reinforced masonry; none to reinforced masonry designed to resist lateral forces. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed pilings broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

- General panic: Weak masonry destroyed; ordinary masonry heavily damaged, sometimes with complete collapse; reinforced masonry seriously damaged. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas, sand and mud ejected; earthquake fountains, sand craters.

- Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, and so on. Sand and mud shifted horizontally on beaches and flat land. Railway rails bent slightly.

- Rails bent greatly: Underground pipelines completely out of service.

- Damage nearly total: Large rock masses displaced. Lines of sight and level distorted. Objects thrown into air.

With the use of an intensity scale, it is possible to summarize such data for an earthquake by constructing isoseismal curves, which are lines that connect points of equal intensity. If there were complete symmetry about the vertical through the earthquake's focus, isoseismals would be circles with the epicentre (the point at the surface of the Earth immediately above where the earthquake originated) as the centre. However, because of the many unsymmetrical geologic factors influencing intensity, the curves are often far from circular. The most probable position of the epicentre is often assumed to be at a point inside the area of highest intensity. In some cases, instrumental data verify this calculation, but not infrequently the true epicentre lies outside the area of greatest intensity.

Earthquake Magnitude

Earthquake magnitude is a measure of the "size," or amplitude, of the seismic waves generated by an earthquake source and recorded by seismographs. Because the size of earthquakes varies enormously, it is necessary for purposes of comparison to compress the range of wave amplitudes measured on seismograms by means of a mathematical device. In 1935 the American seismologist Charles F. Richter set up a magnitude scale of earthquakes as the logarithm to base 10 of the maximum seismic wave amplitude (in thousandths of a millimetre) recorded on a standard seismograph (the Wood-Anderson torsion pendulum seismograph) at a distance of 100 km (60 miles) from the earthquake epicentre. Reduction of amplitudes observed at various distances to the amplitudes expected at the standard distance of 100 km is made on the basis of empirical tables. Richter magnitudes ML are computed on the assumption that the ratio of the maximum wave amplitudes at two given distances is the same for all earthquakes and is independent of azimuth.

Richter first applied his magnitude scale to shallow-focus earthquakes recorded within 600 km of the epicentre in the southern California region. Later, additional empirical tables were set up, whereby observations made at distant stations and on seismographs other than the standard type could be used. Empirical tables were extended to cover earthquakes of all significant focal depths and to enable independent magnitude estimates to be made from body- and surface-wave observations. A current form of the Richter scale is shown in the table.

Richter Scale of Earthquake Magnitude

Magnitude level	Category	Effects	Earthquakes per year
Less than 1.0 to 2.9	Micro	Generally not felt by people, though recorded on local instruments	More than 100,000
3.0–3.9	Minor	Felt by many people; no damage	12,000–100,000
4.0–4.9	Light	Felt by all; minor breakage of objects	2,000–12,000
5.0–5.9	Moderate	Some damage to weak structures	200–2,000
6.0–6.9	Strong	Moderate damage in populated areas	20–200
7.0–7.9	Major	Serious damage over large areas; loss of life	3–20
8.0 and higher	Great	Severe destruction and loss of life over large areas	Fewer than 3

At the present time a number of different magnitude scales are used by scientists and engineers as a measure of the relative size of an earthquake. The *P*-wave magnitude (M_b), for one, is defined in terms of the amplitude of the *P* wave recorded on a standard seismograph. Similarly, the surface-wave magnitude (M_s) is defined in terms of the logarithm of the maximum amplitude of ground motion for surface waves with a wave period of 20 seconds.

As defined, an earthquake magnitude scale has no lower or upper limit. Sensitive seismographs can record earthquakes with magnitudes of negative value and have recorded magnitudes up to about 9.0. (The 1906 San Francisco earthquake, for example, had a Richter magnitude of 8.25.)

A scientific weakness is that there is no direct mechanical basis for magnitude as defined above. Rather, it is an empirical parameter analogous to stellar magnitude assessed by astronomers. In modern practice a more soundly based mechanical measure of earthquake size is used—namely, the seismic moment (M_o). Such a parameter is related to the angular leverage of the forces that produce the slip on the causative fault. It can be calculated both from recorded seismic waves and from field measurements of the size of the fault rupture. Consequently, seismic moment provides a more uniform scale of earthquake size based on classical mechanics. This measure allows a more scientific magnitude to be used called moment magnitude (M_w). It is proportional to the logarithm of the seismic moment; values do not differ greatly from M_s values for moderate earthquakes. Given the above definitions, the great Alaska earthquake of 1964, with a Richter magnitude (M_L) of 8.3, also had the values $M_s = 8.4$, $M_o = 820 \times 10^{27}$ dyne centimetres, and $M_w = 9.2$.

Earthquake Energy

Energy in an earthquake passing a particular surface site can be calculated directly from the recordings of seismic ground motion, given, for example, as ground velocity. Such recordings indicate an energy rate of 10^5 watts per square metre (9,300 watts per square foot) near a moderate-size earthquake source. The total power output of a rupturing fault in a shallow earthquake is on the order of 10^{14} watts, compared with the 10^5 watts generated in rocket motors.

The surface-wave magnitude M_s has also been connected with the surface energy E_s of an earthquake by empirical formulas. These give $E_s = 6.3 \times 10^{11}$ and 1.4×10^{25} ergs for earthquakes of M_s = 0 and 8.9, respectively. A unit increase in M_s corresponds to approximately a 32-fold increase in energy. Negative magnitudes M_s correspond to the smallest instrumentally recorded earthquakes, a magnitude of 1.5 to the smallest felt earthquakes, and one of 3.0 to any shock felt at a distance of up to 20 km (12 miles). Earthquakes of magnitude 5.0 cause light damage near the epicentre; those of 6.0 are destructive over a restricted area; and those of 7.5 are at the lower limit of major earthquakes.

The total annual energy released in all earthquakes is about 10^{25} ergs, corresponding to a rate of work between 10 million and 100 million kilowatts. This is approximately one one-thousandth the annual amount of heat escaping from the Earth's interior. Ninety percent of the total seismic energy comes from earthquakes of magnitude 7.0 and higher—that is, those whose energy is on the order of 10^{23}ergs or more.

Frequency

There also are empirical relations for the frequencies of earthquakes of various magnitudes. Suppose N to be the average number of shocks per year for which the magnitude lies in a range about M_s. Then,

$$\log_{10} N = a - bM_s$$

fits the data well both globally and for particular regions; for example, for shallow earthquakes worldwide, $a = 6.7$ and $b = 0.9$ when $M_s > 6.0$. The frequency for larger earthquakes therefore increases by a factor of about 10 when the magnitude is diminished by one unit. The increase in frequency with reduction in M_s falls short, however, of matching the decrease in the energy E. Thus, larger earthquakes are overwhelmingly responsible for most of the total seismic energy release. The number of earthquakes per year with $M_b > 4.0$ reaches 50,000.

Occurrence of Earthquakes

Tectonic Associations

Global seismicity patterns had no strong theoretical explanation until the dynamic model called plate tectonics was developed during the late 1960s. This theory holds that the Earth's upper shell, or lithosphere, consists of nearly a dozen large, quasi-stable slabs called plates. The thickness of each of these plates is roughly 80 km (50 miles). The plates move horizontally relative to neighbouring plates at a rate of 1 to 10 cm (0.4 to 4 inches) per year over a shell of lesser strength called the asthenosphere. At the plate edges where there is contact between adjoining plates, boundary tectonic forces operate on the rocks, causing physical and chemical changes in them. New lithosphere is created at oceanic ridges by the upwelling and cooling of magma from the Earth's mantle. The horizontally moving plates are believed to be absorbed at the ocean trenches, where a subduction process carries the lithosphere downward into the Earth's interior. The total amount of lithospheric material destroyed at these subduction zones equals that generated at the ridges.

Seismological evidence (such as the location of major earthquake belts) is everywhere in agreement with this tectonic model. Earthquake sources are concentrated along the oceanic ridges, which correspond to divergent plate boundaries. At the subduction zones, which are associated with convergent plate boundaries, intermediate- and deep-focus earthquakes mark the location of the upper part of a dipping lithosphere slab. The focal mechanisms indicate that the stresses are aligned with the dip of the lithosphere underneath the adjacent continent or island arc.

Some earthquakes associated with oceanic ridges are confined to strike-slip faults, called transform faults, that offset the ridge crests. The majority of the earthquakes occurring along such horizontal shear faults are characterized by slip motions. Also in agreement with the plate tectonics theory is the high seismicity encountered along the edges of plates where they slide past each other. Plate boundaries of this kind, sometimes called fracture zones, include the San Andreas Fault in California and the North Anatolian fault system in Turkey. Such plate boundaries are the site of interplate earthquakes of shallow focus.

The low seismicity within plates is consistent with the plate tectonic description. Small to large earthquakes do occur in limited regions well within the boundaries of plates; however, such intraplate seismic events can be explained by tectonic mechanisms other than plate boundary motions and their associated phenomena.

Shallow, Intermediate, and Deep Foci

Most parts of the world experience at least occasional shallow earthquakes—those that originate within 60 km (40 miles) of the Earth's outer surface. In fact, the great majority of earthquake foci are shallow. It should be noted, however, that the geographic distribution of smaller earthquakes is less completely determined than more severe quakes, partly because the availability of relevant data is dependent on the distribution of observatories.

Of the total energy released in earthquakes, 12 percent comes from intermediate earthquakes—that is, quakes with a focal depth ranging from about 60 to 300 km. About 3 percent of total energy comes from deeper earthquakes. The frequency of occurrence falls off rapidly with increasing focal depth in the intermediate range. Below intermediate depth the distribution is fairly uniform until the greatest focal depths, of about 700 km (430 miles), are approached.

The deeper-focus earthquakes commonly occur in patterns called Benioff zones that dip into the Earth, indicating the presence of a subducting slab. Dip angles of these slabs average about 45°, with some shallower and others nearly vertical. Benioff zones coincide with tectonically active island arcs such as Japan, Vanuatu, Tonga, and the Aleutians, and they are normally but not always associated with deep ocean trenches such as those along the South American Andes. Exceptions to this rule include Romania and the Hindu Kush mountain system. In most Benioff zones, intermediate- and deep-earthquake foci lie in a narrow layer, although recent precise hypocentral locations in Japan and elsewhere show two distinct parallel bands of foci 20 km apart.

Aftershocks, Foreshocks, and Swarms

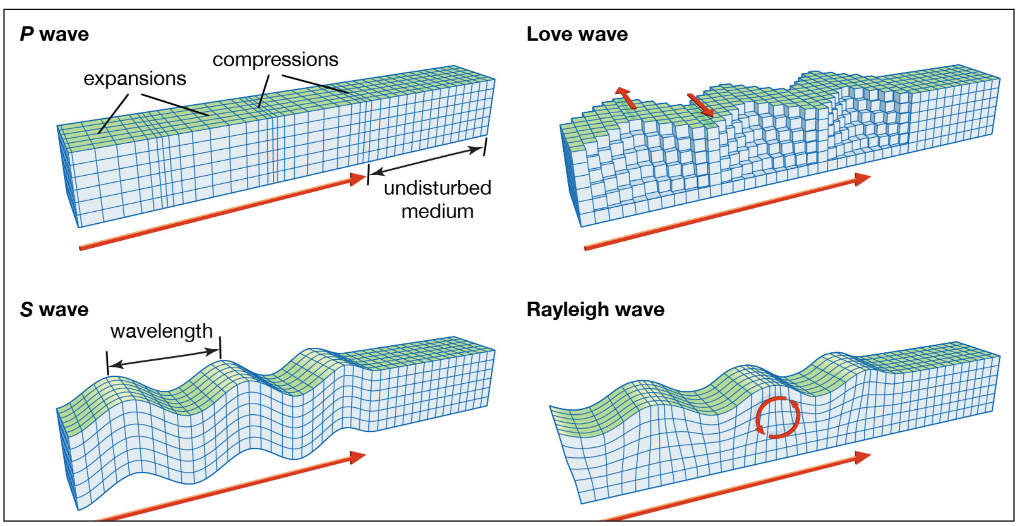
Usually, a major or even moderate earthquake of shallow focus is followed by many lesser-size earthquakes close to the original source region. This is to be expected if the fault rupture producing a major earthquake does not relieve all the accumulated strain energy at once. In fact, this dislocation is liable to cause an increase in the stress and strain at a number of places in the vicinity of the focal region, bringing crustal rocks at certain points close to the stress at which fracture occurs. In some cases an earthquake may be followed by 1,000 or more aftershocks a day.

Sometimes a large earthquake is followed by a similar one along the same fault source within an hour or perhaps a day. An extreme case of this is multiple earthquakes. In most instances, however, the first principal earthquake of a series is much more severe than the aftershocks. In general, the number of aftershocks per day decreases with time. The aftershock frequency is roughly inversely proportional to the time since the occurrence of the largest earthquake of the series.

Most major earthquakes occur without detectable warning, but some principal earthquakes are preceded by foreshocks. In another common pattern, large numbers of small earthquakes may occur in a region for months without a major earthquake. In the Matsushiro region of Japan, for instance, there occurred between August 1965 and August 1967 a series of hundreds of thousands of earthquakes, some sufficiently strong (up to Richter magnitude 5) to cause property damage but no casualties. The maximum frequency was 6,780 small earthquakes on April 17, 1966. Such series of earthquakes are called earthquake swarms. Earthquakes associated with volcanic activity often occur in swarms, though swarms also have been observed in many nonvolcanic regions.

Seismic Waves Principal Types of Seismic Waves

Seismic waves generated by an earthquake source are commonly classified into three main types. The first two, the P (or primary) and S (or secondary) waves, propagate within the body of the Earth, while the third, consisting of Love and Rayleigh waves, propagates along its surface. The existence of these types of seismic waves was mathematically predicted during the 19th century, and modern comparisons show that there is a close correspondence between such theoretical calculations and actual measurements of the seismic waves.



Seismic wave: The main types of seismic waves: P (primary), S (secondary), Love, and Rayleigh.

The P seismic waves travel as elastic motions at the highest speeds. They are longitudinal waves that can be transmitted by both solid and liquid materials in the Earth's interior. With P waves, the particles of the medium vibrate in a manner similar to sound waves—the transmitting media is alternately compressed and expanded. The slower type of body wave, the S wave, travels only through solid material. With S waves, the particle motion is transverse to the direction of travel and involves a shearing of the transmitting rock.

Because of their greater speed, P waves are the first to reach any point on the Earth's surface. The first P-wave onset starts from the spot where an earthquake originates. This point, usually at some depth within the Earth, is called the focus, or hypocentre. The point at the surface immediately above the focus is known as the epicentre.

Love and Rayleigh waves are guided by the free surface of the Earth. They follow along after the P and S waves have passed through the body of the planet. Both Love and Rayleigh waves involve horizontal particle motion, but only the latter type has vertical ground displacements. As Love and Rayleigh waves travel, they disperse into long wave trains, and, at substantial distances from the source in alluvial basins, they cause much of the shaking felt during earthquakes.

Properties of Seismic Waves

At all distances from the focus, mechanical properties of the rocks, such as incompressibility, rigidity, and density, play a role in the speed with which the waves travel and the shape and duration of the wave trains. The layering of the rocks and the physical properties of surface soil also affect wave characteristics. In most cases, elastic behaviour occurs in earthquakes, but strong shaking of surface soils from the incident seismic waves sometimes results in nonelastic behaviour, including slumping (that is, the downward and outward movement of unconsolidated material) and the liquefaction of sandy soil.

When a seismic wave encounters a boundary that separates rocks of different elastic properties, it undergoes reflection and refraction. There is a special complication because conversion between the wave types usually also occurs at such a boundary: an incident P or S wave can yield reflected P and S waves and refracted P and S waves. Boundaries between structural layers also give rise to diffracted and scattered waves. These additional waves are in part responsible for the complications observed in ground motion during earthquakes. Modern research is concerned with computing synthetic records of ground motion that are realistic in comparison with observed ground shaking, using the theory of waves in complex structures.

The frequency range of seismic waves is large, from as high as the audible range (greater than 20 hertz) to as low as the frequencies of the free oscillations of the whole Earth, with the gravest period being 54 minutes. Attenuation of the waves in rock imposes high-frequency limits, and in small to moderate earthquakes the dominant frequencies extend in surface waves from about 1 to 0.1 hertz.

The amplitude range of seismic waves is also great in most earthquakes. Displacement of the ground ranges from 10^{-10} to 10^{-1} metre (4^{-12} to 4 inches). In the greatest earthquakes the ground amplitude of the predominant *P* waves may be several centimetres at periods of two to five seconds. Very close to the seismic sources of great earthquakes, investigators have measured large wave amplitudes with accelerations of the ground exceeding that of gravity (9.8 metres, or 32.2 feet, per second squared) at high frequencies and ground displacements of 1 metre at low frequencies.

Measurement of Seismic Waves

Seismographs and Accelerometers

Seismographs are used to measure ground motion in both earthquakes and microseisms (small oscillations described below). Most of these instruments are of the pendulum type. Early mechanical seismographs had a pendulum of large mass (up to several tons) and produced seismograms by scratching a line on smoked paper on a rotating drum. In later instruments, seismograms were recorded by means of a ray of light from the mirror of a galvanometer through which passed an electric current generated by electromagnetic induction when the pendulum of the seismograph moved. Technological developments in electronics have given rise to higher-precision pendulum seismometers and sensors of ground motion. In these instruments the electric voltages produced by motions of the pendulum or the equivalent are passed through electronic circuitry to amplify and digitize the ground motion for more exact readings.

Generally speaking, seismographs are divided into three types: short-period, long- (or intermediate-) period, and ultralong-period, or broadband, instruments. Short-period instruments are used to record P and S body waves with high magnification of the ground motion. For this purpose, the seismograph response is shaped to peak at a period of about one second or less. The intermediate-period instruments of the type used by the World-Wide Standardized Seismographic Network had a response maximum at about 20 seconds. Recently, in order to provide as much flexibility as possible for research work, the trend has been toward the operation of very broadband seismographs with digital representation of the signals. This is usually accomplished with very long-period pendulums and electronic amplifiers that pass signals in the band between 0.005 and 50 hertz.

When seismic waves close to their source are to be recorded, special design criteria are needed. Instrument sensitivity must ensure that the largest ground movements can be recorded without exceeding the upper scale limit of the device. For most seismological and engineering purposes the wave frequencies that must be recorded are higher than 1 hertz, and so the pendulum or its equivalent can be small. For this reason accelerometers that measure the rate at which the ground velocity is changing have an advantage for strong-motion recording. Integration is then performed to estimate ground velocity and displacement. The ground accelerations to be registered range up to two times that of gravity. Recording such accelerations can be accomplished mechanically with short torsion suspensions or force-balance mass-spring systems.

Because many strong-motion instruments need to be placed at unattended sites in ordinary buildings for periods of months or years before a strong earthquake occurs, they usually record only when a trigger mechanism is actuated with the onset of ground motion. Solid-state memories are now used, particularly with digital recording instruments, making it possible to preserve the first few seconds before the trigger starts the permanent recording and to store digitized signals on magnetic cassette tape or on a memory chip. In past design absolute timing was not provided on strong-motion records but only accurate relative time marks; the present trend, however, is to provide Universal Time (the local mean time of the prime meridian) by means of special radio receivers, small crystal clocks, or GPS (global positioning system) receivers from satellite clocks.

The prediction of strong ground motion and response of engineered structures in earthquakes depends critically on measurements of the spatial variability of earthquake intensities near the seismic wave source. In an effort to secure such measurements, special arrays of strong-motion seismographs have been installed in areas of high seismicity around the world. Large-aperture seismic arrays (linear dimensions on the order of 1 to 10 km, or 0.6 to 6 miles) of strong-motion accelerometers can now be used to improve estimations of speed, direction of propagation, and types of seismic wave components. Particularly important for full understanding of seismic wave patterns at the ground surface is measurement of the variation of wave motion with depth. To aid in this effort, special digitally recording seismometers have been installed in deep boreholes.

Ocean-Bottom Measurements

Because 70 percent of the Earth's surface is covered by water, there is a need for ocean-bottom seismometers to augment the global land-based system of recording stations. Field tests have established the feasibility of extensive long-term recording by instruments on the seafloor. Japan already has a semipermanent seismograph system of this type that was placed on the seafloor off the Pacific coast of central Honshu in 1978 by means of a cable.

Because of the mechanical difficulties of maintaining permanent ocean-bottom instrumentation, different systems have been considered. They all involve placement of instruments on the bottom of the ocean, though they employ various mechanisms for data transmission. Signals may be transmitted to the ocean surface for retransmission by auxiliary apparatus or transmitted via cable to a shore-based station. Another system is designed to release its recording device automatically, allowing it to float to the surface for later recovery.

The use of ocean-bottom seismographs should yield much-improved global coverage of seismic waves and provide new information on the seismicity of oceanic regions. Ocean-bottom seismographs will enable investigators to determine the details of the crustal structure of the seafloor and, because of the relative thinness of the oceanic crust, should make it possible to collect clear seismic information about the upper mantle. Such systems are also expected to provide new data on plate boundaries, on the origin and propagation of microseisms, and on the nature of ocean-continent margins.

Measuring Microseisms

Small ground motions known as microseisms are commonly recorded by seismographs. These weak wave motions are not generated by earthquakes, and they complicate accurate recording of the latter. However, they are of scientific interest because their form is related to the Earth's surface structure.

Some microseisms have local causes—for example, those due to traffic or machinery or due to local wind effects, storms, and the action of rough surf against an extended steep coast. Another class of microseisms exhibits features that are very similar on records traced at earthquake observatories that are widely separated, including approximately simultaneous occurrence of maximum amplitudes and similar wave frequencies. These microseisms may persist for many hours and have more or less regular periods of about five to eight seconds. The largest amplitudes of such microseisms are on the order of 10–3 cm (0.0004 inch) and occur in coastal regions. The amplitudes also depend to some extent on local geologic structure. Some microseisms are produced when large standing water waves are formed far out at sea. The period of this type of microseism is half that of the standing wave.

Observation of Earthquakes

Earthquake Observatories

Worldwide during the late 1950s, there were only about 700 seismographic stations, which were equipped with seismographs of various types and frequency responses. Few instruments were calibrated; actual ground motions could not be measured, and timing errors of several seconds were common. The World-Wide Standardized Seismographic Network (WWSSN), the first modern worldwide standardized system, was established to help remedy this situation. Each station of the WWSSN had six seismographs—three short-period and three long-period seismographs. Timing and accuracy were maintained by crystal clocks, and a calibration pulse was placed daily on each record. By 1967 the WWSSN consisted of about 120 stations distributed over 60 countries. The resulting data provided the basis for significant advances in research on earthquake mechanisms, global tectonics, and the structure of the Earth's interior.

By the 1980s a further upgrading of permanent seismographic stations began with the installation of digital equipment by a number of organizations. Among the global networks of digital seismographic stations now in operation are the Seismic Research Observatories in boreholes 100 metres (330 feet) deep and modified high-gain, long-period surface observatories. The Global Digital Seismographic Network in particular has remarkable capability, recording all motions from Earth tides to microscopic ground motions at the level of local ground noise. At present there are about 128 sites. With this system the long-term seismological goal will have been accomplished to equip global observatories with seismographs that can record every small earthquake anywhere over a broad band of frequencies.

Locating Earthquake Epicentres

Many observatories make provisional estimates of the epicentres of important earthquakes. These estimates provide preliminary information locally about particular earthquakes and serve as first approximations for the calculations subsequently made by large coordinating centres.

If an earthquake's epicentre is less than 105° away from an observatory, the epicentre's position can often be estimated from the readings of three seismograms recording perpendicular components of the ground motion. For a shallow earthquake the epicentral distance is indicated by the interval between the arrival times of P and S waves; the azimuth and angle of wave emergence at the surface are indicated by a comparison of the sizes and directions of the first movements shown in the seismograms and by the relative sizes of later waves, particularly surface waves. It should be noted, however, that in certain regions the first wave movement at a station arrives from a direction differing from the azimuth toward the epicentre. This anomaly is usually explained by strong variations in geologic structures.

When data from more than one observatory are available, an earthquake's epicentre may be estimated from the times of travel of the P and S waves from source to recorder. In many seismically active regions, networks of seismographs with telemetry transmission and centralized timing and recording are common. Whether analog or digital recording is used, such integrated systems greatly simplify observatory work: multichannel signal displays make identification and timing of phase onsets easier and more reliable. Moreover, online microprocessors can be programmed to pick automatically, with some degree of confidence, the onset of a significant common phase, such as P, by correlation of waveforms from parallel network channels. With the aid of specially designed computer programs, seismologists can then locate distant earthquakes to within about 10 km (6 miles) and the epicentre of a local earthquake to within a few kilometres.

Catalogs of earthquakes felt by humans and of earthquake observations have appeared intermittently for many centuries. The earliest known list of instrumentally recorded earthquakes with computed times of origin and epicentres is for the period 1899–1903. In subsequent years, cataloging of earthquakes has become more uniform and complete. Especially valuable is the service provided by the International Seismological Centre (ISC) at Newbury, Eng. Each month it receives more than 1,000,000 readings from more than 2,000 stations worldwide and preliminary estimates of the locations of approximately 1,600 earthquakes from national and regional agencies and observatories. The ISC publishes a monthly bulletin—with about a two-year delay—that provides all available information on each of more than 5,000 earthquakes.

Various national and regional centres control networks of stations and act as intermediaries between individual stations and the international organizations. Examples of long-standing national centres include the Japan Meteorological Agency and United States National Earthquake Information Center in Colorado (a subdivision of the United States Geological Survey). These centres normally make estimates of the magnitudes, epicentres, origin times, and focal depths of local earthquakes. On the Internet, data on global seismicity is continually accessible through the Web site of the Incorporated Research Institutions for Seismology (IRIS).

An important research technique is to infer the character of faulting in an earthquake from the recorded seismograms. For example, observed distributions of the directions of the first onsets in waves arriving at the Earth's surface have been effectively used. Onsets are called "compressional" or "dilatational" according to whether the direction is away from or toward the focus, respectively. A polarity pattern becomes recognizable when the directions of the P-wave onsets are plotted on a map—there are broad areas in which the first onsets are predominantly compressions, separated from predominantly dilatational areas by nodal curves near which the P-wave amplitudes are abnormally small.

In 1926 the American geophysicist Perry E. Byerly used patterns of P onsets over the entire globe to infer the orientation of the fault plane in a large earthquake. The polarity method yields two P-nodal curves at the Earth's surface; one curve is in the plane containing the assumed fault, and the other is in the plane (called the auxiliary plane) that passes through the focus and is perpendicular to the forces of the plane. The recent availability of worldwide broad-based digital recording has enabled computer programs to be written that estimate the fault mechanism and seismic moment from the complete pattern of seismic wave arrivals. Given a well-determined pattern at a number of earthquake observatories, it is possible to locate two planes, one of which is the plane containing the fault.

Earthquake Prediction

Observation and Interpretation of Precursory Phenomena

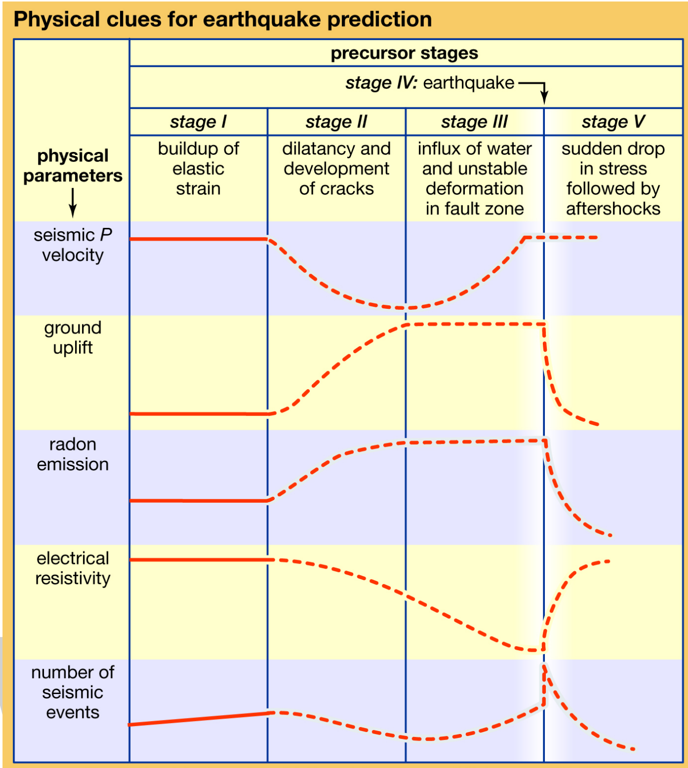
The search for periodic cycles in earthquake occurrence is an old one. Generally, periodicities in time and space for major earthquakes have not been widely detected or accepted. One problem is that long-term earthquake catalogs are not homogeneous in their selection and reporting. The most extensive catalog of this kind comes from China and begins about 700 BCE. The catalog contains some information on about 1,000 destructive earthquakes. The sizes of these earthquakes have been assessed from the reports of damage, intensity, and shaking.

Another approach to the statistical occurrence of earthquakes involves the postulation of trigger forces that initiate the rupture. Such forces have been attributed to severe weather conditions, volcanic activity, and tidal forces, for example. Usually correlations are made between the physical phenomena assumed to provide the trigger and the repetition of earthquakes. Inquiry must always be made to discover whether a causative link is actually present, but in no cases to the present has a trigger mechanism, at least for moderate to large earthquakes, been unequivocally found that satisfies the various necessary criteria.

Statistical methods also have been tried with populations of regional earthquakes. It has been suggested, but never established generally, that the slope b of the regression line between the logarithm of the number of earthquakes and the magnitude for a region may change characteristically with time. Specifically, the claim is that the b value for the population of foreshocks of a major earthquake may be significantly smaller than the mean b value for the region averaged over a long interval of time.

The elastic rebound theory of earthquake sources allows rough prediction of the occurrence of large shallow earthquakes. Harry F. Reid gave, for example, a crude forecast of the next great earthquake near San Francisco. (The theory also predicted, of course, that the place would be along the San Andreas or an associated fault.) The geodetic data indicated that during an interval of 50 years relative displacements of 3.2 metres (10.5 feet) had occurred at distant points across the fault. The maximum elastic-rebound offset along the fault in the 1906 earthquake was 6.5 metres. Therefore, (6.5 ÷ 3.2) × 50, or about 100, years would again elapse before sufficient strain accumulated for the occurrence of an earthquake comparable to that of 1906. The premises are that the regional strain will grow uniformly and that various constraints have not been altered by the great 1906 rupture itself (such as by the onset of slow fault slip). Such strain rates are now being more adequately measured along a number of active faults such as the San Andreas, using networks of GPS sensors.

For many years prediction research has been influenced by the basic argument that strain accumulates in the rock masses in the vicinity of a fault and results in crustal deformation. Deformations have been measured in the horizontal direction along active faults (by trilateration and triangulation) and in the vertical direction by precise leveling and tiltmeters. Some investigators believe that changes in groundwater level occur prior to earthquakes; variations of this sort have been reported mainly from China. Because water levels in wells respond to a complex array of factors such as rainfall, such factors will have to be removed if changes in water level are to be studied in relation to earthquakes.



The theory of dilatancy (that is, an increase in volume) of rock prior to rupture once occupied a central position in discussions of premonitory phenomena of earthquakes, but it now receives less support. It is based on the observation that many solids exhibit dilatancy during deformation. For earthquake prediction the significance of dilatancy, if real, is in its effects on various measurable quantities of the Earth's crust, such as seismic velocities, electric resistivity, and ground and water levels. The consequences of dilatancy for earthquake prediction are summarized in the table. The best-studied consequence is the effect on seismic velocities. The influence of internal cracks and pores on the elastic properties of rocks can be clearly demonstrated in laboratory measurements of those properties as a function of hydrostatic pressure. In the case of saturated rocks, experiments predict—for shallow earthquakes—that dilatancy occurs as a portion of the crust is stressed to failure, causing a decrease in the velocities of seismic waves. Recovery of velocity is brought about by subsequent rise of the pore pressure of water, which also has the effect of weakening the rock and enhancing fault slip.

Strain buildup in the focal region may have measurable effects on other observable properties, including electrical conductivity and gas concentration. Because the electrical conductivity of rocks depends largely on interconnected water channels within the rocks, resistivity may increase before the cracks become saturated. As pore fluid is expelled from the closing cracks, the local water table would rise and concentrations of gases such as radioactive radon would increase. No unequivocal confirming measurements have yet been published.

Geologic methods of extending the seismicity record back from the present also are being explored. Field studies indicate that the sequence of surface ruptures along major active faults associated with large earthquakes can sometimes be constructed. An example is the series of large earthquakes in Turkey in the 20th century, which were caused mainly by successive westward ruptures of the North Anatolian Fault. Liquefaction effects preserved in beds of sand and peat have provided evidence—when radiometric dating methods are used—for large paleoearthquakes extending back for more than 1,000 years in many seismically active zones, including the Pacific Northwest coast of the United States.

Less well-grounded precursory phenomena, particularly earthquake lights and animal behaviour, sometimes draw more public attention than the precursors discussed above. Many reports of unusual lights in the sky and abnormal animal behaviour preceding earthquakes are known to seismologists, mostly in anecdotal form. Both these phenomena are usually explained in terms of a release of gases prior to earthquakes and electric and acoustic stimuli of various types. At present there is no definitive experimental evidence to support claims that animals sometimes sense the coming of an earthquake.

Methods of Reducing Earthquake Hazards

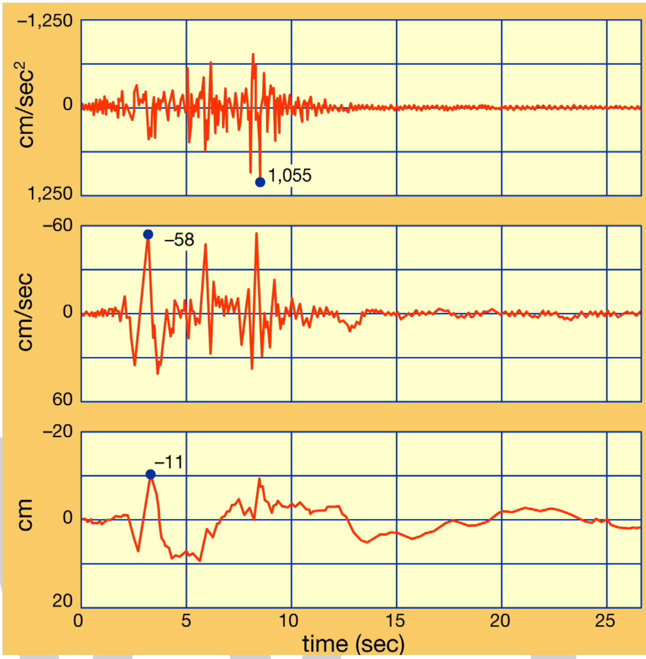
Considerable work has been done in seismology to explain the characteristics of the recorded ground motions in earthquakes. Such knowledge is needed to predict ground motions in future earthquakes so that earthquake-resistant structures can be designed. Although earthquakes cause death and destruction through such secondary effects as landslides, tsunamis, fires, and fault rupture, the greatest losses—both of lives and of property—result from the collapse of man-made structures during the violent shaking of the ground. Accordingly, the most effective way to mitigate the damage of earthquakes from an engineering standpoint is to design and construct structures capable of withstanding strong ground motions.

Interpreting Recorded Ground Motions

Most elastic waves recorded close to an extended fault source are complicated and difficult to interpret uniquely. Understanding such near-source motion can be viewed as a three-part problem. The first part stems from the generation of elastic waves by the slipping fault as the moving rupture sweeps out an area of slip along the fault plane within a given time. The pattern of waves produced is dependent on several parameters, such as fault dimension and rupture velocity. Elastic waves of various types radiate from the vicinity of the moving rupture in all directions. The geometry and frictional properties of the fault critically affect the pattern of radiation from it.

The second part of the problem concerns the passage of the waves through the intervening rocks to the site and the effect of geologic conditions. The third part involves the conditions at the recording site itself, such as topography and highly attenuating soils. All these questions must be considered when estimating likely earthquake effects at a site of any proposed structure.

Experience has shown that the ground strong-motion recordings have a variable pattern in detail but predictable regular shapes in general (except in the case of strong multiple earthquakes). An example of actual shaking of the ground (acceleration, velocity, and displacement) recorded during an earthquake is given in the . In a strong horizontal shaking of the ground near the fault source, there is an initial segment of motion made up mainly of P waves, which frequently manifest themselves strongly in the vertical motion. This is followed by the onset of S waves, often associated with a longer-period pulse of ground velocity and displacement related to the near-site fault slip or fling. This pulse is often enhanced in the direction of the fault rupture and normal to it. After the S onset there is shaking that consists of a mixture of S and P waves, but the S motions become dominant as the duration increases. Later, in the horizontal component, surface waves dominate, mixed with some S body waves. Depending on the distance of the site from the fault and the structure of the intervening rocks and soils, surface waves are spread out into long trains.



Recording of the San Fernando earthquake, near Pacoima Dam, California, 1971, showing (top) ground acceleration, (centre) velocity, and (bottom) displacement.

Constructing Seismic Hazard Maps

In many regions, seismic expectancy maps or hazard maps are now available for planning purposes. The anticipated intensity of ground shaking is represented by a number called the peak acceleration or the peak velocity.

To avoid weaknesses found in earlier earthquake hazard maps, the following general principles are usually adopted today:

1. The map should take into account not only the size but also the frequency of earthquakes.
2. The broad regionalization pattern should use historical seismicity as a database, including the following factors: major tectonic trends, acceleration attenuation curves, and intensity reports.
3. Regionalization should be defined by means of contour lines with design parameters referred to ordered numbers on neighbouring contour lines (this procedure minimizes sensitivity concerning the exact location of boundary lines between separate zones).
4. The map should be simple and not attempt to microzone the region.
5. The mapped contoured surface should not contain discontinuities, so that the level of hazard progresses gradually and in order across any profile drawn on the map.

Developing Resistant Structures

Developing engineered structural designs that are able to resist the forces generated by seismic waves can be achieved either by following building codes based on hazard maps or by appropriate methods of analysis. Many countries reserve theoretical structural analyses for the larger, more costly, or critical buildings to be constructed in the most seismically active regions, while simply requiring that ordinary structures conform to local building codes. Economic realities usually determine the goal, not of preventing all damage in all earthquakes but of minimizing damage in moderate, more common earthquakes and ensuring no major collapse at the strongest intensities. An essential part of what goes into engineering decisions on design and into the development and revision of earthquake-resistant design codes is therefore seismological, involving measurement of strong seismic waves, field studies of intensity and damage, and the probability of earthquake occurrence.

Earthquake risk can also be reduced by rapid post-earthquake response. Strong-motion accelerographs have been connected in some urban areas, such as Los Angeles, Tokyo, and Mexico City, to interactive computers. The recorded waves are correlated with seismic intensity scales and rapidly displayed graphically on regional maps via the World Wide Web.

Exploration of the Earth's Interior with Seismic Waves

Seismological Tomography

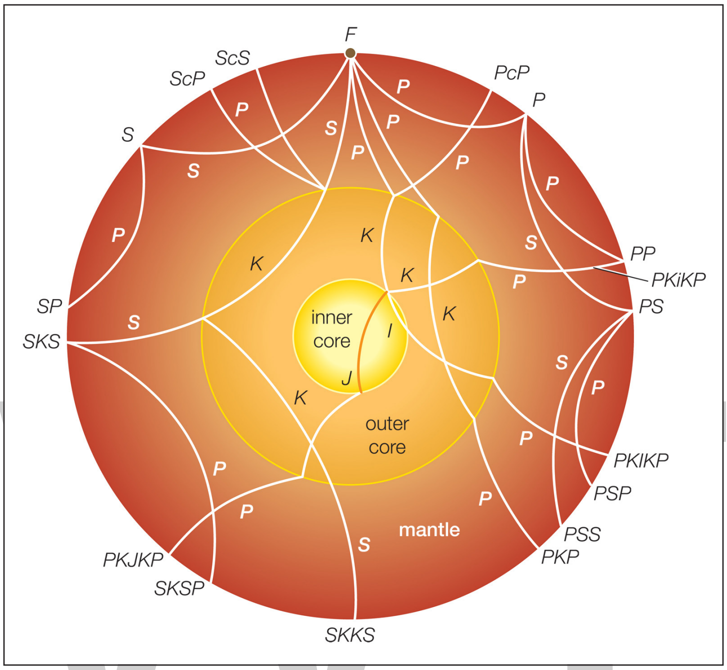
Seismological data on the Earth's deep structure come from several sources. These include P and S waves in earthquakes and nuclear explosions, the dispersion of surface waves from distant earthquakes, and vibrations of the whole Earth from large earthquakes.

One of the major aims of seismology is to infer the minimum set of properties of the Earth's interior that will explain recorded seismic wave trains in detail. Notwithstanding the tremendous progress made in the exploration of the Earth's deep structure during the first half of the 20th century, realization of this goal was severely limited until the 1960s because of the laborious effort required to evaluate theoretical models and to process the large amounts of earthquake data recorded. The application of high-speed computers with their enormous storage and rapid retrieval capabilities opened the way for major advances in both theoretical work and data handling.

Since the mid-1970s, researchers have studied realistic models of the Earth's structure that include continental and oceanic boundaries, mountains, and river valleys rather than simple structures such as those involving variation only with depth. In addition, various technical developments have benefited observational seismology. For example, the implications of seismic exploratory techniques developed by the petroleum industry (such as seismic reflection) have been recognized and the procedures adopted. Equally significant has been the application of three-dimensional imaging methods to the exploration of the Earth's deep structure. This has been made possible by the development of very fast microprocessors and computers with peripheral display equipment.

The major method for determining the structure of the Earth's deep interior is the detailed analysis of seismograms of seismic waves. (Such earthquake readings also provide estimates of wave velocities, density, and elastic and inelastic parameters in the Earth.) The primary procedure is to measure the travel times of various wave types, such as P and S, from their source to the recording seismograph. First, however, identification of each wave type with its ray path through the Earth must be made.

Seismic rays for many paths of P and S waves leaving the earthquake focus F are shown in the figure. Rays corresponding to waves that have been reflected at the Earth's outer surface (or possibly at one of the interior discontinuity surfaces) are denoted as PP, PS, SP, PSS, and so on. For example, PS corresponds to a wave that is of P type before surface reflection and of S type afterward. In addition, there are rays such as pPP, sPP, and sPS, the symbols p and s corresponding to an initial ascent to the outer surface as P or S waves, respectively, from a deep focus.



Seismic ray types in Earth's interior from an earthquake at F.

An especially important class of rays is associated with a discontinuity surface separating the central core of the Earth from the mantle at a depth of about 2,900 km (1,800 miles) below the outer surface. The symbol c is used to indicate an upward reflection at this discontinuity. Thus, if a P wave travels down from a focus to the discontinuity surface in question, the upward reflection into an S wave is recorded at an observing station as the ray PcS and similarly with PcP, ScS, and ScP. The symbol K is used to denote the part (of P type) of the path of a wave that passes through the liquid central core. Thus, the ray SKS corresponds to a wave that starts as an S wave, is refracted into the central core as a P wave, and is refracted back into the mantle, wherein it finally emerges as an S wave. Such rays as SKKS correspond to waves that have suffered an internal reflection at the boundary of the central core.

The discovery of the existence of an inner core in 1936 by the Danish seismologist Inge Lehmann made it necessary to introduce additional basic symbols. For paths of waves inside the central core, the symbols i and I are used analogously to c and K for the whole Earth; therefore, i indicates reflection upward at the boundary between the outer and inner portions of the central core, and I corresponds to the part (of P type) of the path of a wave that lies inside the inner portion. Thus, for instance, discrimination needs to be made between the rays PKP, PKiKP, and PKIKP. The first of these corresponds to a wave that has entered the outer part of the central core but has not reached the inner core, the second to one that has been reflected upward at the inner core boundary, and the third to one that has penetrated into the inner portion.

By combining the symbols p, s, P, S, c, K, i, and I in various ways, notation is developed for all the main rays associated with body earthquake waves. The symbol J has been introduced to correspond to S waves in the inner core, should evidence ever be found for such waves.

Finally, the use of times of travel along rays to infer hidden structure is analogous to the use of X-rays in medical tomography. The method involves reconstructing an image of internal anomalies from measurements made at the outer surface. Nowadays, hundreds of thousands of travel times of P and S waves are available in earthquake catalogs for the tomographic imaging of the Earth's interior and the mapping of internal structure.

Structure of the Earth's Interior

Studies with earthquake recordings have given a picture inside the Earth of a solid but layered and flow-patterned mantle about 2,900 km (1,800 miles) thick, which in places lies within 10 km (6 miles) of the surface under the oceans.

The thin surface rock layer surrounding the mantle is the crust, whose lower boundary is called the Mohorovičić discontinuity. In normal continental regions the crust is about 30 to 40 km thick; there is usually a superficial low-velocity sedimentary layer underlain by a zone in which seismic velocity increases with depth. Beneath this zone there is a layer in which P-wave velocities in some places fall from 6 to 5.6 km per second. The middle part of the crust is characterized by a heterogeneous zone with P velocities of nearly 6 to 6.3 km per second. The lowest layer of the crust (about 10 km thick) has significantly higher P velocities, ranging up to nearly 7 km per second.

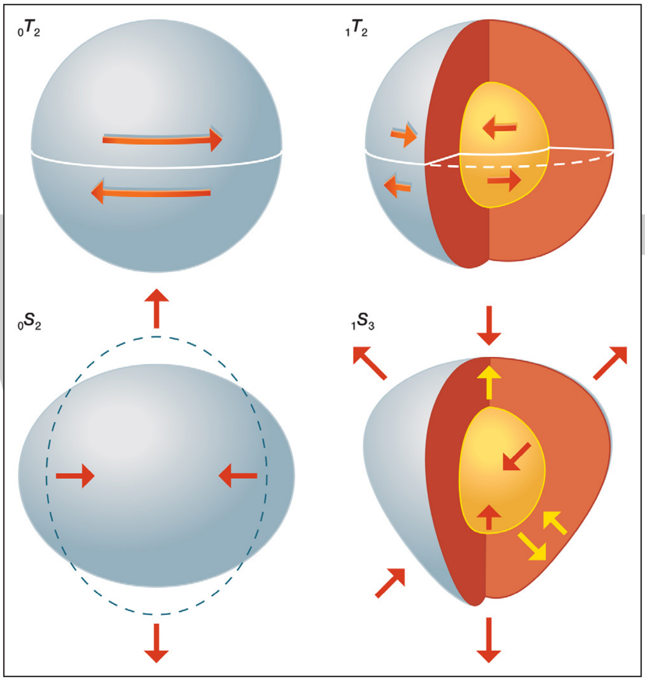
In the deep ocean there is a sedimentary layer that is about 1 km thick. Underneath is the lower layer of the oceanic crust, which is about 4 km thick. This layer is inferred to consist of basalt that formed where extrusions of basaltic magma at oceanic ridges have been added to the upper part of lithospheric plates as they spread away from the ridge crests. This crustal layer cools as it moves away from the ridge crest, and its seismic velocities increase correspondingly.

Below the mantle lies a shell that is 2,255 km thick, which seismic waves show to have the properties of a liquid. At the very centre of the planet is a separate solid core with a radius of 1,216 km. Recent work with observed seismic waves has revealed three-dimensional structural details inside the Earth, especially in the crust and lithosphere, under the subduction zones, at the base of the mantle, and in the inner core. These regional variations are important in explaining the dynamic history of the planet.

Long-period Oscillations of the Globe

Sometimes earthquakes are large enough to cause the whole Earth to ring like a bell. The deepest tone of vibration of the planet is one with a period (the length of time between the arrival of successive crests in a wave train) of 54 minutes. Knowledge of these vibrations has come from a remarkable extension in the range of periods of ground movements that can be recorded by modern digital long-period seismographs that span the entire allowable spectrum of earthquake wave periods: from ordinary *P* waves with periods of tenths of seconds to vibrations with periods on the order of 12 and 24 hours such as those that occur in Earth tidal movements.

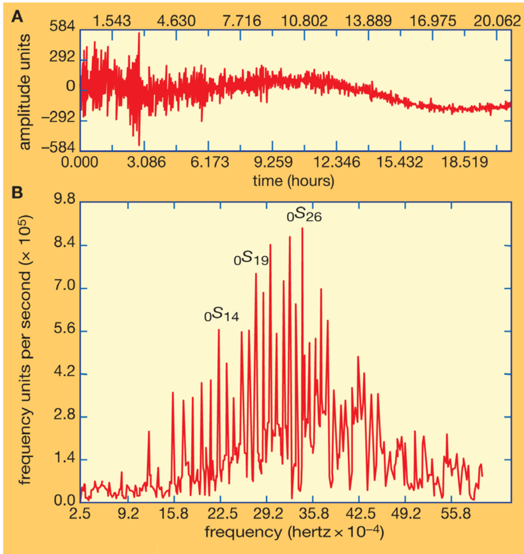
The measurements of vibrations of the whole Earth provide important information on the properties of the interior of the planet. It should be emphasized that these free vibrations are set up by the energy release of the earthquake source but continue for many hours and sometimes even days. For an elastic sphere such as the Earth, two types of vibrations are known to be possible. In one type, called *S* modes, or spheroidal vibrations, the motions of the elements of the sphere have components along the radius as well as along the tangent. In the second type, which are designated as *T* modes, or torsional vibrations, there is shear but no radial displacements. The nomenclature is *nSl* and *nTl*, where the letters *n* and *l* are related to the surfaces in the vibration at which there is zero motion. Four examples are illustrated in the figure. The subscript *n* gives a count of the number of internal zero-motion (nodal) surfaces, and *l* indicates the number of surface nodal lines.



Displacements of the Earth in four types of free vibrations.

Several hundred types of *S* and *T* vibrations have been identified and the associated periods measured. The amplitudes of the ground motion in the vibrations have been determined for particular earthquakes, and, more important, the attenuation of each component vibration has been measured. The dimensionless measure of this decay constant is called the quality factor *Q*. The greater the value of *Q*, the less the wave or vibration damping. Typically, for ${}_0S_{10}$ and ${}_0T_{10}$, the *Q* values are about 250.

The rate of decay of the vibrations of the whole Earth with the passage of time can be seen in the figure, where they appear superimposed for 20 hours of the 12-hour tidal deformations of the Earth. At the bottom of the figure these vibrations have been split up into a series of peaks, each with a definite frequency, similar to that of the spectrum of light. Such a spectrum indicates the relative amplitude of each harmonic present in the free oscillations. If the physical properties of the Earth's interior were known, all these individual peaks could be calculated directly. Instead, the internal structure must be estimated from the observed peaks.



(A) Recorded ground motion for 20 hours at Whiskeytown, California, in the large Indonesian earthquake,1977. (B) Frequency spectrum of the Earth's oscillations from that record.

Recent research has shown that observations of long-period oscillations of the Earth discriminate fairly finely between different Earth models. In applying the observations to improve the resolution and precision of such representations of the planet's internal structure, a considerable number of Earth models are set up, and all the periods of their free oscillations are computed and checked against the observations. Models can then be successively eliminated until only a small range remains. In practice, the work starts with existing models; efforts are made to amend them by sequential steps until full compatibility with the observations is achieved, within the uncertainties of the observations. Even so, the resulting computed Earth structure is not a unique solution to the problem.

Extraterrestrial Seismic Phenomena

Space vehicles have carried equipment to the surface of the Moon and Mars with which to record seismic waves, and seismologists on Earth have received telemetered signals from seismic events in both cases.

By 1969, seismographs had been placed at six sites on the Moon during the U.S. Apollo missions. Recording of seismic data ceased in September 1977. The instruments detected between 600 and 3,000 moonquakes during each year of their operation, though most of these seismic events were very small. The ground noise on the lunar surface is low compared with that of the Earth, so that the seismographs could be operated at very high magnifications. Because there was more than one station on the Moon, it was possible to use the arrival times of P and S waves at the lunar stations from the moonquakes to determine foci in the same way as is done on the Earth.

Moonquakes are of three types. First, there are the events caused by the impact of lunar modules, booster rockets, and meteorites. The lunar seismograph stations were able to detect meteorites hitting the Moon's surface more than 1,000 km (600 miles) away. The two other types of moonquakes had natural sources in the Moon's interior: they presumably resulted from rock fracturing, as on Earth. The most common type of natural moonquake had deep foci, at depths of 600 to 1,000 km; the less common variety had shallow focal depths.

Seismological research on Mars has been less successful. Only one of the seismometers carried to the Martian surface by the U.S. Viking landers during the mid-1970s remained operational, and only one potential marsquake was detected in 546 Martian days.

LANDSLIDES

Landslides are among the many natural disasters causing massive destructions and loss of lives across the globe. According to a survey study by the International Landslide Centre at Durham University, UK, 2,620 fatal landslides occurred between 2004 and 2010. These landslides resulted in the death of over 32,322 people. The figure does not include landslides caused by earthquakes. This research result is astonishing considering the number of people killed by landslides. It is, thus, paramount to know the causes and warning signs of a potential landslide to minimize losses.

A landslide, sometimes known as landslip, slope failure or slump, is an uncontrollable downhill flow of rock, earth, debris or the combination of the three. Landslides stem from the failure of materials making up the hill slopes and are beefed up by the force of gravity. When the ground becomes saturated, it can become unstable, losing its equilibrium in the long run. That's when a landslide breaks loose. When people are living down these hills or mountains, it's usually just a matter of time before disaster happens.

Causes of Landslides

While landslides are considered naturally occurring disasters, human-induced changes in the environment have recently caused their upsurge. Although the causes of landslides are wide ranging, they have 2 aspects in common; they are driven by forces of gravity and result from failure of soil and rock materials that constitute the hill slope:

Natural Causes of Landslides

- Climate: Long-term climatic changes can significantly impact soil stability. A general reduction in precipitation leads to lowering of water table and reduction in overall weight of soil mass, reduced solution of materials and less powerful freeze-thaw activity. A significant upsurge in precipitation or ground saturation would dramatically increase the level of ground water. When sloped areas are completely saturated with water, landslides can occur. If there is absence of mechanical root support, the soils start to run off.

- Earthquakes: Seismic activities have, for a long time, contributed to landslides across the globe. Any moment tectonic plates move, the soil covering them also moves along. When earthquakes strike areas with steep slopes, on numerous occasion, the soil slips leading to landslides. In addition, ashen debris flows instigated by earthquakes could also cause mass soil movement.
- Weathering: Weathering is the natural procedure of rock deterioration that leads to weak, landslide-susceptive materials. Weathering is brought about by the chemical action of water, air, plants and bacteria. When the rocks are weak enough, they slip away causing landslides.
- Erosion: Erosion caused by sporadic running water such as streams, rivers, wind, currents, ice and waves wipes out latent and lateral slope support enabling landslides to occur easily.
- Volcanoes: Volcanic eruptions can trigger landslides. If an eruption occurs in a wet condition, the soil will start to move downhill instigating a landslide. Stratovolcano is a typical example of volcano responsible for most landslides across the globe.
- Forest fires: Forest fires instigate soil erosion and bring about floods, which might lead to landslides.
- Gravity: Steeper slopes coupled with gravitational force can trigger a massive landslide.

Human Causes of Landslides

- Mining: Mining activities that utilize blasting techniques contribute mightily to landslides. Vibrations emanating from the blasts can weaken soils in other areas susceptible to landslides. The weakening of soil means a landslide can occur anytime.
- Clear cutting: Clear cutting is a technique of timber harvesting that eliminates all old trees from the area. This technique is dangerous since it decimates the existing mechanical root structure of the area.

Effects of Landslides

- Lead to economic decline: Landslides have been verified to result in destruction of property. If the landslide is significant, it could drain the economy of the region or country. After a landslide, the area affected normally undergoes rehabilitation. This rehabilitation involves massive capital outlay. For example, the 1983 landslide at Utah in the United States resulted in rehabilitation cost of about $500 million. The annual loss as a result of landslides in U.S. stands at an estimated $1.5 billion.
- Decimation of infrastructure: The force flow of mud, debris, and rocks as a result of a landslide can cause serious damage to property. Infrastructure such as roads, railways, leisure destinations, buildings and communication systems can be decimated by a single landslide.

- Loss of life: Communities living at the foot of hills and mountains are at a greater risk of death by landslides. A substantial landslide carries along huge rocks, heavy debris and heavy soil with it. This kind of landslide has the capacity to kills lots of people on impact. For instance, Landslides in the UK that happened a few years ago caused rotation of debris that destroyed a school and killed over 144 people including 116 school children aged between 7 and 10 years. In a separate event, NBC News reported a death toll of 21 people in the March 22, 2014, landslide in Oso, Washington.
- Affects beauty of landscapes: The erosion left behind by landslides leaves behind rugged landscapes that are unsightly. The pile of soil, rock and debris downhill can cover land utilized by the community for agricultural or social purposes.
- Impacts river ecosystems: The soil, debris, and rock sliding downhill can find way into rivers and block their natural flow. Many river habitats like fish can die due to interference of natural flow of water. Communities depending on the river water for household activities and irrigation will suffer if flow of water is blocked.

Types of Landslides

- Falls: Falls are sudden movements of loads of soil, debris, and rock that break away from slopes and cliffs. Falls landslides occur as a result of mechanical weathering, earthquakes, and force of gravity.
- Slides: This is a kind of mass movement whereby the sliding material breakaways from underlying stable material. The kinds of slides experienced during this type of landslide include rotational and transitional. Rotational slides are sometimes known as slumps since they move with rotation.

  Transitional slides consist of a planer or 2 dimensional surface of rupture. They involve landslide mass movement following a roughly planar surface with reduced rotation or backward slanting. Slides occur when the toe of the slope is undercut. They move moderately, and the consistency of material is maintained.
- Topples: Topple landslides occur when the topple fails. Topple failure encompasses the forward spinning and movement of huge masses of rock, debris, and earth from a slope. This type of slope failure takes place around an axis near or at the bottom of the block of rock. A topple landslide mostly lead to formation of a debris cone below the slope. This pile of debris is known as a Talus cone.
- Spreads: They are commonly known as lateral spreads and takes place on gentle terrains via lateral extension followed by tensile fractures.
- Flows: This type of landslide is categorized into five; earth flows, debris avalanche, debris flow, mudflows, and creep, which include seasonal, continuous and progressive.

Flows are further subcategorized depending upon the geological material, for example, earth, debris, and bedrock.

The most prevalent occurring landslides are rock falls and debris flow.

LAHAR

A lahar is a violent type of mudflow or debris flow composed of a slurry of pyroclastic material, rocky debris and water. The material flows down from a volcano, typically along a river valley.

Lahars are extremely destructive: they can flow tens of metres per second (22 mph or more), they have been known to be up to 140 metres (460 ft) deep, and large flows tend to destroy any structures in their path. Notable lahars include those at Mount Pinatubo and Nevado del Ruiz, the latter of which covered entire towns and killed thousands of people.

A lahar travels down a river valley in Guatemala near the Santa Maria volcano, 1989.

Causes

Lahars have several possible causes:

- Snow and glaciers can be melted by lava or pyroclastic surges during an eruption.
- Lava can erupt from open vents and mix with wet soil, mud or snow on the slope of the volcano making a very viscous, high energy lahar. The higher up the slope of the volcano, the more gravitational potential energy the flows will have.
- A flood caused by a glacier, lake breakout, or heavy rainfalls can generate lahars, also called glacier run or jökulhlaup
- Water from a crater lake, combined with volcanic material in an eruption.
- Heavy rainfall on unconsolidated pyroclastic deposits.
- Volcanic landslides mixed with water.

In particular, although lahars are typically associated with the effects of volcanic activity, lahars can occur even without any current volcanic activity, as long as the conditions are right to cause the collapse and movement of mud originating from existing volcanic ash deposits.

- Snow and glaciers can melt during periods of mild to hot weather.
- Earthquakes underneath or close to the volcano can shake material loose and cause it to collapse, triggering a lahar avalanche.

- Rainfall can cause the still-hanging slabs of solidified mud to come rushing down the slopes at a speed of more than 30 kilometres per hour (20 mph), causing devastating results.

Mudline left behind on trees on the banks of the Muddy River after the 1980 eruption of MountSt. Helens showing the height of the lahar.

Places at Risk

The aftermath of a lahar from the 1982 eruption of Galunggung, Indonesia.

Several mountains in the world, including Mount Rainier in the United States, Mount Ruapehu in New Zealand, Merapi and Galunggung in Indonesia, are considered particularly dangerous due to the risk of lahars. Several towns in the Puyallup River valley in Washington state, including Orting, are built on top of lahar deposits that are only about 500 years old. Lahars are predicted to flow through the valley every 500 to 1,000 years, so Orting, Sumner, Puyallup, Fife, and the Port of Tacoma face considerable risk. The USGS has set up lahar warning sirens in Pierce County, Washington, so that people can flee an approaching debris flow in the event of a Mount Rainier eruption.

A lahar warning system has been set up at Mount Ruapehu by the New Zealand Department of Conservation and hailed as a success after it successfully alerted officials to an impending lahar on 18 March 2007.

Since mid-June 1991, when violent eruptions triggered Mount Pinatubo's first lahars in 500 years, a system to monitor and warn of lahars has been in operation. Radio-telemetered rain gauges provide data on rainfall in lahar source regions, acoustic flow monitors on stream banks detect ground vibration as lahars pass, and manned watchpoints further confirm that lahars are rushing down Pinatubo's slopes. This system has enabled warnings to be sounded for most but not all major lahars at Pinatubo, saving hundreds of lives. Physical preventative measures by the Philippine government were not adequate to stop over 20 feet (6.1 m) of mud from flooding many villages around Mount Pinatubo from 1992 through 1998.

Scientists and governments try to identify areas with a high risk of lahars based on historical events and computer models. Volcano scientists play a critical role in effective hazard education by informing officials and the public about realistic hazard probabilities and scenarios (including potential magnitude, timing, and impacts); by helping evaluate the effectiveness of proposed risk-reduction strategies; by helping promote acceptance of (and confidence in) hazards information through participatory engagement with officials and vulnerable communities as partners in risk reduction efforts; and by communicating with emergency managers during extreme events. An example of such a model is TITAN2D. These models are directed towards future planning: identifying low-risk regions to place community buildings, discovering how to mitigate lahars with dams, and constructing evacuation plans.

Examples

Nevado Del Ruiz

The lahar from the 1985 eruption of Nevado del Ruiz that wiped out the town of Armero in Colombia.

In 1985, the volcano Nevado del Ruiz erupted in central Colombia. As pyroclastic flows erupted from the volcano's crater, they melted the mountain's glaciers, sending four enormous lahars down its slopes at 60 kilometers per hour (40 miles per hour). The lahars picked up speed in gullies and coursed into the six major rivers at the base of the volcano; they engulfed the town of Armero, killing more than 20,000 of its almost 29,000 inhabitants.

Casualties in other towns, particularly Chinchiná, brought the overall death toll to 23,000. Footage and photographs of Omayra Sánchez, a young victim of the tragedy, were published around the world. Other photographs of the lahars and the impact of the disaster captured attention worldwide and led to controversy over the degree to which the Colombian government was responsible for the disaster.

Mount Pinatubo

A before-and-after photograph of a river valley filled in by lahars from Mount Pinatubo.

The 1991 eruption of Mount Pinatubo caused lahars: the first eruption itself killed six people, but the lahar killed more than 1500. The eye of Typhoon Yunya passed over the volcano during its eruption on June 15, 1991. The rain from the typhoon triggered the flow of volcanic ash, boulders, and water down the rivers surrounding the volcano. In Pampanga, Angeles City and neighbouring cities and towns were damaged by the volcano's lahar when Sapang Balen Creek and the Abacan River became the channels for the mudflows and carried it to the heart of the city and surrounding areas.

Over 6 metres (20 ft) of mud inundated and damaged the towns of Castillejos, San Marcelino and Botolan in Zambales, Porac and Mabalacat City in Pampanga, Tarlac City, Capas, Concepcion and Bamban in Tarlac. The lahar in the Sacobia-Bamban River scoured all structures in its path, including the bridges and dikes by the Parua River in Concepcion. The Tarlac River in Tarlac City was inundated by over 6 metres (20 ft) of lahar, causing the river to lose the ability to hold water.

On the morning of October 1, 1995, pyroclastic material which clung to the slopes of Pinatubo and surrounding mountains rushed down because of heavy rain, and turned into an 8-metre (25 ft) lahar. This mudflow killed hundreds of people in Barangay Cabalantian in Bacolor. The Philippine government under President Fidel V. Ramos ordered the construction of the FVR Mega Dike in an attempt to protect people from further mudflows.

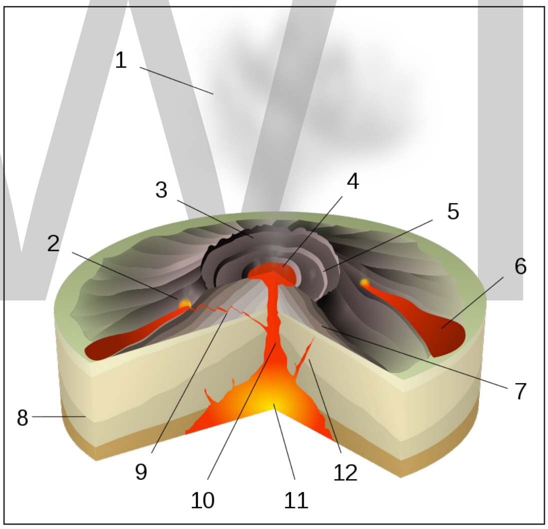
VOLCANIC ERUPTIONS

Volcanic eruptions happen when lava and gas are discharged from a volcanic vent. The most common consequences of this are population movements as large numbers of people are often forced to flee the moving lava flow. Volcanic eruptions often cause temporary food shortages and volcanic ash landslides called Lahar.

The most dangerous type of volcanic eruption is referred to as a 'glowing avalanche'. This is when freshly erupted magma forms hot pyroclastic flow which have temperatures of up to 1,200 degrees. The pyroclastic flow is formed from rock fragments following a volcanic explosion , the flow surges down the flanks of the volcano at speeds of up to several hundred kilometres per hour, to distances often up to 10 km and occasionally as far as 40 km from the original disaster site.

HAWAIIAN ERUPTION

A Hawaiian eruption is a type of volcanic eruption where lava flows from the vent in a relatively gentle, low level eruption; it is so named because it is characteristic of Hawaiian volcanoes. Typically they are effusive eruptions, with basaltic magmas of low viscosity, low content of gases, and high temperature at the vent. Very small amounts of volcanic ash are produced. This type of eruption occurs most often at hotspot volcanoes such as Kīlauea on Hawaii's big island and in Iceland, though it can occur near subduction zones (e.g. Medicine Lake Volcano in California, United States) and rift zones. Another example of Hawaiian eruptions occurred on the island of Surtsey in Iceland from 1964 to 1967, when molten lava flowed from the crater to the sea.



Hawaiian eruption: 1, Ash plume; 2, Lava fountain; 3, Crater; 4, Lava lake; 5, Fumarole; 6, Lava flow; 7, Layers of lava and ash; 8, Stratum; 9, Sill; 10, Magma conduit; 11, Magma chamber; 12, Dike.

Hawaiian eruptions may occur along fissure vents, such as during the eruption of Mauna Loa in 1950, or at a central vent, such as during the 1959 eruption in Kīlauea Iki Crater, which created a lava fountain 580 meters (1,900 ft) high and formed a 38-meter cone named Pu'u Pua'i. In fissure-type eruptions, lava spurts from a fissure on the volcano's rift zone and feeds lava streams that flow downslope. In central-vent eruptions, a fountain of lava can spurt to a height of 300 meters or more (heights of 1600 meters were reported for the 1986 eruption of Mount Mihara on Izu Ōshima, Japan).

Hawaiian eruptions usually start by the formation of a crack in the ground from which a curtain of incandescent magma or several closely spaced magma fountains appear. The lava can overflow the fissure and form a'ā or pāhoehoe style of flows. When such an eruption from a central cone is protracted, it can form lightly sloped shield volcanoes, for example Mauna Loa or Skjaldbreiður in Iceland.

Petrology of Hawaiian Basalts

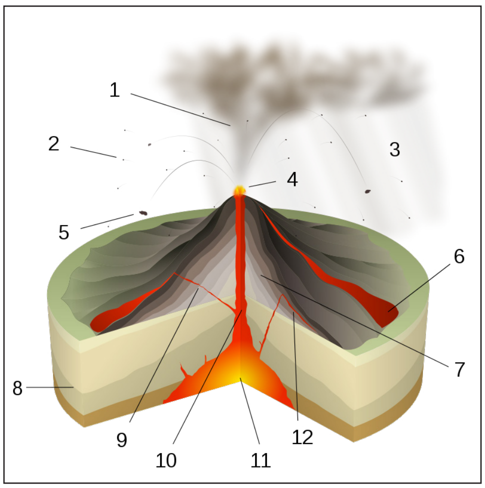
The key factors in generating a Hawaiian eruption are basaltic magma and a low percentage of dissolved water (less than one percent). The lower the water content, the more peaceful is the resulting flow. Almost all lava that comes from Hawaiian volcanoes is basalt in composition. Hawaiian basalts that make up almost all of the islands are tholeiite. These rocks are similar but not identical to those that are produced at ocean ridges. Basalt relatively richer in sodium and potassium (more alkaline) has erupted at the undersea volcano of Lōʻihi at the extreme southeastern end of the volcanic chain, and these rocks may be typical of early stages in the "evolution" of all Hawaiian islands. In the late stages of eruption of individual volcanoes, more alkaline basalt also was erupted, and in the very late stages after a period of erosion, rocks of unusual composition such as nephelinite were produced in very small amounts. These variations in magma composition have been investigated in great detail, in part to try to understand how mantle plumes may work.

Safety

Hawaiian eruptions are considered less dangerous than other types of volcanic eruptions, due to the lack of ash and the generally slow movement of lava flows. However, they can still cause injuries or deaths.

In 1993, a photographer attempting to take pictures of a lava ocean entry died, and several tourists were injured, when a lava bench collapsed. In 2000, two people were found dead near a lava ocean entry from Kīlauea, likely killed by laze. Sulfur Dioxide emissions can also be fatal, especially to people suffering from respiratory ailments. In 2018 lava spatter from Kīlauea broke a man's leg, and another 23 people on a tour boat were injured by a steam explosion at a lava ocean entry from the same eruption.

STROMBOLIAN ERUPTION



A diagram of a strombolian eruption: 1: ash plume, 2: lapilli, 3: volcanic ash fall, 4: lava fountain, 5: volcanic bomb,6: lava flow, 7: layers of lava and ash, 8: stratum, 9: dike, 10: magma conduit, 11: magma chamber, 12: sill.

A Strombolian eruption

Strombolian eruptions are relatively mild blasts having a volcanic explosivity index of about 1 to 3. Strombolian eruptions consist of ejection of incandescent cinders, lapilli, and lava bombs, to altitudes of tens to a few hundreds of metres. The eruptions are small to medium in volume, with sporadic violence. This type of eruption is named for the Italian volcano Stromboli.

The Italian vulcanologist Giuseppe Mercalli studied eruptions at Stromboli and Vulcano in 1888–1890, and observed that the characteristic features of eruptions were different between the two. To distinguish between them, Mercalli defined Strombolian eruptions as "Mildly explosive at discrete but fairly regular intervals of seconds to minutes".

The tephra typically glows red when leaving the vent, but its surface cools and assumes a dark to black colour and may significantly solidify before impact. The tephra accumulates in the vicinity of the vent, forming a cinder cone. Cinder is the most common product; the amount of volcanic ash is typically rather minor.

The lava flows are more viscous, and therefore shorter and thicker, than the corresponding Hawaiian eruptions; it may or may not be accompanied by production of pyroclastic rock.

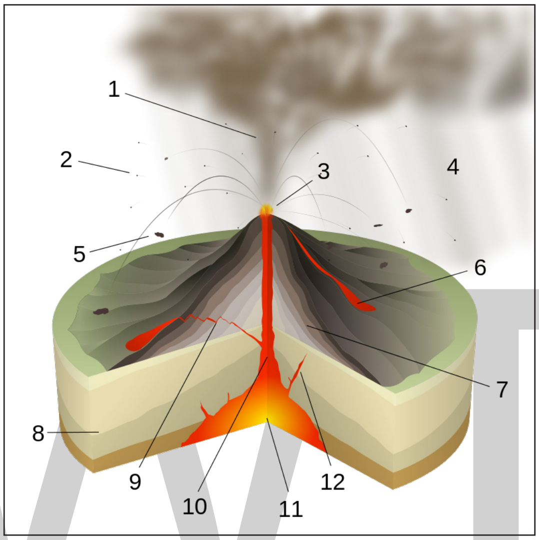
Instead the gas coalesces into bubbles, called gas slugs, that grow large enough to rise through the magma column, bursting near the top due to the decrease in pressure and throwing magma into the air. Each episode thus releases volcanic gases, sometimes as frequently as a few minutes apart. Gas slugs can form as deep as 3 kilometers, making them difficult to predict.

Strombolian eruptive activity can be very long-lasting because the conduit system is not strongly affected by the eruptive activity, so that the eruptive system can repeatedly reset itself.

Monogenetic cones usually erupt in the Strombolian style. For example, the Parícutin volcano erupted continuously between 1943–1952, Mount Erebus, Antarctica has produced Strombolian eruptions for at least many decades, and Stromboli itself has been producing Strombolian eruptions for over two thousand years. The Romans referred to Stromboli as the "Lighthouse of the Mediterranean".

VULCANIAN ERUPTION

The term Vulcanian was first used by Giuseppe Mercalli, witnessing the 1888–1890 eruptions on the island of Vulcano. His description of the eruption style is now used all over the world. Mercalli described Vulcanian eruptions as "Explosions like cannon fire at irregular intervals" Their explosive nature is due to increased silica content of the magma. Almost all types of magma can be involved, but magma with about 55% or more silica (e.g. basaltic andesite) is most common. Increasing silica levels increase the viscosity of the magma which means increased explosiveness.



Vulcanian eruption: 1 ash plume, 2 lapilli, 3 lava fountain, 4 volcanic ash fall, 5 volcanic bomb, 6 lava flow,7 layers of lava and ash, 8 stratum, 9 sill, 10 magma conduit, 11 magma chamber, 12 dike.

Characteristics

Vulcanian eruptions display several common characteristics. The mass of rock ejected during the eruption is usually between 102 - 106 tonnes and contains a high proportion of non-juvenile material (> 50%). During active periods of volcanic activity, intervals between explosions vary from less than 1 minute (e.g. Anak Krakatoa) to about a day. Pyroclastic flows are also common features of this type of eruption. The gas streaming phase of Vulcanian eruptions are characterised by discrete cannon-like explosions. These expulsions of gas can reach supersonic velocities resulting in shock waves.

The tephra is dispersed over a wider area than that from Strombolian eruptions. The pyroclastic rock and the base surge deposits form an ash volcanic cone, while the ash covers a large surrounding area. The eruption ends with a flow of viscous lava. Vulcanian eruptions may throw large metre-size blocks several hundred metres, occasionally up to several kilometres.

Vulcanian eruptions are dangerous to persons within several hundred metres of the vent. Volcanic bombs are common products of this type of eruption. These are initially molten blobs of lava, which rapidly cool into blocks often 2 to 3 m across. At Galeras, a Vulcanian eruption ejected bombs which struck several volcanologists who were in the crater, some of whom died or suffered severe injuries.

PELÉAN ERUPTION

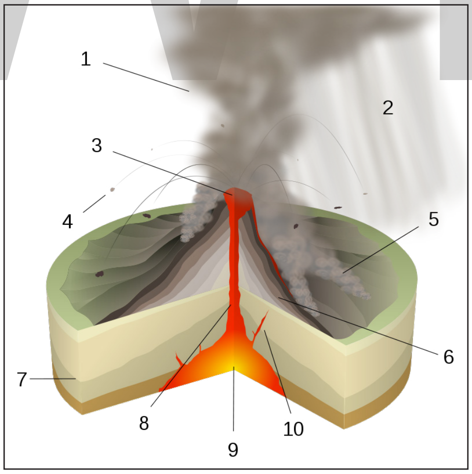
Peléan eruptions are a type of volcanic eruption. They can occur when viscous magma, typically of rhyolitic or andesitic type, is involved, and share some similarities with Vulcanian eruptions. The most important characteristic of a Peléan eruption is the presence of a glowing avalanche of hot volcanic ash, a pyroclastic flow. Formation of lava domes is another characteristic. Short flows of ash or creation of pumice cones may be observed as well.

The initial phases of eruption are characterized by pyroclastic flows. The tephra deposits have lower volume and range than the corresponding Plinian and Vulcanian eruptions. The viscous magma then forms a steep-sided dome or volcanic spine in the volcano's vent. The dome may later collapse, resulting in flows of ash and hot blocks. The eruption cycle is usually completed in a few years, but in some cases may continue for decades, like in the case of Santiaguito.

The 1902 explosion of Mount Pelée is the first described case of a Peléan eruption, and gave it its name.

Some other examples include the following:

- The 1948–1951 eruption of Hibok-Hibok.
- The 1951 eruption of Mount Lamington, which remains the most detailed observation of this kind.
- The 1968 eruption of Mayon Volcano.



Peléan eruption: 1 Ash plume, 2 Volcanic ash fall, 3 Lava dome, 4 Volcanic bomb, 5 Pyroclastic flow, 6 Layers of lava and ash, 7 Stratum, 8 Magma conduit, 9 Magma chamber, 10 Dike.

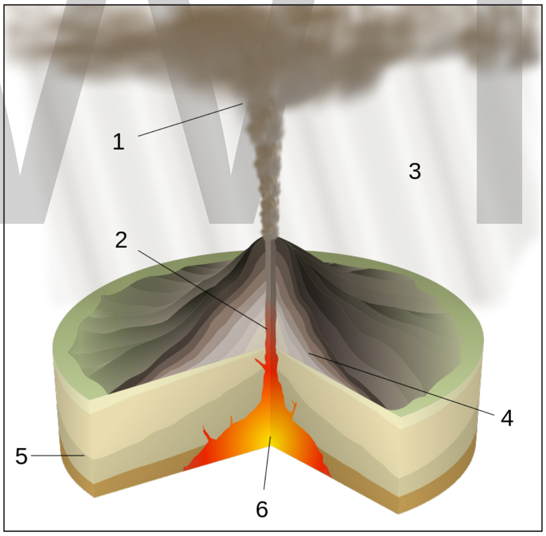
PLINIAN ERUPTION

Plinian eruptions or Vesuvian eruptions are volcanic eruptions marked by their similarity to the eruption of Mount Vesuvius in 79 AD, which destroyed the ancient Roman cities of Herculaneum and Pompeii. The eruption was described in a letter written by Pliny the Younger, after the death of his uncle Pliny the Elder.

Plinian/Vesuvian eruptions are marked by columns of volcanic debris and hot gases ejected high into the stratosphere, the second layer of Earth's atmosphere. The key characteristics are ejection of large amount of pumice and very powerful continuous gas-driven eruptions. According to the Volcanic Explosivity Index, Plinian eruptions have a VEI of 4, 5 or 6, sub-Plinian 3 or 4, and ultra-Plinian 6, 7 or 8.

Short eruptions can end in less than a day, but longer events can continue for several days or months. The longer eruptions begin with production of clouds of volcanic ash, sometimes with pyroclastic surges. The amount of magma erupted can be so large that it depletes the magma chamber below, causing the top of the volcano to collapse, resulting in a caldera. Fine ash and pulverized pumice can deposit over large areas. Plinian eruptions are often accompanied by loud noises, such as those generated by the 1883 eruption of Krakatoa. The sudden discharge of electrical charges accumulated in the air around the ascending column of volcanic ashes also often causes lightning strikes as depicted by the English geologist George Julius Poulett Scrope in his painting of 1822.

The lava is usually dacitic or rhyolitic, rich in silica. Basaltic, low-silica lavas are unusual for Plinian eruptions; the most recent basaltic example is the 1886 eruption of Mount Tarawera on New Zealand's North Island.



Plinian eruption: 1: ash plume, 2: magma conduit, 3: volcanic ash fall, 4: layers of lava and ash, 5: stratum, 6: magma chamber.

PHREATOMAGMATIC ERUPTION

Phreatomagmatic eruptions are volcanic eruptions resulting from interaction between magma and water. They differ from exclusively magmatic eruptions and phreatic eruptions. Unlike phreatic eruptions, the products of phreatomagmatic eruptions contain juvenile (magmatic) clasts. It is common for a large explosive eruption to have magmatic and phreatomagmatic components.

Ashfall deposit of phreatomagmatic origin, overlying magmatic lapilli fall deposit of magmatic origin.

Mechanisms

Several competing theories exist as to the exact mechanism of ash formation. The most common is the theory of explosive thermal contraction of particles under rapid cooling from contact with water. In many cases the water is supplied by the sea, for example with Surtsey. In other cases the water may be present in a lake or caldera-lake, for example Santorini, where the phreatomagmatic component of the Minoan eruption was a result of both a lake and later the sea. There have also been examples of interaction between magma and water in an aquifer. Many of the cinder cones on Tenerife are believed to be phreatomagmatic because of these circumstances.

The other competing theory is based on fuel-coolant reactions, which have been modeled for the nuclear industry. Under this theory the fuel (in this case, the magma) fragments upon contact with a coolant (the sea, a lake or aquifer). The propagating stress waves and thermal contraction widen cracks and increase the interaction surface area, leading to explosively rapid cooling rates. The two mechanisms proposed are very similar and the reality is most likely a combination of both.

Deposits

Phreatomagmatic ash is formed by the same mechanisms across a wide range of compositions, basic and acidic. Blocky and equant clasts with low vesicle content are formed. The deposits of phreatomagmatic explosive eruptions are also believed to be better sorted and finer grained than the deposits of magmatic eruption. This is a result of the much higher fragmentation of phreatomagmatic eruptions.

Hyaloclastite

Hyaloclastite is glass found with pillow basalts that were produced by non-explosive quenching and fracturing of basaltic glass. These are still classed as phreatomagmatic eruptions, as they produce juvenile clasts from the interaction of water and magma. They can be formed at water depths of >500 m, where hydrostatic pressure is high enough to inhibit vesiculation in basaltic magma.

Hyalotuff

Hyalotuff is a type of rock formed by the explosive fragmentation of glass during phreatomagmatic eruptions at shallow water depths (or within aquifers). Hyalotuffs have a layered nature that is believed to be a result of dampened oscillation in discharge rate, with a period of several minutes. The deposits are much finer grained than the deposits of magmatic eruptions, due to the much higher fragmentation of the type of eruption. The deposits appear better sorted than magmatic deposits in the field because of their fine nature, but grain size analysis reveals that the deposits are much more poorly sorted than their magmatic counterparts. A clast known as an accretionary lapilli is distinctive to phreatomagmatic deposits, and is a major factor for identification in the field. Accretionary lapilli form as a result of the cohesive properties of wet ash, causing the particles to bind. They have a circular structure when specimens are viewed in hand and under the microscope.

A further control on the morphology and characteristics of a deposit is the water to magma ratio. It is believed that the products of phreatomagmatic eruptions are fine grained and poorly sorted where the magma/water ratio is high, but when there is a lower magma/water ratio the deposits may be coarser and better sorted.

Surface Features

There are two types of vent landforms from the explosive interaction of magma and ground or surface water; tuff cones and tuff rings. Both of the landforms are associated with monogenetic volcanoes and polygenetic volcanoes. In the case of polygenetic volcanoes they are often interbedded with lavas, ignimbrites and ash- and lapilli-fall deposits. It is expected that tuff rings and tuff cones might be present on the surface of Mars.

Tuff Rings

Crest of old tuff ring, including part of the maar crater of a monogenetic volcano, Tenerife, Canary Islands.The maar crater has been used for agriculture.

Tuff rings have a low profile apron of tephra surrounding a wide crater (called a maar crater) that is generally lower than the surrounding topography. The tephra is often unaltered and thinly bedded, and is generally considered to be an ignimbrite, or the product of a pyroclastic density current. They are built around a volcanic vent located in a lake, coastal zone, marsh or an area of abundant groundwater.

Fort Rock, an eroded tuff ring in Oregon, USA.

Tuff Cones

Koko Crater is an old extinct tuff cone in the Hawaiian Island of Oahu.

Tuff cones are steep sloped and cone shaped. They have wide craters and are formed of highly altered, thickly bedded tephra. They are considered to be a taller variant of a tuff ring, formed by less powerful eruptions. Tuff cones are usually small in height. Koko Crater is 1,208 feet.

Examples of Phreatomagmatic Eruptions

Minoan Eruption of Santorini

Santorini is part of the Southern Aegean volcanic arc, 140 km north of Crete. The Minoan eruption of Santorini, was the latest eruption and occurred in the first half of the 17th century BC. The eruption was of predominantly rhyodacite composition. The Minoan eruption had four phases. Phase 1 was a white to pink pumice fallout with dispersal axis trending ESE. The deposit has a maximum thickness of 6 m and ash flow layers are interbedded at the top. Phase 2 has ash and lapilli beds that are cross stratified with mega-ripples and dune like structures. The deposit thicknesses vary from 10 cm to 12 m. Phases 3 and 4 are pyroclastic density current deposits. Phases 1 and 3 were phreatomagmatic.

1991 Eruption of Mount Pinatubo

Mount Pinatubo is on the Central Luzon landmass between the South China Sea and the Philippine Sea. The 1991 eruption of Pinatubo was andesite and dacite in the pre-climactic phase but only dacite in the climactic phase. The climactic phase had a volume of 3.7–5.3 km^3. The eruption consisted of sequentially increasing ash emissions, dome growth, 4 vertical eruptions with continued dome growth, 13 pyroclastic flows and a climactic vertical eruption with associated pyroclastic flows. The pre-climactic phase was phreatomagmatic.

Lake Taupo

The Hatepe eruption in 232+/-12 AD was the latest major eruption at Lake Taupo in New Zealand's Taupo Volcanic Zone. There was minor initial phreatomagmatic activity followed by the dry venting of 6 km^3 of rhyolite forming the Hatepe Plinian Pumice. The vent was then infiltrated by large amounts of water causing the phreatomagmatic eruption that deposited the 2.5 km^3 Hatepe Ash. The water eventually stopped the eruption though large amounts of water were still erupted from the vent. The eruption resumed with phreatomagmatic activity that deposited the Rotongaio Ash.

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Common Hydrologic Hazards

CHAPTER 4

Hydrologic hazards include hazards which are caused by water such as flood, tsunami, etc. This chapter has been carefully written to provide an easy understanding of the varied facets of these hydrologic hazards.

FLOOD

Floods are natural occurrences where an area or land that is normally dry abruptly becomes submerged in water. In simple terms, flood can be defined as an overflow of large quantities of water onto a normally dry land. Flooding happens in many ways due to overflow of streams, rivers, lakes or oceans or as a result of excessive rain.

Whenever flooding takes place, there is the possibility of loss of life, hardship to people, and extensive damage to property. This is because flooding can carry bridges, cars, houses, and even people. Flooding also destroys crops and can wipe away trees and other important structures on land. Some floods occur abruptly and recede quickly whereas others take several days or even months to form and to recede because of variation in size, duration, and the area affected.

Causes of Flooding

Many conditions result in flooding. Hurricanes, clogged drainages, and rainfall are some of the conditions that have led to flooding in various regions across the globe. Here are the leading causes of flooding.

1. Rain

Rain is the leading contributor to most of the flooding cases witnessed across the world. Too much rain causes water to flow overland contributing to flooding. In particular, it is due to high rainfall intensity over a prolonged period.

Depending on the rainfall distribution, the amount of rain, and soil moisture content, short rainfall period can also result in flooding. Light rains for longer periods – several days or weeks, can also result in floods. The rain water erosive force can weaken the foundations of buildings, causing tumbles and cracks.

2. River Overflows

Rivers or streams can overflow their banks. This happens when the river or stream holds more water upstream than usual, and it flows downstream to the neighboring low-lying areas, typically referred to as the floodplains. As a consequence, this creates a sudden discharge of water into the adjacent lands leading to flooding.

Dams in rivers may also at times overwhelm rivers when the carriage capacity is exceeded, causing the water to burst and get into the floodplains. Flood caused by river overflow has the potential of sweeping everything in its path downstream.

3. Lakes and Coastal Flooding

Lake and Coastal flooding occurs when large storms or tsunamis causes the water body to surge inland. These overflows have destructive power since they can destroy ill-equipped structures to withstand water's strength such as bridges, houses, and cars.

In the coastal areas, strong and massive winds and hurricanes drive water onto the dry coastal lands and give rise to flooding. The situation is even worsened when the winds blowing from the ocean carry rains in them. Sea waters from the tsunami or hurricane can cause widespread damage.

4. Dam Breakage

Dams are man-made structures used to hold water from flowing down from a raised ground. The potential energy stored in the dam water is used to generate electricity. At times, the walls can become weak and break because of overwhelming carriage capacity. Due to this reason, breakage of the dam can cause extensive flooding in the adjacent areas.

Flooding occurs when the embankments built along the sides of the river to stop high water from flowing onto the land breaks. Sometimes, the excess water from the dam is deliberately released from the dam to prevent it from breaking thereby causing floods.

5. Melting of the Glaciers and Mountain Tops

In the cold regions, ice and snows build up during the winters. When the temperature rises in summer, the accumulated snows and ice are subjected to melting resulting in vast movements of water into lands that are normally dry. Regions with mountains that have ice on top of them also experience the same outcome when the atmospheric temperature rises. This type of flooding is usually termed as snowmelt flood.

6. Clogged Drainages

Flooding also takes place when snowmelt or rainfall runoff cannot be channeled appropriately into the drainage systems forcing the water to flow overland. Clogged or lack of proper drainage system is usually the cause of this type of flooding.

The areas remain flooded until the stormwater systems or waterways are rectified. Instances where the systems or water ways are not rectified, the areas remain flooded until the excess water evaporates or is transpired into the atmosphere by plants.

COASTAL FLOODING

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:

- Wind setup
- Barometric setup
- 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

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.

Groynes are engineered structures that aim to prevent erosion of the beach front.

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 highbiomass 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

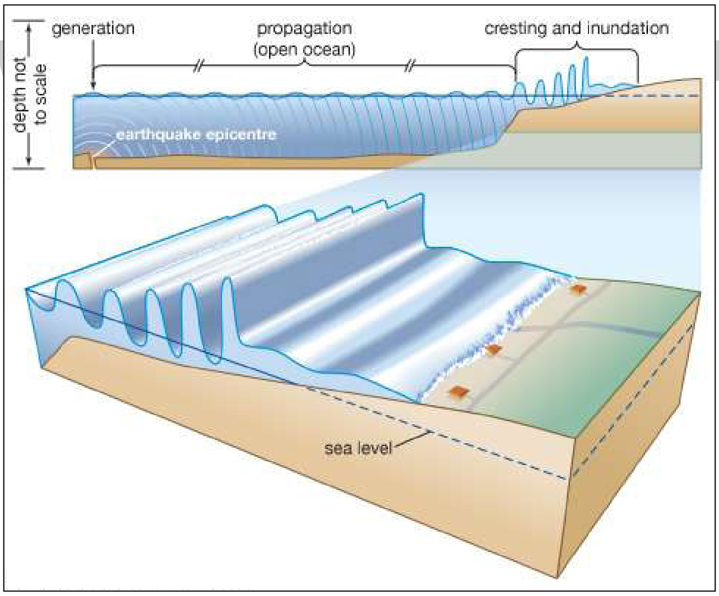
Coastal flooding can result in a wide variety of environmental impacts on different spatial and temporal scales. Flooding can destroy coastal habitats such as coastal wetlands and estuaries and can erode dune systems. These places are characterised by their high biological diversity therefore coastal 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.

TSUNAMI

Tsunami, also called as Seismic wave or Tidal Wave, is a type of catastrophic wave which is caused by 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.

Origin and Development

After an earthquake or other generating impulse occurs, a train of simple, progressive oscillatory waves is propagated great distances over the ocean surface in ever-widening circles, much like the waves produced by a pebble falling into a shallow pool. In deep water a tsunami can travel as fast as 800 km (500 miles) per hour. The wavelengths are enormous, about 100 to 200 km (60 to 120 miles), but the wave amplitudes (heights) are very small, only about 30 to 60 cm (1 to 2 feet). The waves' periods (the lengths of time for successive crests or troughs to pass a single point) are very long, varying from five minutes to more than an hour. These long periods, coupled with the extremely low steepness and height of the waves, enables them to be completely obscured in deep water by normal wind waves and swell. A ship on the high seas experiences the passage of a tsunami as an insignificant rise and fall of only half a metre (1.6 feet), lasting from five minutes to an hour or more.



Tsunami after being generated by an undersea earthquake or landslide, a tsunami may propagate unnoticed over vast reaches of open ocean before cresting in shallow water and inundating a coastline.

As the waves approach the coast of a continent, however, friction with the rising sea bottom reduces the velocity of the waves. As the velocity lessens, the wavelengths become shortened and the wave amplitudes (heights) increase. Coastal waters may rise as high as 30 metres (about 100 feet) above normal sea level in 10 to 15 minutes. The continental shelf waters begin to oscillate after the rise in sea level. Between three and five major oscillations generate most of the damage, frequently appearing as powerful "run-ups" of rushing water that uproot trees, pull buildings off their foundations, carry boats far inshore, and wash away entire beaches, peninsulas, and other low-lying coastal formations. Frequently the succeeding outflow of water is just as destructive as the run-up or even more so. In any case, oscillations may continue for several days until the ocean surface reaches equilibrium.

Much like any other water waves, tsunamis are reflected and refracted by the topography of the seafloor near shore and by the configuration of a coastline. As a result, their effects vary widely from place to place. Occasionally, the first arrival of a tsunami at a coast may be the trough of the wave, in which case the water recedes and exposes the shallow seafloor. Such an occurrence took place in the bay of Lisbon, Portugal, on November 1, 1755, after a large earthquake; many curious people were attracted to the bay floor, and a large number of them were drowned by the wave crest that followed the trough only minutes later.

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.

Extraterrestrial Tsunamis

Tsunami waves are not limited to Earth's surface. An analysis of the Martian surface conducted in 2016, which examined the desert planet's northern plains by using photographs and thermal imagery, revealed evidence of two separate tsunami events that occurred long ago. These events are thought to have been caused by comet or asteroid impacts.

SUBMARINE EARTHQUAKE

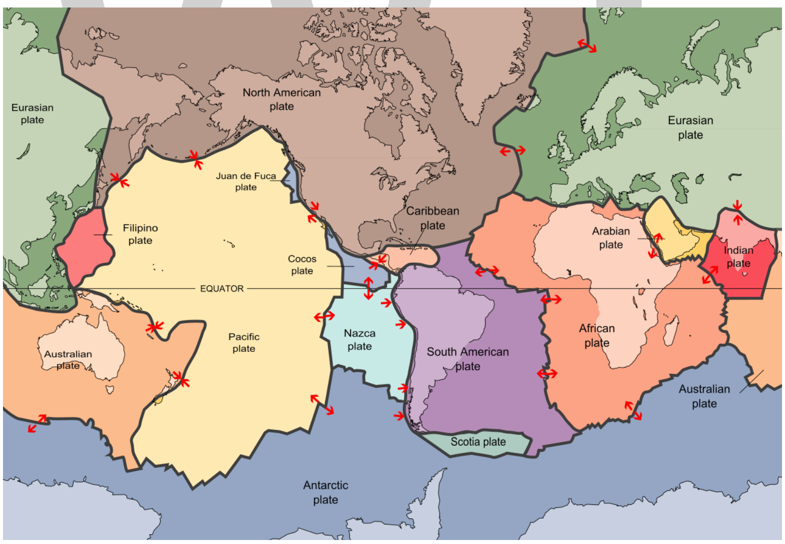
A submarine, undersea, or underwater earthquake is an earthquake that occurs underwater at the bottom of a body of water, especially an ocean. They are the leading cause of tsunamis. The magnitude can be measured scientifically by the use of the moment magnitude scale and the intensity can be assigned using the Mercalli intensity scale.

Understanding plate tectonics helps to explain the cause of submarine earthquakes. The Earth's surface or lithosphere comprises tectonic plates which average approximately 50 miles in thickness, and are continuously moving very slowly upon a bed of magma in the asthenosphere and inner mantle. The plates converge upon one another, and one subducts below the other, or, where there is only shear stress, move horizontally past each other. Little movements called fault creep are minor and not measurable. The plates meet with each other, and if rough spots cause the movement to stop at the edges, the motion of the plates continue. When the rough spots can no longer hold, the sudden release of the built-up motion releases, and the sudden movement under the sea floor causes a submarine earthquake. This area of slippage both horizontally and vertically is called the epicenter, and has the highest magnitude, and causes the greatest damage.

As with a continental earthquake the severity of the damage is not often caused by the earthquake at the rift zone, but rather by events which are triggered by the earthquake. Where a continental earthquake will cause damage and loss of life on land from fires, damaged structures, and flying objects; a submarine earthquake alters the seabed, resulting in a series of waves, and depending on the length and magnitude of the earthquake, tsunami, which bear down on coastal cities causing property damage and loss of life.

Submarine earthquakes can also damage submarine communications cables, leading to widespread disruption of the Internet and international telephone network in those areas. This is particularly common in Asia, where many submarine links cross submarine earthquake zones such as the Pacific Ring of Fire.

Tectonic Plate Boundaries

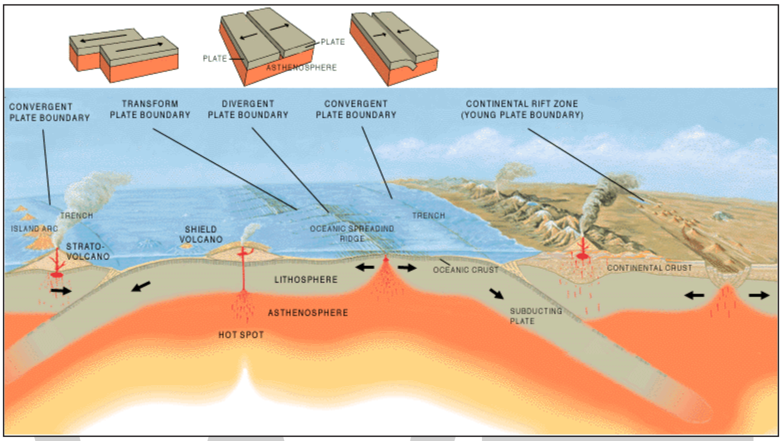


Tectonic plate boundaries, showing the directions of plate movements.

The different ways in which tectonic plates rub against each other under the ocean or sea floor to create submarine earthquakes. The type of friction created may be due to the characteristic of the geologic fault or the plate boundary as follows. Some of the main areas of large tsunami producing submarine earthquakes are the Pacific Ring of Fire and the Great Sumatran fault.

Convergent Plate Boundary

The older, and denser plate moves below the lighter plate. The further down it moves, the hotter it becomes, until finally melting altogether at the asthenosphere and inner mantle and the crust is actually destroyed. The location where the two oceanic plates actually meet become deeper and deeper creating trenches with each successive action. There is an interplay of various densities of lithosphere rock, asthenosphere magma, cooling ocean water and plate movement for example the Pacific Ring of Fire. Therefore, the site of the sub oceanic trench will be a site of submarine earthquakes; for example the Mariana Trench, Puerto Rico Trench, and the volcanic arc along the Great Sumatran fault.



Different kinds of boundaries.

Transform Plate Boundary

A transform-fault boundary, or simply a transform boundary is where two plates will slide past each other, and the irregular pattern of their edges may catch on each other. The lithosphere is neither added to from the asthenosphere nor is it destroyed as in convergent plate action. For example, along the San Andreas fault strike-slip fault zone, the Pacific Tectonic Plate has been moving along at about 5 cm/yr in a northwesterly direction, whereas the North American Plate is moving south-easterly.

Divergent Plate Boundary

Rising convection currents occur where two plates are moving away from each other. In the gap, thus produced hot magma rises up, meets the cooler sea water, cools, and solidifies, attaching to either or both tectonic plate edges creating an oceanic spreading ridge. When the fissure again appears, again magma will rise up, and form new lithosphere crust. If the weakness between the two plates allows the heat and pressure of the asthenosphere to build over a large amount of time, a large quantity of magma will be released pushing up on the plate edges and the magma will solidify under the newly raised plate edges If the fissure is able to come apart because of the two plates moving apart, in a sudden movement, an earthquake tremor may be felt for example at the Mid-Atlantic Ridge between North America and Africa.

HYDROLOGICAL DROUGHT

Hydrological drought refers to a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater.

It is part of the bigger drought phenomenon that denotes a recurrent natural hazard. Societies around the world are exposed to a multitude of natural hazards, such as earthquakes, volcanic eruptions, hurricanes, storms, tornadoes, floods, and droughts. Hydrological extremes (floods and hydrological droughts) are natural hazards that are not confined to specific regions, but occur worldwide and, therefore, impact a very large number of people. Flooding events receive most attention, both in the news and in scientific literature, due to their fast, clearly visible, and dramatic consequences. Drought events, also called 'the creeping disaster', develop slower and often unnoticed and have diverse and indirect consequences. Hydrological droughts can, however, cover extensive areas and can last for months to years, with devastating impacts on the ecological system and many economic sectors. Examples of affected sectors are drinking water supply, crop production (irrigation), waterborne transportation, electricity production (hydropower or cooling water).

Hydrological Drought Process

There are a multitude of relevant processes underlying the development and also the recovery of hydrological drought. In this topic, an overview is provided of the current knowledge of these processes.

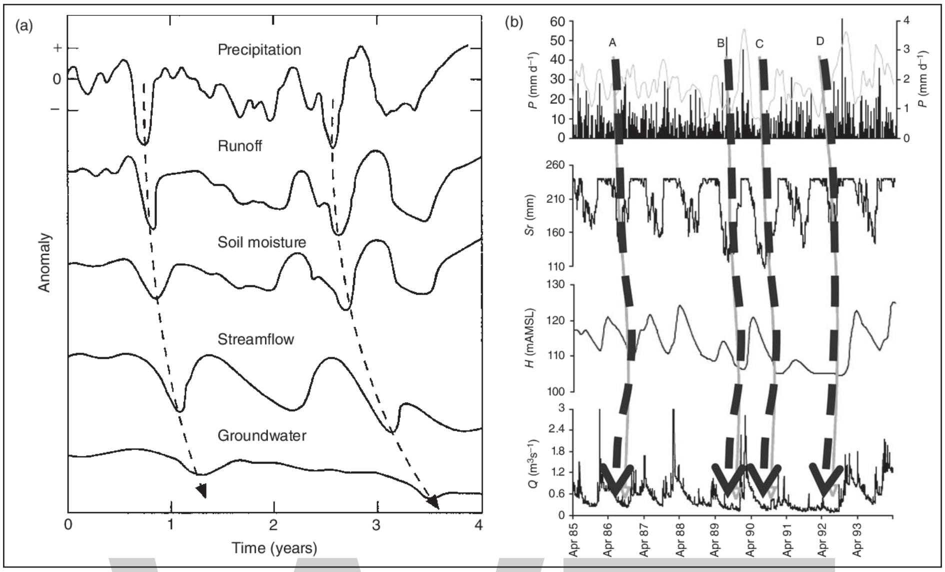
Drought Propagation

Reasons for the occurrence of hydrological drought are complex, because they are dependent not only on the atmosphere, but also on the hydrological processes that feed moisture to the atmosphere and cause storage of water and runoff to streams.

The atmospheric processes that are the starting point of hydrological drought development are a result of climatic variability. Generally, a prolonged precipitation deficiency generates less input to the hydrological system. Causative mechanisms of precipitation deficits can be blocking high-pressure systems and monsoon failure. Alternatively, hydrological drought can be triggered by anomalies in temperature, such as prolonged freezing conditions in winter in snow-dominated catchments or low temperatures in summer in glacier-dominated catchments. Both temperature and precipitation anomalies can be associated with largescale atmospheric or ocean patterns like ENSO, NAO, and sea surface temperatures.

Depletion of soil moisture storage is related to its antecedent condition, evaporation from bare soil, evapotranspiration through plants, drainage to the groundwater, and runoff to streams. During a dry spell, drainage and runoff are usually low, but potential evapotranspiration can increase due to increased radiation, wind speed, or vapor pressure deficit (e.g., caused by a decreased moisture availability or an increased temperature). This can lead to increased actual evapotranspiration, resulting in an extra loss of water from the soil and open water bodies. In extreme drought, a lack of available soil moisture and wilting of plants can limit evapotranspiration, thus limiting a further soil moisture depletion, but possibly also limiting locally generated precipitation, contributing to the maintenance of drought conditions. Vegetation is an important factor in modifying these feedbacks. Examples with evidence for strong feedbacks are given in D'Odorico and Porporato, Teuling et al., Bierkens and van den Hurk, Dekker et al., Ivanov et al., and Seneviratne et al.

The depletion of soil moisture storage causes a decreased recharge to the groundwater system, resulting in declining groundwater levels. Actual groundwater levels are dependent on the preevent conditions and the rate of decline, which again depends on the amount of recharge and discharge and the storage characteristics of the aquifer.



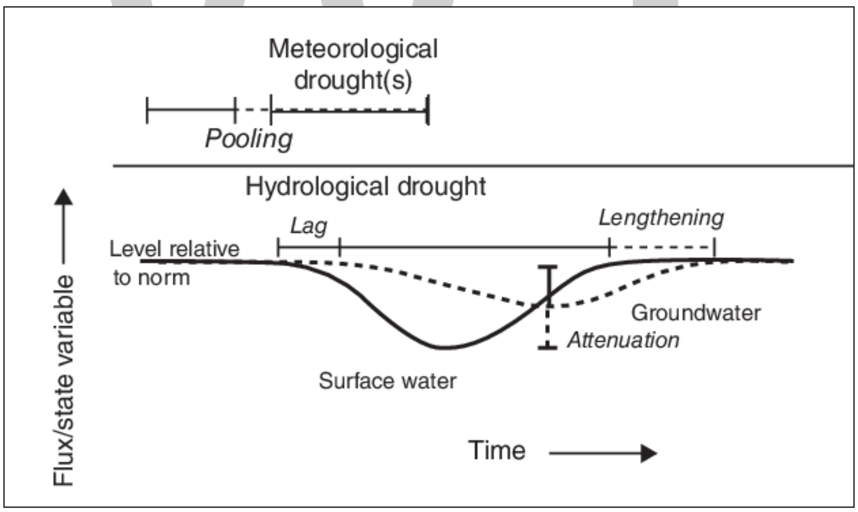
Propagation of a precipitation anomaly through the terrestrial part of the hydrological cycle for various variables, (a) synthetic time series 80: 0, mean, +, positive anomaly, –, negative anomaly, (b) time series of the Pang catchment53 (UK): P, precipitation, Sr, soil moisture storage in the root zone, H, groundwater level, and Q, streamflow. Propagation of drought events is indicated by the arrows. Note that the order of the variables is different in (a) and (b).

The reaction of groundwater to climatic input is often delayed and smoothed, a groundwater drought does not always develop, but when it does it often shows long periods of below-normal groundwater levels. As discharge is strongly linked to storage, low groundwater levels lead to decreased groundwater discharge, which slows down the drying process of the aquifer, but also causes decreased streamflow e.g. During drought the main contribution to discharge is via these slow pathways of groundwater discharge (baseflow). The fast pathways that contribute to discharge during wetter periods (surface runoff, interflow) are usually limited during drought. This chain of processes is summarized with the term 'drought propagation', which denotes the change of the drought signal as it moves through the terrestrial part of the hydrological cycle.

The relationship between precipitation, soil moisture, runoff, recharge, groundwater, and dis-charge is an old concept in hydrology, but the application of this knowledge to drought is relatively recent. The first research addressing changes in the drought signal due to propagation through the hydrological cycle was done in Illinois, USA, by Changnon Jr and Eltahir and Yeh. The latter were the first to use the word 'propagation' in the context of the translation from meteorological to hydrological drought. This work was continued by Peters who published a study on the propagation of drought in groundwater. In recent years, drought propagation has been studied by, among others, Tallaksen and Van Lanen, Peters et al., Van Lanen, Tallaksen et al., Tallaksen et al., Di Domenico et al., Vidal et al., and Van Loon.

Note that in the climate community the term 'drought propagation' is sometimes used for the spatial migration of a drought event, due to atmospheric transport of anomalously warm and dry air. For example, in eastern China and west ern USA, a southward migration of meteorological drought was found and in Europe, droughts starting in southern Europe were found to spread northwards. In this paper, we use the term ‘drought propagation’ strictly for the translation from anomalous meteorological conditions to hydrological drought.

The propagation of drought by means of (1) synthetic time series of anomalies in different hydro-meteorological variables by Changnon Jr, and (2) a real-world example from the Pang catchment (UK) by Peters. The general differences between the variables (in both figure (a) and (b)) are: many anomalies in precipitation, fewer and smaller anomalies in soil moisture, and fewer and longer anomalies in groundwater. Streamflow occupies an intermediate position in this sequence, because it is a composite of fast (direct runoff and interflow) and slow (baseflow) flow routes within a catchment. The relative position of streamflow in relation to soil moisture and groundwater is different for different areas, i.e., if a river is mainly discharging groundwater (like the Pang catchment) the streamflow drought signal is comparable to the groundwater drought signal. In figure (a), it should also be noted that the hydrological drought of year 1 is followed by a long period with sufficient recharge to let the system recover to its original state, whereas the drought in year 3 is not compensated by sufficient recharge to assure a complete recovery of the system. The positive precipitation anomaly after the drought in year is almost completely used to recover soil moisture levels and little remains for recovering streamflow and groundwater levels. If the system does not recover before the next meteorological drought develops it turns into a multiyear drought, as is apparent in the groundwater signal. This is also visible in the time series of the Pang catchment (drought C and D in figure (b)).



Features characterizing the propagation of meteorological drought(s) to hydrological drought: pooling, lag, attenuation, and lengthening.

Propagation of drought is characterized by a number of features, which are related to the fact that the terrestrial part of the hydrological cycle acts as a low-pass filter to the meteorological forcing. Here, they are shortly summarized and visualized in figure.

- Pooling: Meteorological droughts are combined into a prolonged hydrological drought.
- Attenuation: Meteorological droughts are attenuated in the stores, causing a smoothing of the maximum negative anomaly.

- Lag: A lag occurs between meteorological, soil moisture, and hydrological drought, i.e., the timing of the onset is later when moving through the hydrological cycle.
- Lengthening: Droughts last longer when moving from meteorological drought via soil moisture drought to hydrological drought.

These features are controlled by catchment characteristics and climate. Lag and attenuation are governed by catchment control, and pooling and lengthening by both catchment control and climate control.

Climate Control on Hydrological Drought

Drought propagation is dependent on climate. A broad overview is given of hydroclimatological regimes and potential for drought development in different climates around the world. Recent global-scale studies on the effect of climate on hydrological drought are for example Van Lanen et al. and Van Loon et al.

In general, hydrological droughts develop differently in relatively constant climates as compared with climates with strong seasonality. In a constant climate, the main factor for drought development is a below-normal precipitation (possibly combined with higher than normal potential evapotranspiration). In a seasonal climate, additional processes lead to the development of summer or winter droughts. In warm seasonal climates, most recharge occurs in a distinct wet season. A drought in this wet season decreases storage and can influence dry-season conditions. During the dry season, potential evapotranspiration is generally higher than precipitation, which potentially gives evapotranspiration a larger role in drought development. This type of hydrological drought is termed wet-to-dry-season drought in Van Loon and Van Lanen and was found to occur predominantly in Mediterranean, savannah, and monsoonal climates.

The role of evapotranspiration, however, is still highly uncertain. For example, Kriauciuniene et al. found that in Lithuanian rivers (based on data starting in 1810) precipitation was more important than temperature (reflecting evapotranspiration) for the timing of dry periods in summer. Teuling et al., however, Drought Propagation Processes (Including Development and Recovery) per Hydrological Drought Type and Subtype argue in favor of a large contribution of anomalies in evapotranspiration to anomalies in storage, based on observational evidence from central and western European catchments.

Hydrological Drought Type	Governing Process(es)	Development	(Lack of)Recovery
Classical rainfall deficit	Rainfall deficit (in any season)	P control	P control
Rain-to-dry-season drought	Rainfall deficit in rain season, drought continues into dry season	P control	T control
Wet-to-dry-season drought	Rainfall deficit in wet season, drought continues into dry season	P control	P and T control
Cold snow season drought	Low temperature in snow season, leading to;		
Subtype A	Early beginning to snow season	T control	T control
Subtype B	Delayed snow season	T control	T control

Subtype C	No recharge	T control	T control
Warm snow season drought	High temperature in snow season, leading to:		
Subtype A	Early snow melt	T control	P control
Subtype B	In combination with rainfall deficit, no recharge	P and T control	P control
Snowmelt drought	Lack of snowmelt in spring due to low P and high T in winter	P and T control	P control
Glaciermelt drought	Lack of glaciermelt in summer due to low T in summer	T Control	P and T control
Composite drought	Combination of a number of drought events over various seasons	P and T control	P control

In seasonal climates with below-zero temperatures and snow accumulation in winter, snow-related processes play a role in drought development. Snow accumulation and frozen soils cause storage of water and prevent recharge to the groundwater, resulting in decreasing groundwater levels and streamflow throughout the winter. Early or late snow melt influences hydrological processes, namely the timing of recharge and discharge to streams. Barnett et al. and Van Loon et al. found that not only the timing of the snowmelt (or glaciermelt) is important, but also the amount. A lack of snow or glaciermelt can cause water deficiencies in the high flow season. Frozen soils have a dual effect on drought development. On the one hand they immobilize water in the winter season, but on the other hand they can cause a fast direct runoff when snow melt and rainfall during the (early) melting period cannot infiltrate into the soil. This then leads to less recharge to the groundwater system, which can eventually enhance a summer drought in groundwater. However, many studies indicate that the effect of soil frost enhancing surface runoff during snow melt is limited, at least in forested catchments.

In monsoon climates, dry and wet seasons alternate, due to large-scale atmospheric processes. As this is the normal situation in these climates, such a dry season is normally not defined as a 'drought'. A drought occurs when the onset of the monsoon is delayed or a complete or partial failure of the monsoon takes place. This results in a lack of soil moisture replenishment and recharge after the dry season, causing storage to decrease to below-normal levels.

In arid climates, dry periods are irregular and can last long due to erratic precipitation. Streamflow in these climates is highly dependent on groundwater discharge, showing a long recession during periods without rain. These differences in processes underlying drought development in different climates pose challenges to drought quantification.

Catchment Control on Hydrological Drought

According to Van Lanen et al. catchment control is as important for hydrological drought as climate control. The propagation of a drought in a fast responding catchment differs from that in a slow responding catchment, i.e., pooling, lag, attenuation, and lengthening of the drought signal are influenced by the catchment characteristics. Not only the hydrological variables discharge and groundwater levels themselves are related to catchment characteristics e.g., but also the dry anomalies of these variables, i.e., low flow and drought, as has been shown in many studies. For instance, Keyantash and Dracup related drought severity to surface-water storage, Engeland et al. determined regression equations between low-flow indices and catchment characteristics, Tokarczyk and Jakubowski concluded that different types of rock result in a different development of low flow. Eng and Milly evaluated from previous studies which catchment parameters show a significant relation with low-flow characteristics and found that catchment area and soil type are important. Van Lanen et al. provide a comprehensive overview of the mechanisms by which hydrological processes and catchment characteristics influence hydrological drought. Smakhtin, Demuth and Young, and Laaha et al. do the same for low flows, showing the relationship between low-flow indices and catchment characteristics.

When the response time of a catchment is very long, lag times between meteorological and hydrological drought are very long as well, which can cause a hydrological drought to occur in a different season than the meteorological drought that is causing it. A lack of recharge in winter can then be an important factor in causing a hydrological drought in summer in some slow responding catchments. Peters et al., for example, found that in a specific groundwater-fed catchment in the UK a sequence of dry winters resulted in a multiyear drought. Marsh et al., Parry et al. and Kendon et al. put that study in a longer term and wider spatial perspective by showing that multiyear droughts due to a number of dry winters in a row are recurrent in northwestern Europe. Multiyear droughts are also called composite droughts by Van Loon and Van Lanen, because drought events with different causing mechanisms are combined. Parry et al. investigated characteristics, spatiotemporal evolution, and synoptic climate drivers of multiyear drought events in Europe and found considerable differences between the events.

For hydrological drought development, the most important catchment characteristic is the storage capacity of a catchment. Major stores in a catchment are: snow and glaciers, peat swamps and bogs, the soil column (in particular when groundwater levels are low), the groundwater system, and lakes and reservoirs. These stores create a long memory in the hydrological system, which determines the transformation of the drought signal. In general, storage in a catchment is determined by factors such as the climate (in case of snow and glaciers) and the geology of the catchment (i.e., percentage of hard rock and types of rock), topography, soil (e.g., soil texture and structure), drainage network, land use, and vegetation. Van Loon and Laaha showed that none of these factors is dominant in explaining streamflow drought severity. Only the combination of a large number of storage factors could explain variability in drought duration in a large number of catchments in Austria.

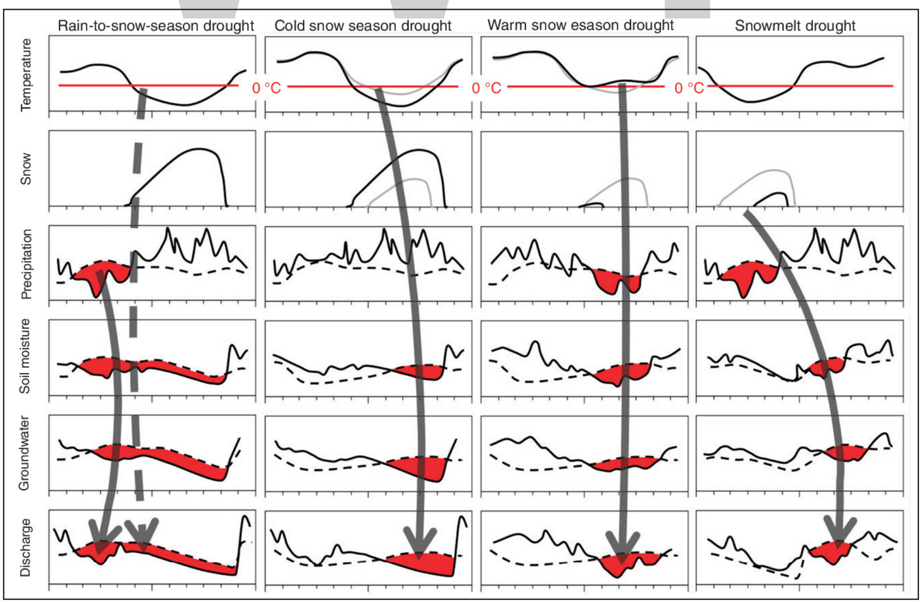
Aquifers are the dominant source of water storage in many regions around the world. Aquifer characteristics, therefore, have a strong influence on hydrological drought development and recovery. Stoelzle et al., for example, found that in Germany karstic and fractured aquifers have a short-term sensitivity to drought, whereas porous and complex aquifers have a more long-term sensitivity to drought. In porous and complex aquifers drought propagation is more catchment-controlled than in karstic and fractured aquifers. For the UK, similar results were found by Bloomfield and Marchant: in fractured aquifers (e.g., chalk) groundwater drought characteristics were determined by the recharge time series, whereas in granular aquifers (e.g., sandstones) intrinsic saturated flow and storage properties of the aquifer were dominant.

Not all catchment characteristics are constant, some change over time. Some change over geological time scales, some change on an interannual of intraannual time scale (like a seasonal snow cover), and some change within a drought event. Eltahir and Yeh, for example, found that drainage density is dependent on groundwater level and thus on the drought state of the system. This nonlinear behavior of storage factors results in an asymmetric response of streamflow to a drought signal.

Hydrological Drought Types

Parallel to the flood types of Merz and Bloschl, classifying floods into long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods, Van Loon and Van Lanen85 and Van Loon et al. developed a hydrological drought typology. They classified hydrological droughts based on their causing factors and propagation processes into classical rainfall deficit drought, rain-to-snow-season drought, wet-to-dry-season drought, cold snow season drought, warm snow season drought, snowmelt drought, glaciermelt drought, and composite drought. Table summarizes the underlying processes for each hydrological drought type, related to precipitation (P control), temperature (T control), or a combination of both. Above-normal evapotranspiration was not found to be the cause of hydrological drought. Evapotranspiration can aggravate a drought event and, in a dry season, can prevent recovery, but it has not been found to be the sole cause of hydrological drought.

On the basis of this research, the examples in figure have been developed as alternative drought propagation graphs instead of figure. Temperature-based processes are important for the development of hydrological drought just as they are for floods, as is reflected by a number of flood types that are related to air temperature, such as rain-on-snow and snowmelt floods. In Merz and Bloschl, two out of five flood types were (partly) governed by T control, whereas for the drought typology T control played a role in five to six out of the eight types. And these temperature-controlled drought types also ranked higher than the precipitation-controlled drought types in the selection of the most severe drought events in the case study areas of Van Loon and Van Lanen. In an application of the hydrological drought typology to global scale, Van Loon et al. found that drought characteristics of hydrological drought types can be distinctly different.

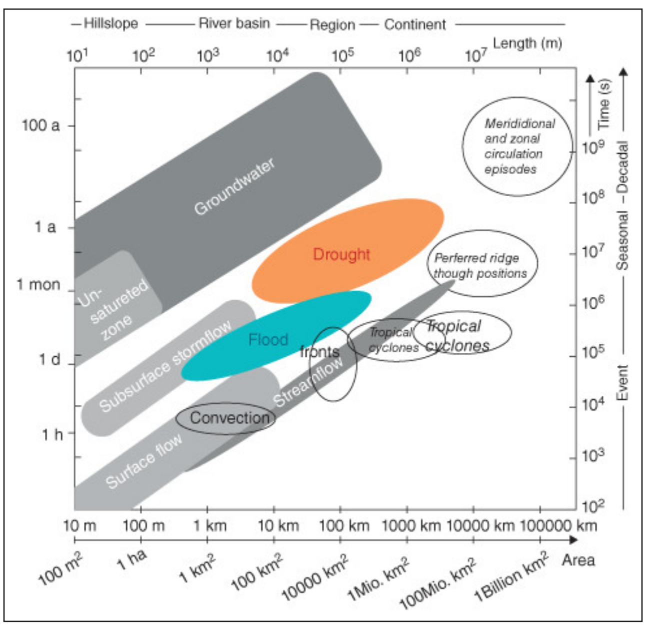


Synthetic time series representing the propagation of a meteorological anomaly (precipitation and/or temperature) through the terrestrial hydrological cycle for a selection of hydrological drought types. The x-axis represents one year and the tick marks indicate the months. The black lines are the time series of each hydrometeorological variable, the gray lines in the upper two rows are long-term averages of air temperature and snow, the dashed lines represent the threshold levels, and the red surfaces indicate drought events. Propagation of drought events is indicated by the arrows, dashed arrows represent a lack of recovery of the hydrological drought (meteorological drought ceased).

Making the distinction between hydrological drought types is important for statistical analysis, attribution of change, and prediction of hydrological drought development and recovery. The different processes underlying hydrological drought development should not be confused in trend analysis or climate change impact assessment. The hydrological drought typology is a recent development based on a limited number of catchments and modeling on the global scale. It urgently needs validation in a wider range of catchments, especially to test its use in more practical applications.

Hydrological Drought Scales and Spatial Characteristics

As was mentioned previously, droughts occur on other time and spatial scales than floods. Figure relates the scale of drought to typical scales of meteorological and hydrological phenomena. Droughts typically occur on catchment to continental scales, but there are also differences in scale between meteorological and hydrological drought. Tallaksen et al. found that, for a small (170 km^2) and relatively uniform catchment in the UK, meteorological droughts are short (1–2 months) and frequently cover the whole catchment, whereas hydrological droughts have a longer duration (4–5 months) and cover a smaller area. Meteorological droughts are dependent on large-scale atmospheric drivers that usually cover a large area. In contrast, the spatial pattern of hydrological drought is more patchy, because it is more dependent on local catchment characteristics and how they change the drought signal when it propagates through the terrestrial hydrological cycle. Zaidman et al. found the same for the 1976 drought in Europe and concluded that there was a higher level of autocorrelation in the streamflow time series than in the precipitation time series, resulting in a lower areal coverage, but higher persistence in streamflow droughts.



Spatial and temporal scales of hydrological processes including floods and droughts..

This was confirmed by Hannaford et al. concluding that also for other events meteorological droughts in European regions were more coherent than hydrological droughts. However, large differences existed between regions and methodological differences in the calculation of indices might have influenced this conclusion. In regions where convective thunderstorms are the dominant precipitation type and catchment conditions are relatively uniform, spatial drought patterns might be reversed, with more patchy meteorological droughts and spatially more coherent hydrological droughts. Trambauer et al., for example, found a higher spatial variability in meteorological and soil moisture drought indices than in a groundwater drought index for a specific drought year in model results of the Limpopo basin in Africa.

Depending on the scale, different processes are dominant. For example, in large catchments elevation differences result in a large variation in precipitation and temperature over the catchment. This leads to high spatial variability, which dampens the spatial development of hydrological drought. Also the travel time within the catchment needs to be taken into account in large catchments, as it results in a different response in upstream and downstream parts of the catchment. Pandey et al. found that the upper reaches of the Betwa river (43,000 km2) in India were more prone to severe drought than the lower reaches. Trambauer et al. also noted differences between the subbasins and the total basin of the Limpopo basin (415,000 km2) in Africa. Even in a small catchment spatial variation can be important. Peters et al. for example, found that for the Pang catchment (170 km^2) in the UK short groundwater droughts are more severe near the stream and are attenuated at greater distances. Long periods of below-normal recharge have relatively more effect near the groundwater divide.

Other important spatial aspects of drought are synchronicity, clustering and breaking up of drought clusters. Most studies focused on spatial aspects of meteorological drought e.g., there has been relatively limited research on the spatial aspects of hydrological drought. One of the first clustering methods suitable for hydrological drought is the algorithm developed by Andreadis etal. for droughts in soil moisture and runoff in the USA. This clustering algorithm has subsequently been applied by Sheffield et al. and Wang for soil moisture drought analysis on a global scale and in China, respectively. In these studies, severity-area-duration (SAD) curves have been applied to identity severe drought events and study their characteristics and trends. Following Andreadis et al., Vidal et al. developed a clustering algorithm for meteorological and agricultural drought in France, which was applied by Vidal et al. for the evaluation of the impacts of climate projections on drought characteristics. Corzo Perez et al. proposed a further methodological development for the spatiotemporal characterization of hydrological drought on the global scale, allowing for runoff drought cluster evaluation at each time step. Tallaksen and Stahl153 used the annual maximum drought cluster area as a measure of drought severity to compare large-scale model results and observations for runoff drought in Europe. They concluded that different groups of models can be distinguished based on their ability to estimate drought cluster area.

Other drought studies that do not specifically use clustering algorithms, but do include a spatial dimension are Burn and DeWit, Changnon, Zaidman et al., Peters et al., Tallaksen et al., Santos et al., and Van Huijgevoort et al.

Hydrological Drought Recovery

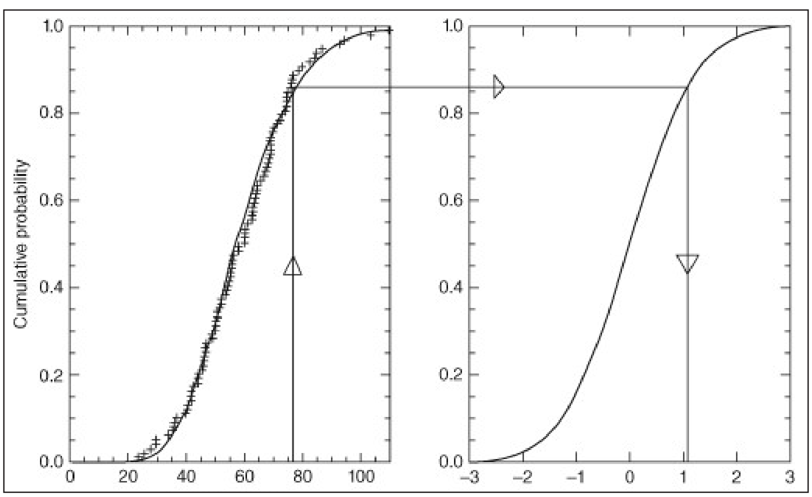
Research focusing specifically on hydrological drought recovery is still limited. Andreadis et al. found that, using model results for the USA, droughts in runoff recover more quickly than droughts in soil moisture in response to a precipitation event. Pan et al. found significant uncertainty in soil moisture drought recovery using a probabilistic framework focusing on precipitation in central USA. Van Loon and Van Lanen stated that hydrological drought recovery can be hampered by snow accumulation in cold seasonal climates and by evapotranspiration in warm seasonal climates. Parry et al. were the first to propose a quantitative methodology specifically aimed at characterizing hydrological drought termination. They tested the new methodology on long records of streamflow and groundwater levels for the Thames river in the UK and argue for further application of the approach to better understand the processes underlying drought termination in contrasting climates and catchment types.

Hydrological Drought Quantification

For adequate drought management, quantification of hydrological drought is essential. This includes identification of historical droughts and prediction of future droughts.

Drought Identification and Indices

In order to understand hydrological drought processes and impacts, drought characteristics such as the timing, duration, severity (or intensity), and spatial extent of a drought event need to be identified. Their slow onset and slow recovery, the different drought categories and impacted sectors make droughts very difficult to define quantitatively, giving rise to a multitude of indices. Reviews of drought indices can be found in Heim Jr., Keyantash and Dracup, Hisdal et al., Niemeyer et al., Mishra and Singh, Wanders et al., Dai, Sheffield and Wood, Seneviratne et al., and Tsakiris et al. The choice of index and its implementation are important as they can result in different conclusions, especially in the light of trends and global change. However, there seems to be scientific consensus that there is no 'best' hydrological drought index and that a quest for the 'best' index is useless. Every type of index, focusing on a specific part of the hydrological cycle or using a specific methodology, has its merit for a specific application and multiple indices should be used to quantify the diversity of drought impacts .



Methodology to determine the Standardized Precipitation Index.

In this topic, we do not go into details on the multitude of existing drought indices. Instead we focus on a few widely used groups of indices for the characterization of hydrological drought, including some meteorological and soil moisture drought indices that are frequently used in drought propagation studies or to represent hydrological drought. Drought indices can roughly be divided into standardized indices and threshold-based indices.

Standardized Drought Indices

One group of drought indices are standardized drought indices. They have in common that they represent anomalies from a normal situation in a standardized way. The advantage is that regional comparison of drought values is possible. A drawback of standardized indices is that the severity of a drought event is expressed only in relative terms, while in water resources management absolute values of the lacking amount of water with regard to 'normal' conditions (i.e., deficit volume) are needed. The set of standardized drought indices (including those focusing on hydrological drought) originate from the Standardized Precipitation Index (SPI).

SPI is the most-used standardized meteorological drought index. It is based on long-term precipitation records that are fitted to a probability distribution. This distribution is then transformed to a normal distribution, ensuring zero mean and unit standard deviation. Because precipitation has a high spatial and temporal variability, meteorological drought indices often use monthly values. SPI can be computed over several time scales and thus indirectly considers effects of accumulating precipitation deficits.

Experts participating in a WMO drought workshop in 2009 recommended that the SPI be used by all National Meteorological and Hydrological Services (NMHSs) around the world to characterize meteorological drought. Advantages of SPI are that its calculation results in normalized values and that it can be computed for different time scales.8 Disadvantages of SPI are that only precipitation is considered, while other meteorological drivers might be important too. Additionally, the length of a precipitation record and the fitted probability distribution have significant impact on the SPI values. Finding the most suitable distribution can be a challenge, especially in dry climates, which limits the use of SPI on a global scale.

As precipitation is not the only meteorological variable influencing drought conditions, some meteorological indices also include (a proxy for) evapotranspiration. As an alternative for SPI, Vicente-Serrano et al. developed the Standardized Precipitation and Evapotranspiration Index (SPEI). SPEI considers cumulated anomalies of the climatic water balance (precipitation minus potential evapotranspiration) and, like SPI, fits a probability distribution and transforms it into a normal distribution.

In snow-influenced catchments, the SPI does not always give sufficient information for drought management. To account for snowmelt explicitly, Staudinger et al. introduced the Standardized Snow Melt and Rain Index (SMRI). SMRI quantifies both rain and snowmelt deficits.

Another index that reflects both precipitation and evapotranspiration and that is used in a standardized way is the Palmer Drought Severity Index (PDSI). It has been developed by Palmer for the USA as a tool for estimating agricultural drought damage. The PDSI is applied mainly in the USA, both for scientific and operational purposes, but also increasingly on global scale. It measures the departure of the moisture balance from normal conditions using a simple water balance model and can be regarded as a hydrological accounting system. PDSI is sometimes classified as a meteorological drought index and sometimes as a soil moisture drought index. Despite its worldwide application, PDSI has important shortcomings that should limit its use on the global scale: i) the calculation procedure is complex and non-transparent,8 ii) the time scale is fixed, iii) it uses a potential evaporation method based on absolute temperature, which in some regions can have large impact, iv) as it is calibrated for the USA, re-calibration is needed for application to other regions, and v) snow accumulation is not accounted for and no soil moisture or vegetation control on evapotranspiration is included. Palmer also developed a soil moisture drought index (Z-index) and a hydrological drought index (PHDI), which have calculation procedures similar to PDSI and, therefore, the same advantages and disadvantages.

Various other standardized index for soil moisture have been proposed. For example, Orlowsky and Seneviratne calculated standardized soil-moisture anomalies (SMA) by subtracting the mean and dividing by the standard deviation. Sheffield et al. and Samaniego et al. took a different approach for their soil moisture index and used a Beta probability distribution and kernel density estimation, respectively, to fit the data and calculate soil moisture quantiles.

Standardized indices for the characterization of hydrological drought use different hydrological variables (from observed or simulated data) as input. Most common is a focus on streamflow, because streamflow is most measured, most easily simulated, and of most interest to water resources management. Other variables used in hydrological drought indices include groundwater levels and lake levels. The Standardized Runoff Index (SRI) uses simulated runoff and the Standardized Streamflow Index (SSI) focuses on (observed or simulated) streamflow. Both have a calculation procedure similar to SPI, fitting a distribution to the data and transforming it to a normal distribution. Based on a similar principle, but using a nonparametric transformation instead of distribution fitting, is the Standardized Groundwater level Index (SGI), recently developed by Bloomfield and Marchant. The limitations of SPI also apply to SRI/SSI and SGI, i.e., the length of the data record and the fitted distribution strongly influence SRI/SSI and SGI values.

Another issue with these (and actually all) indices is that a reference period has to be chosen, which can cause difficulties under multidecadal climate variability, like Núñez et al. found for the SSI. Sensitivity of drought indices for the chosen reference period is large, similar to the sensitivity of drought trend analysis to the selection of periods.

Since standardized indices with similar calculation procedures are available for all variables of the terrestrial hydrological cycle (i.e., SPI, SPEI, SMRI, SMA, SRI/SSI, SGI), they can be a useful tool in drought propagation studies, in which droughts in different compartments of the hydrological cycle are compared. Standardized meteorological drought indices (based on precipitation only, e.g., SPI), calculated over long time scales are sometimes used as an approximation of hydrological drought. In other studies this is not recommended as indices based on precipitation alone cannot capture all relevant propagation processes.

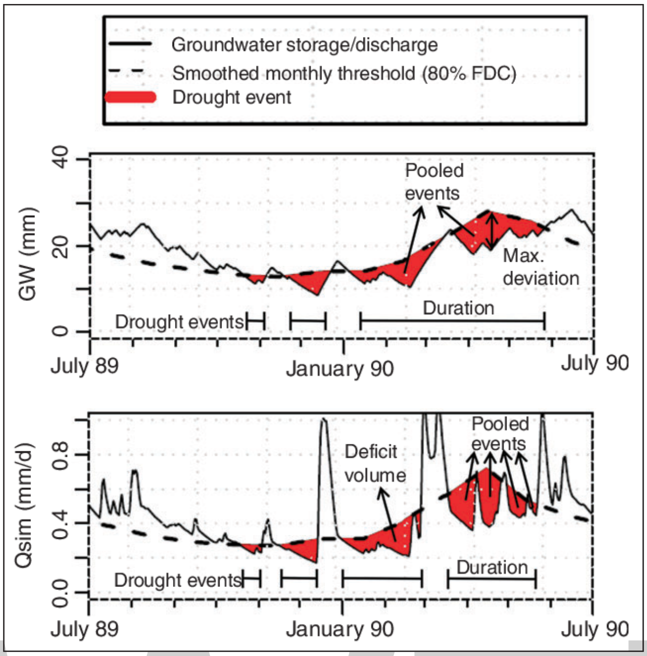
Threshold Level Method

Drought characteristics can also be derived from time series of observed or simulated hydrometeorological variables using a pre-defined threshold level. When the variable is below this level, the site is in drought. Drought duration, severity, and frequency can easily be calculated. This approach is called 'threshold level method' but the term 'deficit index' is also used, because it measures the 'lacking' volume of water below a certain threshold (deficit volume). This is a big advantage of the threshold level method, because deficit volume is an important drought characteristic in water resources management. An example of the use of the threshold level method in water management are the calculations of drought statistical characteristics of inflows into the Júcar water resource system performed by Ochoa-Rivera et al. Thresholds are, however, more often used as points for action when monitoringdischarge or water volumes stored in natural and artificial reservoirs. Examples are the use of thresholds in water allocation discussions during drought in the Netherlands, as reference values for discharge to inform drought management (levels: alert, alarm, and emergency) in the Po River in Italy, and for reservoir management during drought in the UK.

Calculation procedures for the threshold level method are elaborated in Van Loon. Here, they will shortly be summarized. When one uses the threshold level method selection of a threshold level is crucial. Ideally the threshold level should be related to drought impacted sectors/systems, e.g., irrigation water requirements, cooling water for industry, drinking water supply, reservoir operation levels, minimum water depth for navigation, or environmental flows to support stream ecology. Often, this information is not available or the drought analysis aims at a number of sectors/systems with different requirements and, therefore, different threshold levels. Consequently, for practical reasons thresholds are often derived from percentiles of the flow duration curve, commonly ranging between the 70th and 95th percentile for perennial rivers. Either a fixed or a variable (seasonal, monthly, or daily) threshold can be used. A variable threshold can be chosen when seasonal patterns need to be then taken into account. A variable threshold level has been used by e.g., Stahl, Nyabeze, Hirabayashi et al., Vidal et al., Hannaford et al., Prudhomme et al., Van Huijgevoort et al., Parry et al., Van Loon and Van Lanen, Sung and Chung, Van Loon et al., Prudhomme et al. Beyene et al. investigate how a variable threshold can best be calculated in contrasting climates. A variable threshold is most comparable to standardized indices like SPI, because for SPI a distribution is fitted for every month (or period of n months) separately (section Standardized Drought Indices). According to Fleig et al., there is no single threshold level that is preferable and the selection of a specific threshold level remains a subjective decision.

Each drought event can be characterized by its duration and by some measure of the severity of the event. Drought duration and severity are related, but not always linearly, as has been shown by Van Loon et al. and Van Loon and Laaha. For fluxes (i.e., precipitation and discharge) the most commonly used severity measure is deficit volume, calculated by summing up the differences between the actual flux and the threshold level over the drought period Hisdal et al.,58 Fleig et al.62. This deficit can be standardized by dividing by the mean of the hydrometeorological variable, resulting in a variable denoting the number of days with mean flow needed to compensate for the deficit. For state variables (i.e., soil moisture and groundwater storage) the maximum deviation from the threshold can be used as the severity measure.

Like with standardized indices, all three categories of drought (meteorological, soil moisture, and hydrological drought) can be analysed with the threshold level method. This makes comparison between variables possible, which is required when studying drought propagation. Therefore, studies on drought propagation commonly use the threshold level method e.g., Another advantage of the threshold level method is that it stays as close to the original time series as possible. It does not need to fit a distribution to the data (like SPI) or use water balance computations and calibration.



Threshold level method with variable threshold for groundwater storage (upper row) and discharge (lower row) including an illustration of pooling method and drought characteristics duration, deficit volume, and maximum deviation.

A disadvantage of the threshold level method is that no standard drought classes are calculated, so that in global drought studies standardization is needed to prevent large differences between climate types and to enable comparison. Furthermore, subjective choices cannot be avoided, for example on the threshold level to use. This is comparable to the choices of fitting a distribution when calculating standardized indices. An additional disadvantage of the threshold level method (and actually almost all drought analysis methods) for global analysis occurs in extremely dry areas with ephemeral rivers. This is due to long periods with almost no precipitation and natural zero flow, resulting in a threshold level of zero. In arid climates, the use of a zero-streamflow day or zero-streamflow month approach (comparable to the Consecutive Dry Days method, or CDD, which counts the number of consecutive days with precipitation less than 1 mm) is more appropriate than the threshold level method. Van Huijgevoort et al. therefore developed a new method for the characterization of streamflow drought on large scales based on a combination of the threshold level method and the CDD method. In other global scale stud ies arid regions are removed from the analysis.

Recent Developments in Drought Indices

Besides at-site indices, some regional indices exist that quantify the spatial aspect of drought. Most of these indices calculate the portion or percentage of an area in drought. The Regional Deficiency Index (RDI), for example, divides the number of catchments in drought by the total number of catchments and the Regional Drought Area Index (RDAI) divides the drought area by the total area of the region.

For hydrological drought characterization often composite drought indices are recommended. These should incorporate 'streamflow, precipitation, reservoir levels, snowpack, and groundwater levels'. The European Drought Observatory (EDO), for example, uses a Combined Drought

Indicator (CDI). EDO provides 10-day updates of the agricultural drought status in Europe by integrating the meteorological index SPI (on 1, 3, and 12-month scales), simulated soil moisture anomalies, and a vegetation stress indicator derived from satellite information. Currently, no hydrological drought information is incorporated in the CDI of the European Drought Observatory yet. In contrast, the US Drought Monitor uses streamflow percentiles and other hydrological indices to come to drought intensity categories.

Like CDI, some newly developed drought indices are derived from or incorporate satellite information. Advantages are that satellite data provide a large spatial coverage and high spatial resolution. Most of them, however, focus on soil moisture and vegetation.

Use of Observational Data in Hydrological Drought Quantification

For the calculation of drought indices, availability of long time series of undisturbed, good-quality observational data is essential. It is beyond the scope of this paper to discuss all data sources that are or can be used in hydrological drought research. Currently, the best description of observational data with a focus on low flow and drought is Rees et al. Here, we give an overview of some recent developments and approaches to deal with uncertainty and ungauged catchments.

Observational data sources used in drought studies are either station data (e.g., meteorological stations, discharge gauging stations, groundwater wells) or gridded data (e.g., reanalysis data, satellite data). In hydrological drought studies, most commonly used data are streamflow measurements. Large-scale river flow archives, like the Global Runoff Data Centre (GRDC) and the European Water Archive (EWA), collect and store discharge datasets from stations around the world and in Europe, respectively. These archives are important for low-flow trend studies, comparative streamflow drought studies, and validation of low-flow simulations. For water balance studies, the network of FLUXNET data is useful. Unfortunately, no large-scale data archive exists for timeseries of groundwater levels. The recently started Global Groundwater Monitoring Network (GGMN) initiative of the International Groundwater Resources Assessment Centre (IGRAC) might fill this gap.

Despite the availability of some large-scale datasets, there is limited use of hydrological data in large-scale drought monitoring systems. The drought monitor of the European Drought Observatory (EDO) is based on precipitation measurements, modeled soil moisture, and remotely sensed vegetation state. The US Drought Monitor does include streamflow percentiles in its composite drought categories, but is dominated by meteorological and soil moisture drought information.

Although there are indications that satellite products using vegetation, evaporation, and soil moisture relate to streamflow drought, the use of satellite data focusing on hydrological drought monitoring is still limited. One satellite product that can be applied in hydrological drought monitoring is NASA's Gravity Recovery and Climate Experiment (GRACE). The GRACE satellite measures total terrestrial water storage on a 300–400 km resolution at monthly intervals and drought indices based on GRACE data have been proposed by Houborg et al. and Thomas et al. The US Drought Monitor offers GRACE-based drought information as an experimental product. One of the issues that currently limits the use of datasets like GRACE is their coarse resolution compared with the requirements of local water management. Assimilation of GRACE data into a high-resolution model is needed to overcome this scale gap.

All observational data has uncertainty. In general, discharge measurements are more uncertain in the low-flow range than for average flow conditions. This is important to take into account in streamflow drought analysis. Lack of available data is generally a problem in water management, but especially in drought management. The International Association of Hydrological Sciences (IAHS) recently concluded a decade on Prediction in Ungauged Basins (PUB), which boosted research on this topic. Results of this decade are summarized in Blöschl et al. In the chapter on drought and low flows, Laaha et al. give an overview of regionalization methods used for transferring information about drought and low flow to ungauged basins and their results in a number of case studies.

Hydrological Drought Modeling

Often observational records are not long enough, some variables are not monitored at all, data quality is too low, or observations are influenced by human activities. To overcome these problems hydrological models can be used to extend data series, fill gaps, and naturalize disturbed time series. Modeling is current practice in hydrology, both in science and in operational water management. Hydrological models range from simple statistical models with a few parameters via conceptual models with varying complexity to complex physically based models physically based models, and a synthetic model. The large for an overview of current hydrological modeling approaches, For drought management, which is primarily on catchment scale, conceptual rainfall-runoff models are the main tool.

Hydrological models are usually designed to simulate average and high flows and have been shown to give good results in catchments around the world. Unfortunately, low flows are often not captured satisfactorily by models. Simulating low flows is a challenge. Smakhtin describes a number of difficulties in the modeling of low flows and Staudinger et al. state that 'low flows are often poorly reproduced by commonly used hydrological models, which are traditionally designed to meet peak flow situations'.

Recently, various attempts have been made to improve low-flow modeling using existing models. Perrin et al. improved a lumped rainfall-runoff model to match both high and low flows. Matonse and Kroll used hillslope storage models (i.e., kinematic wave hillslope storage and hillslope storage Boussinesq models) to improve groundwater flow in a small steep headwater catchment. Romanowicz used a combination of a physically based model (TOPMODEL) and stochastic transfer functions based on a logarithmic transformation of flows. Basu et al. focused on riparian zones to improve low-flow modeling in a simple threshold-based model. Pushpalatha et al. added a routing reservoir to a concep tual rainfall-runoff model. These studies show some improvement in the simulation of low flows, but no approach is explicitly the best.

The basic drought propagation processes, e.g., fewer and longer events moving from meteorological drought via soil moisture drought to hydrological drought, an attenuated deficit in hydrological drought compared with meteorological drought, as well as differences between catchments with contrasting climate and catchment characteristics, are generally reproduced by different model types, such as catchment-scale conceptual models, an ensemble of large-scale physically based models, and a synthetic model. The large diversity of the processes underlying drought propagation, however, is not always reproduced well by all model approaches. Gudmundsson et al., Stahl et al., Van Loon et al., Van Huijgevoort et al., and Tallaksen and Stahl tested a number of physically based, distributed, large-scale hydrological models and land surface models from WaterMIP (Water Model Intercomparison Project) on their suitability to reproduce hydrological drought. The conclusions from these studies were that: (1) there are large differences in hydrological drought simulation between the models, (2) the ensemble mean/median is better than any of the individual models, (3) the models' representation of snow and groundwater storage and release processes is problematic since it leads to a lack of persistence. This is in agreement with Dadson et al., who evaluated the role of land surface models for water management decisions under global change.

Just like observational data, model outcomes contain uncertainties. Uncertainty in hydrolog ical model results originates from input data uncertainty, calibration data uncertainty, and model uncertainty. Model uncertainty can be subdivided in structural uncertainty (i.e., related to model structure), parametric uncertainty (i.e., related to model parameters and their identification), and numeric uncertainty (i.e., related to numerical techniques). There is little knowledge of the relative importance of these different sources of uncertainty during low flow and drought, since most studies have focused on average and high flows.

Due to the multitude of sources of uncertainty described above, the quantification of hydrological drought might be regarded as much more uncertain than the quantification of meteorological drought. In contrast, the high temporal variation in precipitation might result in erratic behavior that is apparent in meteorological drought and is filtered out in hydrological drought. This is related to the different scales mentioned previously. As hydrological droughts generally occur on larger time scales than meteorological droughts, whereby the terrestrial hydrological cycle acts as a low-pass filter of the highly variable meteorological inputs, errors in the meteorological forcing are filtered out. This is especially true during dry conditions (more than during floods) because the relative contribution of slow pathways in a catchment to discharge is higher during drought.

Forecasting Hydrological Drought

In operational water management forecasts are important. Knowledge about drought propagation is imperative to various areas of prediction of hydrological drought. Recent developments in drought prediction and forecasting are described in Pozzi et al. The authors explore the need for a global drought early warning system and argue that current challenges are: 'a lack of in situ measurement networks, modest seasonal forecast skill in many regions, and the lack of infrastructure to translate data into useable information'. Pozzi et al. also explicitly mention the diversity of variables that need to be monitored to capture the development of hydrological drought and its impact on different water-related sectors.

Improvement of the seasonal forecasting of hydrological drought is a prerequisite for adequate operational water management (e.g., reservoir operation, irrigation abstractions, or management of wetlands). Most of the recent developments in drought forecasting, however, focus on meteorological drought. Some seasonal forecasting of soil moisture is done for agricultural drought in recent studies, but forecasting of hydrological drought variables is still limited. Luo and Wood focus on seasonal forecasting of hydrological variables using seasonal climate forecasts from an ensemble of climate models and a hydrological model in the Ohio River basin. Fundel et al. use a combination of weather forecast and a hydrological model to predict streamflow drought in the Swiss pre-alpine region. Demirel et al. quantify appropriate lags and temporal resolution for the prediction of low flow indicators in the Rhine River and Demirel et al. found that for the Moselle River models tend to over-predict runoff during low-flow periods and they are more sensitive to ensemble precipitation forecasts than to ensemble PET forecasts. Trambauer et al. review hydrological models for hydrological drought forecasting in Africa.

Another approach is to predict 'drought from drought', meaning the prediction of hydrological drought from meteorological drought. Hannaford et al. attempt to predict hydrological drought for the UK based on meteorological drought indicators of the target region and hydrological drought indicators of other regions in Europe. Wong et al. similarly apply drought propagation knowledge in predicting hydrological drought from preceding meteorological droughts using statistical methods in contrasting catchments in Europe.

Other studies explore the use of the correlation between hydrological drought indices and large-scale ocean-atmospheric modes (like ENSO) for forecasting of hydrological drought e.g., but many conclude that the link is 'not sufficiently strong to consistently predict streamflow accurately'. More research on this issue is needed before hydrological drought forecasting can be successfully applied in operational water management. Special focus is needed on the recovery of hydrological drought during an ongoing event.

Hydrological Drought Impacts and Management

Predictions and future projections of hydrological drought are of little use when the link to the impacts of drought on the ecosystem and society is not clear. Research on the relation between the physical hazard of hydrological drought and its impacts is still in its infancy. Information on drought impacts is now being collected by the Drought Impact Reporter (DIR) of the National Drought Mitigation Center (NDMC) in the USA, by the European Drought Observatory (EDO) of the Joint Research Centre (JRC), and by the European Drought Impact report Inventory (EDII) of the DROUGHT-R & SPI project in Europe. These relatively new data sources are now starting to be explored, Estimates of drought impacts in recent years indicate that drought-related losses are increasing. It is difficult to isolate the impacts of climate change from changes in, for example, land use and increasing vulnerability. Important factors for increased vulnerability are population growth, concentration of people in urban areas and semiarid regions, globalization of food markets, and water accessibility issues. Impacts of drought are likely to increase with time as society's demands on water and environmental services increase. Conflicts between water users have emerged. Worldwide drought has been a stressor for international relations in transboundary rivers and is expected to continue to be so in the future. Although droughts occur everywhere, it is important to note that, in general, the most severe consequences of drought for humans occur in arid or semiarid regions where the availability of water is already low under normal conditions, the demand often is close to or even exceeds the natural availability and society often lacks the ability to adapt to the drought hazard. Therefore, drought management is and will increasingly be crucial.

In the European Union, the Water Framework Directive demands member states to preserve or recover a 'good status' in all water bodies and member states are encouraged to implement drought management measures in River Basin Management Plans. River basin management, which in many places needs to balance between the two hydrological extremes flood and drought, needs information and tools to take both extremes into account equally. All around the world programs exist to save water, to rely more on desalinated water, rainwater harvesting, waste-water reuse, or water transfer, some of which are quite controversial. The main issue is moving from short-term crisis management to long-term planning including pro-active measures.

LIMNIC ERUPTION

A limnic eruption, also termed a lake overturn, is a rare type of natural disaster in which dissolved carbon dioxide (CO_2) suddenly erupts from deep lake waters, forming a gas cloud capable of suffocating wildlife, livestock, and humans. A limnic eruption may also cause tsunamis as the rising CO_2 displaces water. Scientists believe earthquakes, volcanic activity, and other explosive events can serve as triggers for limnic eruptions. Lakes in which such activity occurs are referred to as limnically active lakes or exploding lakes. Some features of limnically active lakes include:

- CO_2- saturated incoming water.
- A cool lake bottom indicating an absence of direct volcanic interaction with lake waters.
- An upper and lower thermal layer with differing CO_2 saturations.
- Proximity to areas with volcanic activity.

Investigations of the Lake Monoun and Lake Nyos casualties led scientists to classify limnic eruptions as a distinct type of disaster event, even though they can be indirectly linked to volcanic eruptions.

Lake Nyos shortly after a limnic eruption.

Due to the largely invisible nature of the underlying cause (CO_2 gas) behind limnic eruptions, it is difficult to determine to what extent eruptions have occurred in the past. In recent history, this phenomenon has been observed twice. The first recorded limnic eruption occurred in Cameroon at Lake Monoun in 1984, causing asphyxiation and death of 37 people living nearby. A second, deadlier eruption happened at neighbouring Lake Nyos in 1986, this time releasing over 80 million m^3 of CO_2, killing around 1,700 people and 3,500 livestock, again by asphyxiation.

A third lake, Lake Kivu, rests on the border between the Democratic Republic of the Congo and Rwanda, and contains massive amounts of dissolved CO_2. Sediment samples from the lake taken by Professor Robert Hecky (University of Michigan) showed an event caused living creatures in the lake to go extinct around every 1000 years, and caused nearby vegetation to be swept back into the lake. Limnic eruptions can be detected and quantified on a CO_2 concentration scale by taking air samples of the affected region.

The Messel pit fossil deposits of Messel, Germany, show evidence of a limnic eruption there in the early Eocene. Among the victims are perfectly preserved insects, frogs, turtles, crocodiles, birds, anteaters, insectivores, early primates, and paleotheres.

Bovine killed by the 1986 limnic eruption at Lake Nyos.

Causes

For a lake to undergo a limnic eruption, the water must be nearly saturated with gas. CO_2 was the primary component in the two observed cases (Lake Nyos and Lake Monoun). In Lake Kivu, scientists are concerned about the concentrations of methane gas as well. CO_2 may originate from volcanic gas emitted from under the lake or from decomposition of organic material. Before a lake is saturated, it behaves like an unopened carbonated beverage (e.g., a soft drink): the CO_2 is dissolved in the water. In both the lake and the soft drink, CO_2 dissolves much more readily at higher pressure (Henry's law). This is why bubbles in a can of soda form only after the can is opened; when the pressure is released, the CO_2 comes out of solution. In the case of lakes, the bottom is at a much higher pressure; the deeper it is, the higher the pressure is at the bottom. Therefore, huge amounts of CO_2 can be dissolved in large, deep lakes. CO_2 also dissolves more readily in cooler water, such as that found at a lake bottom. A small rise in water temperature can lead to the release of a large amount of CO_2.

Once a lake is saturated with CO_2, it is very unstable, but a trigger is needed to set off an eruption. In the case of the 1986 Lake Nyos eruption, landslides were the suspected triggers, but a volcanic eruption, an earthquake, or even wind and rain storms are potential triggers. Another possible cause of a limnic eruption is gradual gas saturation at specific depths which can trigger spontaneous gas development. For any of these cases, the trigger pushes some of the gas-saturated water higher in the lake, where pressure is insufficient to keep CO_2 in solution. As bubbles start forming the water is lifted even higher in the lake (buoyancy), where yet more CO_2 comes out of solution. This process forms a column of gas, at which point the water at the bottom of this column is pulled up by suction, and it, too, loses CO_2 in a runaway process. This eruption discharges CO_2 into the air and can even displace enough water to form a tsunami.

Limnic eruptions are exceptionally rare for several reasons. First, a CO_2 source must exist (regions with volcanic activity are most at risk). Second, the vast majority of lakes are holomictic (i.e., their layers mix regularly), preventing a buildup of dissolved gases. Only meromictic lakes do not mix and remain stratified, allowing CO_2 to remain dissolved. It is estimated only one meromictic lake exists for every 1,000 holomictic lakes. Finally, a lake must be deep enough to have sufficient pressure to dissolve large amounts of CO_2.

Consequences

Once an eruption occurs, a large CO_2 cloud forms above the lake and expands to the surrounding region. Because CO_2 is denser than air, it has a tendency to sink to the ground, simultaneously displacing breathable air, resulting in asphyxia. CO_2 can make human bodily fluids highly acidic and potentially cause CO_2 poisoning. As victims gasp for air, they actually accelerate asphyxia by inhaling CO_2 gas.

At Lake Nyos, the gas cloud descended into a nearby village where it settled, killing nearly everyone; casualties as far as 25 km (16 mi) were reported. A change in skin color on some bodies led scientists to hypothesize the gas cloud may have contained dissolved acid such as hydrogen chloride, though this hypothesis is disputed. Many victims were found with blisters on their skin, thought to have been caused by pressure ulcers, which were likely caused by low blood oxygen levels in those asphyxiated by carbon dioxide. Nearby vegetation was largely unaffected, except any growing immediately adjacent to the lake. There, vegetation was damaged or destroyed by a 24 m (79 ft) high tsunami caused by the violent eruption.

Degassing

Efforts are under way to develop a solution for removing the gas from these lakes and to prevent a build-up which could lead to another catastrophe. A team led by French scientist Michel Halbwachs began experimenting at Lake Monoun and Lake Nyos in 1990 using siphons to degas the waters of these lakes in a controlled manner. The team positions a pipe vertically in the lake with its upper end above the water surface. Water saturated with CO_2 enters the bottom of the pipe and rises to the top. The lower pressure at the surface allows the gas to come out of solution. Only a small amount of water must be mechanically pumped initially through the pipe to start the flow. As saturated water rises, the CO_2 comes out of solution and forms bubbles. The natural buoyancy of the bubbles draws the water up the pipe at high velocity resulting in a fountain at the surface. The degassifying water acts like a pump, drawing more water into the bottom of the pipe, and creating a self-sustaining flow. This is the same process which leads to a natural eruption, but in this case it is controlled by the size of the pipe.

Each pipe has a limited pumping capacity and several would be required for both Lake Monoun and Lake Nyos to degas a significant fraction of the deep lake water and render the lakes safe. The deep lake waters are slightly acidic due to the dissolved CO_2 which causes corrosion to the pipes and electronics, necessitating ongoing maintenance. There is some concern CO_2 from the pipes could settle on the surface of the lake forming a thin layer of unbreathable air and thus potentially causing problems for wildlife.

In January 2001, a single pipe was installed by the French-Cameroonian team on Lake Nyos, and two more pipes were installed in 2011 with funding support from the United Nations Development Programme. A pipe was installed at Lake Monoun in 2003 and two more were added in 2006. These three pipes are thought to be sufficient to prevent an increase in CO_2 levels, removing approximately the same amount of gas that naturally enters at the lake bed. In January 2003, an 18-month project was approved to fully degas Lake Monoun, and the lake has since been rendered safe.

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Disaster Management

5 CHAPTER

Disaster management is the judicious use of resources to deal with any form of disaster. It includes minimizing the effects on human life and property. This chapter discusses in detail the theories and methodologies related to disaster management.

Disaster Management is a strategic planning and procedure that is administered and employed to protect critical infrastructures (also known as “critical assets”) from severe damages when natural or human made calamities and catastrophic even occur. In the United States, Executive Order 13407 is established as policy for the United States to have an effective, reliable, integrated, flexible, and comprehensive system to alert and warn the general public, which is called “Integrated Public Alert and Warning System (IPAWS). In the later year of 2010, Europe started to develop a strategic National Disaster Management after so many natural catastrophes happened in the year of 2010. According to European Academy, there are 725 extremely weather phenomena caused billions of Euro damage and thousands of people’s life.

Disaster management plans are multi-layered and are aimed to address such issues as floods, hurricanes, fires, bombings, and even mass failures of utilities or the rapid spread of disease. The disaster plan is likely to address such as important matters as relinquishing people from an impacted region, arranging temporary housing, food, and medical care.

There is no country that is immune from disaster, though vulnerability to disaster varies. There are four main types of disaster:

- Natural disasters: These disasters include floods, hurricanes, earthquakes and volcano eruptions that can have immediate impacts on human health, as well as secondary impacts causing further death and suffering from floods causing landslides, earthquakes resulting in fires, tsunamis causing widespread flooding and typhoons sinking ferries.
- Environmental emergencies: These emergencies include technological or industrial accidents, usually involving hazardous material, and occur where these materials are produced, used or transported. Large forest fires are generally included in this definition because they tend to be caused by humans.
- Complex emergencies: These emergencies involve a break-down of authority, looting and attacks on strategic installations. Complex emergencies include conflict situations and war.
- Pandemic emergencies: These emergencies involve a sudden onset of a contagious disease that affects health but also disrupts services and businesses, bringing economic and social costs.

Emergency Management

Emergency Management is the generic name of an interdisciplinary field dealing with the strategic organization management processes used to protect asses of an organization from hazard risks that can cause disasters or catastrophes, and to ensure the continuance of the organization within their planned lifetime.

Emergency Management is a systematic process leading to action before, during and after a disaster to save lives and prevent injury. “Disaster” here means a major emergency that exceeds the community’s capacity to respond successfully with its own resources. Emergency Management is organized into four phases:

- Mitigation: Actions taken to eliminate a hazard or reduce its potential impact.
- Preparedness: Planning for major emergencies, including training and exercises.
- Response: Actions taken in response to emergencies.
- Recovery: Actions taken after a disaster to restore services and reconstruct communities.

Disaster Management in Japan.

Medical Kits from the United Kingdom (UK) being Unloaded by the Tajikistan Committee of Emergency Situations.

Pakistan Floods Affect 12 Million People.

Disaster Management in the United States.

Resilience and Prevention

The United States Department of Homeland Security (DHS) and the Federal Emergency Management Agency (FEMA) have resilience and prevention efforts, initiatives, and programs as part of

Emergency Management. Resilience defines the goal of mitigation, preparedness, response, and recovery; which is the capability to recover from catastrophe or misfortune. Prevention is totally avoiding danger or risky events.

Mitigation

Mitigation is the effort to reduce loss of life and property by lessening the impact of disasters. FEMA's Federal Insurance and Mitigation Administration (FIMA) manages the National Flood Insurance Program (NFIP) and impements a variety of programs authorized by Congress to reduce losses that may result from natural disasters.

Preparedness

Preparedness is way of mitigating unwanted outcome and it is one of the crucial actions in achieving safety and security in the event of calamities, disasters, and terrorism.

Response

An emergency response plan must provide the resources and information needed to evaluate the human and environmental health impacts of the event, assess and reduce human exposures to contaminants, and develop science-based strategies for remediation and rebuilding.

Recovery

Once immediate lifesaving operations are accomplished, the focus changes to assisting the critical infrastructures involved in the incidents and recovery. Recovery efforts are primarily concerned with actions that involve rebuilding destroyed property, re-employment, and the repair of other essential infrastructure.

Tools

Various types of tools are available to assist emergency response team and professionals. In 2009, the US Agency for International Development created a web-based tool for estimating populations impacted by disasters. Called Population Explorer the tool uses Landscan population data, developed by Oak Ridge National Laboratory, to distribute population at a resolution 1 km2 for all countries in the world. Used by USAID's FEWS NET Project to estimate populations vulnerable and or impacted by food insecurity, Population Explorer is gaining wide use in a range of emergency analysis and response actions, including estimating populations impacted by floods in Central America and a Pacific Ocean Tsunami event in 2009.

International Organizations

The International Association of Emergency Managers (IAEM) is the primary professional and academic organization of Emergency and Disaster Professionals worldwide. The main goals of this organization are to protect human lives, assets, and the environment during disasters. In addition, the organization's principles are to providing information, networking, education, professional opportunities, and to advance the emergency management profession.

Other Non-Profit Organizations

United Nations

The United Nations (UN) has programs to assist any nation on mitigating the effect of disasters and enhancing the capacity of training institutions and government to develop strategic plans for disaster management. UN provides guidelines and policies for Disaster Risk Reduction (DRR).

Red Cross/Red Crescent

Red Cross/Red Crescent (RC) provides a web-based tool for their personnel including disaster trends, tools, and databases. RC has standard operating procedures to aid affected areas during disasters. Also, the provide immediate funding and food supplies for victims of poverty and disasters as depicted in figure.

Red Cross/Red Crescent Disaster and Emergency Management.

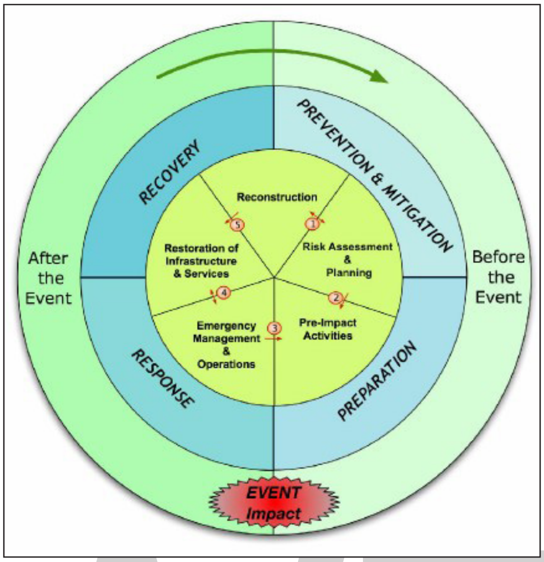
World Bank

World Bank has provided supports for disaster management to countries affected by major disasters. These include post-disaster reconstruction projects, as well as projects with components aimed at preventing and mitigating disaster impacts, in countries such as Argentina, Bangladesh, Colombia, Haiti, India, Mexico, Turkey and Vietnam to name only a few.

European Union

Since 2001, the EU adopted Community Mechanism for Civil Protection which started to play a significant role on the global scene. Mechanism's main role is to facilitate co-operation in civil protection assistance interventions in the event of major emergencies which may require urgent response actions. This applies also to situations where there may be an imminent threat of such major emergencies. The heart of the Mechanism is the Monitoring and Information Centre. It is part of Directorate-General for Humanitarian Aid & Civil Protection of the European Commission and accessible 24 hours a day. It gives countries access to a platform, to a one-stop-shop of civil protection means available amongst the all the participating states. Any country inside or outside the Union affected by a major disaster can make an appeal for assistance through the MIC. It acts as a communication hub at headquarters level between participating states, the affected country and despatched field experts.

EU depicted in figure the breakdown of the general disaster management phases and shows interaction between these activities.



The Disaster Risk Management Cycle.

International Recovery Platform

The International Recovery Platform (IRP) was conceived at the World Conference on Disaster Reduction (WCDR) in Kobe, Hyogo, Japan in January 2005. As a thematic platform of the International Strategy for Disaster Reduction (ISDR) system, IRP is a key pillar for the implementation of the Hyogo Framework for Action (HFA). Building the Resilience of Nations and Communities to Disasters, a global plan for disaster risk reduction for the decade adopted by 168 governments at the WCDR.

DISASTER RESPONSE

Disaster response is the second phase of the disaster management cycle. It consists of a number of elements, for example; warning/evacuation, search and rescue, providing immediate assistance, assessing damage, continuing assistance and the immediate restoration or construction of infrastructure (i.e. provisional storm drains or diversion dams). The aim of emergency response is to provide immediate assistance to maintain life, improve health and support the morale of the affected population. Such assistance may range from providing specific but limited aid, such as assisting refugees with transport, temporary shelter, and food, to establishing semi-permanent settlement in camps and other locations. It also may involve initial repairs to damaged or diversion to infrastructure.

The focus in the response phase is on putting people safe, prevent need disasters and meeting the basic needs of the people until more permanent and sustainable solutions can be found. The main responsibility to address these needs and respond to a disaster lies with the government or governments in whose territory the disaster has occurred. In addition, Humanitarian organizations are often strongly present in this phase of the disaster management cycle, particularly in countries where the government lacks the resources to respond adequately to the needs.

Disaster Response Planning

The United States National Fire Protection Association (NFPA) 1600 Standard specify elements of an emergency response, as defined responsibilities; specific actions to be taken (which must include protective actions for life safety); and communication directives. Within the standard, NFPA recognize that disasters and day-to-day emergencies are characteristically different. Nevertheless, the prescribed response elements are the same.

In support of the NFPA standard, Statoil's practical application of emergency response is across three distinct "lines" that incorporate NFPA's elements. Line 1 is responsible for the operational management of an incident; line 2, typically housed off-site, is responsible for tactical guidance and additional resource management. Finally, in the case of major incidents, line 3 provides strategic guidance, group resource management, and government and media relations.

While it is impossible to plan for every disaster, crisis or emergency, the Statoil investigation into the terrorist attacks on In Amenas place emphasis on the importance of having a disaster response. The report concludes that a disaster response framework may be utilized in an array of disaster situations, such as that at In Amenas.

Organizations

The United Nations Office for the Coordination of Humanitarian Affairs (OCHA); is responsible for bringing together humanitarian actors to ensure a coherent response to emergencies that require an international response. OCHA plays a key role in operational coordination in crisis situations. This includes assessing situations and needs; agreeing common priorities; developing common strategies to address issues such as negotiating access, mobilizing funding and other resources; clarifying consistent public messaging; and monitoring progress.

The organisation in the United Kingdom for the provision of communications disaster response is RAYNET. The UK organisation for the provision of disaster response by off-road vehicles is 4x4 Response.

In Canada, GlobalMedic was established in 1998 as a non-sectarian humanitarian-aid NGO to provide disaster relief services to large scale catastrophes around the world. Time magazine recognized the work of GlobalMedic in its 2010 Time 100 issue. It has a roster of over 1,000 volunteers from across Canada that includes professional rescuers, police officers, firefighters and paramedics who donate their time to respond to international disasters. Their personnel are divided into Rapid Response Teams (RRTs) that operate rescue units, Water Purification Units (WPUs) designed to provide safe drinking water; and Emergency Medical Units (EMUs) that use inflatable field hospitals to provide emergency medical treatment. Since 2004, GlobalMedic teams have deployed to over 60 humanitarian disasters around the world.

In India, the National Disaster Management Authority is responsible for planning for mitigating effects of natural disasters and anticipating and avoiding man-made disasters. It also coordinates the capacity-building and response of government agencies to crises and emergencies. The National Disaster Response Force is an inter-government disaster response agency that specializes in search, rescue and rehabilitation.

In the US, the Federal Emergency Management Agency coordinates federal operational and logistical disaster response capability needed to save and sustain lives, minimize suffering, and protect property in a timely and effective manner in communities that become overwhelmed by disasters. The Centers for Disease Control and Prevention offer information for specific types of emergencies, such as disease outbreaks, natural disasters and severe weather, as well as chemical and radiation accidents. Also, the Emergency Preparedness and Response Program of the National Institute for Occupational Safety and Health develops resources to address responder safety and health during responder and recovery operations.

Among volunteers, the American Red Cross is chartered by Congress in 1900 to lead and coordinate non-profit efforts. They are supported by disaster relief organizations from many religious denominations and community service agencies. Licensed amateur radio operators support most volunteer organizations, and are often affiliated with the American Radio Relay League (ARRL).

Disaster Response Organizations

In addition to the response by the government, a great deal of assistance in the wake of any disaster comes from charities, disaster response and non-governmental organizations. The biggest international umbrella organizations are the Inter-Agency Standing Committee and the International Council of Voluntary Agencies.

Humanitarian OSM Team works to update and provide map in areas struck by disaster.

Disaster Response Technologies

Smart Emergency Response System (SERS) prototype was built in the SmartAmerica Challenge 2013-2014, a United States government initiative. SERS has been created by a team of nine organizations led by MathWorks. The project was featured at the White House in June 2014 and described by Todd Park (U.S. Chief Technology Officer) as an exemplary achievement.

The SmartAmerica initiative challenges the participants to build cyber-physical systems as a glimpse of the future to save lives, create jobs, foster businesses, and improve the economy. SERS primarily saves lives. The system provides the survivors and the emergency personnel with information to locate and assist each other during a disaster. SERS allows to submit help requests to a MATLAB-based mission center connecting first responders, apps, search-and-rescue dogs, a 6-feet-tall humanoid, robots, drones, and autonomous aircraft and ground vehicles. The command and control center optimizes the available resources to serve every incoming requests and generates an action plan for the mission. The Wi-Fi network is created on the fly by the drones equipped with antennas. In addition, the autonomous rotorcrafts, planes, and ground vehicles are simulated with Simulink and visualized in a 3D environment (Google Earth) to unlock the ability to observe the operations on a mass scale.

The International Charter Space and Major Disasters provides for the charitable retasking of satellite assets, providing coverage from 15 space agencies, etc. which is wide albeit contingent. It focuses on the beginning of the disaster cycle, when timely data is of the essence.

Digital technologies are increasingly being used in humanitarian action, they have shown to improve the health and recovery of populations affected by both natural and man-made disasters. They are used in humanitarian response to facilitate and coordinate aid in various stages including preparedness, response, and recovery from emergencies. More specifically, mobile health (mHealth), which is defined as the use of communication devices such as mobile phones for the purpose of health services information. Nowadays, millions of people use mobile phones as a means of daily communication and data transference, out of which 64% live in developing countries. One of the most important characteristics of disasters are the harms caused to infrastructures, accessibility issues, and an exponential need of medical and emergency services. In such situations, the use of mobile phones for mHealth can be vital, especially when other communication infrastructures are hindered. In such conditions, the abundance of mobile technology in developing countries provide the opportunity to be harnessed for helping victims and vulnerable people.

Mobile health information technology platforms, in the acute phase of disaster response, create a common operational framework that improves disaster response by standardizing data acquisition, organizing information storage, and facilitating communication among medical staff. One of the challenges in disaster response is the need of pertinent, effective and continuous analysis of the situation and information in order to evaluate needs and resources. mHealth has been shown to provide effective disaster preparedness with real time collection of medical data as well as helping identify and create needs assessments during disasters. Using mobile technology in heath has set the stage for the dynamic organization of medical resources and promotion of patient care done through quick triage, patient tracking, and documentation storage and maintenance.

Managing an effective and influential response requires cooperation, which is also facilitated through mHealth. A retrospective study demonstrated that applying mHealth can lead to up to 15% decrease of unnecessary hospital transfers during disasters. In addition, they provide field hospital administrators with real-time census information essential for planning, resource allocation, inter-facility patient transfers, and inter-agency collaboration. mHealth technology systems can improve post-operative care and patient handoffs between volunteer providers. Data entry with mobile devices is now widely used to facilitate the registration of displaced individuals, to conduct surveys, identify those in need of assistance, and to capture data on issues such as food security, vaccination rates, and mortality.

Above all, mHealth can harness the power of information to improve patient outcomes. Efforts lead by the Harvard Humanitarian Initiative and Operational Medicine Institute during the Haiti earthquake resulted in the creation of a web-based mHealth system that created a patient log of 617 unique entries used by on-the-ground medical providers and field hospital administrators. This helped facilitate provider triage, improve provider handoffs, and track vulnerable populations such as unaccompanied minors, pregnant women, traumatic orthopedic injuries and specified infectious diseases. Also, during the Haiti earthquake, the International Red Crescent sent more than 45 million SMSs to Viole mobile phone users. This resulted in 95% of the receiver reporting they had gained useful information, and out of these 90% reported the SMS helped in their preparedness.

DISASTER RISK REDUCTION

Disaster risk reduction (DRR) is a systematic approach to identifying, assessing and reducing the risks of disaster. It aims to reduce socio-economic vulnerabilities to disaster as well as dealing with the environmental and other hazards that trigger them. Here it has been strongly influenced by the mass of research on vulnerability that has appeared in print since the mid-1970s. It is the responsibility of development and relief agencies alike. It should be an integral part of the way such organizations do their work, not an add-on or one-off action. DRR is very wide-ranging: Its scope is much broader and deeper than conventional emergency management. There is potential for DRR initiatives in just about every sector of development and humanitarian work.

The most commonly cited definition of DRR is one used by UN agencies such as UNISDR, also known as the UN Office for Disaster Risk Reduction, and UNDP: "The conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development."

WASH and Disaster Risk Management.

Development of the Concept and Approach

The evolution of disaster management thinking and practice since the 1970s has seen a progressively wider and deeper understanding of why disasters happen, accompanied by more integrated, holistic approaches to reduce their impact on society. The modern paradigm of disaster management—disaster risk reduction (DRR)—represents the latest step along this path. DRR is a relatively new concept in formal terms, but it embraces much earlier thinking and practice. It is being widely embraced by international agencies, governments, disaster planners and civil society organisations.

Many see climate change as having a direct impact on the prevalence and seriousness of disasters, as well as causing them to be more frequent in the future. There are growing efforts to closely link DRR and climate change adaptation, both in policy and practice.

DRR is such an all-embracing concept that it has proved difficult to define or explain in detail, although the broad idea is clear enough. Inevitably, there are different definitions in the technical literature, but it is generally understood to mean the broad development and application of policies, strategies and practices to minimise vulnerabilities and disaster risks throughout society. The term 'disaster risk management' (DRM) is often used in the same context and to mean much the same thing: a systematic approach to identifying, assessing and reducing risks of all kinds associated with hazards and human activities. It is more properly applied to the operational aspects of DRR: the practical implementation of DRR initiatives.

There have been growing calls for greater clarity about the components of DRR and about indicators of progress toward resilience — a challenge that the international community took up at the UN's World Conference on Disaster Reduction (WCDR) in Kobe, Japan, in 2005, only days after the 2004 Indian Ocean earthquake. The WCDR began the process of pushing international agencies and national governments beyond the vague rhetoric of most policy statements and toward setting clear targets and commitments for DRR. The first step in this process was the formal approval at the WCDR of the Hyogo Framework for Action (2005–2015) (HFA). This was the first internationally accepted framework for DRR. It set out an ordered sequence of objectives (outcome – strategic goals – priorities), with five priorities for action attempting to 'capture' the main areas of DRR intervention. The UN's biennial Global Platform for Disaster Risk Reduction provided an opportunity for the UN and its member states to review progress against the Hyogo Framework. It held its first session 5–7 June 2007 in Geneva, Switzerland, where UNISDR is based. The subsequent Global Platforms were held in June 2009, May 2011 and May 2013, all in Geneva. The successor accord to the Hyogo Framework was adopted at the World Conference on Disaster Risk Reduction held on March 14–18, 2015 in the Japanese city of Sendai. It is known as the Sendai Framework for Disaster Risk Reduction (2015–2030).

UN initiatives have helped to refine and promote the concept at international level, stimulated initially by the UN's designation of the 1990s as the International Decade for Natural Disaster Reduction. In 1999, UN member states approved the International Strategy for Disaster Risk Reduction, which reflected a shift from the traditional emphasis on disaster response to disaster reduction, by seeking to promote a "culture of prevention".

Chennai damage after 2004 Indian Ocean Earthquake.

Disaster Research

Disaster research deals with conducting field and survey research on group, organizational and community preparation for, response to, and recovery from natural and technological disasters and other community-wide crises.

Related field such as anthropology study human populations, environments, and events that create utter chaos. They research long-lasting effects on multiple areas of society including: social organization, political organization and empowerment, economic consequences, environmental degradation, human and environmental adaptation and interactions, oral history, traditional knowledge, psychological consequences, public health and the broader historical record of the affected region.

Public health preparedness requires cultural awareness, respect and preparation; different parties acting during a relief period are driven by cultural and religious beliefs, including taboos. If these are not acknowledged or known by emergency and medical personnel, treatment can become compromised by both a patient refusing to be treated and by personnel refusing to treat victims because of a violation of values.

Some Issues and Challenges

Priorities

According to Mluver 1996 it is unrealistic to expect progress in every aspect of DRR: capacities and resources are insufficient. Governments and other organisations have to make what are in effect 'investment decisions', choosing which aspects of DRR to invest in, when, and in what sequence. This is made more complicated by the fact that many of the interventions advocated are developmental rather than directly related to disaster management. Most existing DRR guidance sidesteps this issue. One way of focusing is to consider only actions that are intended specifically to reduce disaster risk. This would at least distinguish from more general efforts toward sustainable development. The concept of 'invulnerable development' attempts this: In this formulation, invulnerable development is development directed toward reducing vulnerability to disaster, comprising 'decisions and activities that are intentionally designed and implemented to reduce risk and susceptibility, and also raise resistance and resilience to disaster'.

Research has shown the impact of further investment in effective preparedness, as the benefits with regards to reducing humanitarian caseloads far outweigh the costs; a case study of Niger showed positive cost and benefit results across all scenarios. Three different scenarios were modelled, from the absolute level of disaster loss, to the potential reduction in disaster loss and the discount rate. It is estimated that every $1 spent results in $3.25 of benefit in the most conservative scenario. This increases to $5.31 of benefit for the least conservative scenario.

Partnerships and Inter-Organisational Co-ordination

No single group or organisation can address every aspect of DRR. DRR thinking sees disasters as complex problems demanding a collective response. Co-ordination even in conventional emergency management is difficult, for many, organisations may converge on a disaster area to assist. Across the broader spectrum of DRR, the relationships between types of organisation and between sectors (public, private and non-profit, as well as communities) become much more extensive and complex. DRR requires strong vertical and horizontal linkages (central-local relations become important). In terms of involving civil society organisations, it should mean thinking broadly about which types of organisation to involve (i.e., conventional NGOs and such organisations as trades unions, religious institutions, amateur radio operators (as in the US and India), universities and research institutions).

Communities and their Organizations

Traditional emergency management/civil defense thinking makes two misleading assumptions about communities. First, it sees other forms of social organisation (voluntary and community-based organisations, informal social groupings and families) as irrelevant to emergency action. Spontaneous actions by affected communities or groups (e.g., search and rescue) are viewed as irrelevant or disruptive, because they are not controlled by the authorities. The second assumption is that disasters produce passive 'victims' who are overwhelmed by crisis or dysfunctional behavior (panic, looting, self-seeking activities). They therefore need to be told what to do, and their behavior must be controlled — in extreme cases, through the imposition of martial law. There is plenty of sociological research to refute such 'myths'.

An alternative viewpoint, informed by a considerable volume of research, emphasises the importance of communities and local organisations in disaster risk management. The rationale for community-based disaster risk management that it responds to local problems and needs, capitalises on local knowledge and expertise, is cost-effective, improves the likelihood of sustainability through genuine 'ownership' of projects, strengthens community technical and organisational capacities, and empowers people by enabling them to tackle these and other challenges. Local people and organisations are the main actors in risk reduction and disaster response in any case. Consequently, it has been seen that understanding the social capital already existent in the community can greatly help reducing the risk at the community level.

Learning from a Colombian Community

Widespread flooding affected most of Colombia's 32 regions between 2010 and 2012. Some 3.6 million people were affected. On 24 April 2012, President Juan Manuel Santos enacted a law, which aimed at improving natural disaster response and prevention at both national and local level. The Universidad Del Norte, based in Barranquilla, has investigated how one community reacted to the destruction caused by the floods, in an effort to try to make Colombian communities more resilient to similar events occurring in the future. With funding from the Climate & Development Knowledge Network, the project team spent 18 months working with women from the municipality of Manatí, in the Department of Atlántico.

Here, 5,733 women were affected by the floods. They had to reconstruct their entire lives in a Manatí they could no longer recognise. The project team worked with the women to find out how they coped with the effects of the floods, and to articulate the networks of reciprocity and solidarity that developed in the community. Their findings highlighted resilience strategies that the community used to respond to the extreme event. The researchers suggested that similar strategies could be used to inform government actions to reduce or manage risk from disasters. They also concluded that it is important to consider gender when planning for disasters as women and men often play very different roles and because, on average, disasters kill more women than men.

Governance

The DRR approach requires redefining the role of government disaster reduction. It is generally agreed that national governments should be main actors in DRR: They have a duty to ensure the safety of citizens, the resources and capacity to implement large-scale DRR, a mandate to direct or co-ordinate the work of others, and they create the necessary policy and legislative frameworks. These policies and programmes have to be coherent. More research is needed into why some governments are more successful than others in disaster management. There is still no general consensus on what drives changes in policy and practice. The shifting relationship between central government and other actors is another area requiring research.

Accountability and Rights

The principle of accountability lies at the heart of genuine partnership and participation in DRR. It applies to state institutions that are expected to be accountable through the democratic process and to private sector and non-profit organizations that are not subject to democratic control. Accountability is an emerging issue in disaster reduction work. Accountability should be primarily toward those who are vulnerable to hazards and affected by them.

Many organisations working in international aid and development are now committing themselves to a 'rights-based' approach. This tends to encompass human rights (i.e., those that are generally accepted through international agreements) and other rights that an agency believes should be accepted as human rights. In such contexts, the language of rights may be used vaguely, with a risk of causing confusion. Security against disasters is not generally regarded as a right although it is addressed in some international codes, usually indirectly. The idea of a 'right to safety' is being discussed in some circles.

Policy and Investment

In a June 2012 study, researchers at the Overseas Development Institute highlighted the need for more focus on disaster risk management (DRM) in the international policy frameworks to be agreed in 2015. Economic costs of disasters are on the rise, but most humanitarian investment is currently spent on responding to disasters, rather than managing their future risks. If this pattern continues, the researchers argue, then "spending on reconstruction and relief will become unsustainable." A more developed evidence base, enhanced political commitment, and dialogue across policy areas will be needed for this mainstreaming of disaster risk management to happen.

Further papers also highlighted the need to for strong gender perspective in disaster risk reduction policy. Studies have shown that women are disproportionally impacted by natural disasters. Following the 2004 tsunami in the Indian Ocean, 77% and 72% of the deaths in the districts of North Aceh and Aceh Besar, Indonesia, were female. And in India 62% of people who died were female. A gender-sensitive approach would identify how disasters affect men, women, boys and girls differently and shape policy to people's specific vulnerabilities, concerns and needs.

Context

Only 4% of the estimated $10 billion in annual humanitarian assistance is devoted to prevention, and yet every dollar spent on risk reduction saves between $5 and $10 in economic losses from disasters.

Different kinds of disasters.

Subcontext

If one of the above 4% were dedicated to clean water for the poor who die from drinking contaminated water, if they don't die from lack of even that, the numbers work out to about 200,000 lives saved per year. Tradeoff: save the palace, or save 200,000 lives, leaving 3% to invest in risk reduction worth about $300 million in aid. There's no reason to reduce the humanitarian aid for saving $300 million. A Senator could grant that by voice vote, or a good fund raiser could cover that money, and still leave $100 million to save 200,000 lives with clean drinking water.

Towards the Sendai Framework for Disaster Risk Reduction (2015–2030)

In March 2015, the 10-year-old Hyogo Framework came to an end and was replaced by the Sendai Framework. It sets out four priorities: understanding disaster risk; strengthening disaster risk governance to manage disaster risk; investing in disaster risk reduction for resilience; enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction. To support the assessment of global progress in achieving the outcome and goal of the Sendai Framework, seven global targets have been agreed: substantially reduce global disaster mortality by 2030, aiming to lower average per 100,000 global mortality between 2020–2030 compared to 2005–2015; substantially reduce the number of affected people globally by 2030, aiming to lower the average global figure per 100,000 between 2020–2030 compared to 2005–2015; reduce direct disaster economic loss in relation to global gross domestic product by 2030; substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030; substantially increase the number of countries with national and local disaster risk reduction strategies by 2020; substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of the framework by 2030; substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030.

The Sendai document emerged from three years' of talks, during which UN member states, NGOs and other stakeholders made calls for an improved version of the existing HFA, with a set of common standards, a comprehensive framework with achievable targets, and a legally-based instrument for disaster risk reduction. Member states also emphasised the need to tackle disaster risk reduction and climate change adaption when setting the Sustainable Development Goals, particularly in light of an insufficient focus on risk reduction and resilience in the original Millennium Development Goals.

Emergency preparedness has the potential to be transformative in presenting sustainable and functioning national systems that will reduce the cost of long-term response and relieve the increasing burden on the humanitarian system. However, emergency preparedness is largely underfunded. Where the financing does exist, it is complex, fragmented and disorganised. This is particularly the case for the international contribution, with various separate institutions, mechanisms and approaches defining where the funding is directed and how it is spent. A report by the Overseas Development Institute suggests that although there are advantages to improving existing financing mechanisms for emergency preparedness, it is not sufficient to simply reinforce the current system. Incremental changes will still leave gaps and a global solution should be considered to improve long-term disaster risk reduction.

EARTHQUAKE PREPAREDNESS

Earthquake preparedness is a set of measures taken at the individual, organisational and societal level to minimise the effects of an earthquake. Preparedness measures can range from securing heavy objects, structural modifications and storing supplies, to having insurance, an emergency kit, and evacuation plans.

Preparedness Measures

Preparedness can consist of survival measures, preparation that will improve survival in the event of an earthquake, or mitigating measures, that seek to minimise the effect of an earthquake. Common survival measures include storing food and water for an emergency, and educating individuals what to do during an earthquake. Mitigating measures can include firmly securing large items of furniture (such as bookcases and large cabinets), TV and computer screens that may otherwise fall over in an earthquake. Likewise, avoiding storing items above beds or sofas reduces the chance of objects falling on individuals.

Planning for a related tsunami, tsunami preparedness, can also be part of earthquake preparedness.

Building Design and Retrofitting

Building codes in earthquake prone areas may have specific requirements designed to increase new buildings' resistance to earthquakes. Older buildings and homes that are not up to code may be modified to increase their resistance. Modification and earthquake resistant design are also employed in elevated freeways and bridges.

Codes are not designed to make buildings earthquake proof in the sense of them suffering zero damage. The goal of most building designs is to reduce earthquake damage to a building such that it protects the lives of occupants and thus tolerance of some limited damage is accepted and considered a necessary tradeoff. A supplement or precursor to retrofitting can be the implementation of earthquake proof furniture.

Earthquake modification techniques and modern building codes are designed to prevent total destruction of buildings for earthquakes of no greater than 8.5 on the Richter Scale. Although the Richter Scale is referenced, the localized shaking intensity is one of the largest factors to be considered in building resiliency.

Types of Preparedness

The basic theme behind preparedness is to be ready for an earthquake. Preparedness starts with an individual's everyday life and involves items and training that would be useful in an earthquake. Preparedness continues on a continuum from individual preparedness through family preparedness, community preparedness and then business, non-profit and governmental preparedness. Some organisations blend these various levels. Business continuity planning encourages businesses to have a Disaster Recovery Plan. The US FEMA breaks down preparedness generally into a pyramid, with citizens on the foundational bottom, on top of which rests local government, state government and federal government in that order.

Children may present particular issues and some planning and resources are directly focused on supporting them. The US FEMA has advice noting that "Disasters can leave children feeling frightened, confused, and insecure" whether a child has experienced it first hand, had it happen to a friend or simply seen it on television. People with disabilities or other special needs may have special emergency preparation needs. FEMA's suggestions for people with disabilities include having copies of prescriptions, charging devices for medical devices such as motorized wheel chairs and a week's supply of medication readily available. Preparedness can also cover pets.

Preparedness can also encompass psychological preparedness: resources are designed to support both community members affected by a disaster and the disaster workers serving them.

A multi-hazard approach, where communities are prepared for several hazards, are more resilient than single hazard approaches and have been gaining popularity.

Long term power outages can cause damage beyond the original disaster that can be mitigated with emergency generators or other power sources to provide an emergency power system. The United States Department of Energy states: "homeowners, business owners, and local leaders may have to take an active role in dealing with energy disruptions on their own." Major institutions like hospitals, military bases and educational institutions often have extensive backup power systems. Preparedness does not stop at home or at school. The United States Department of Health and Human Services addresses specific emergency preparedness issues hospitals may have to respond to, including maintaining a safe temperature, providing adequate electricity for life support systems and even carrying out evacuations under extreme circumstances. FEMA encourages all businesses to have an emergency response plan and the Small Business Administration specifically advises small business owners to also focus emergency preparedness and provides a variety of different worksheets and resources.

Given the explosive danger posed by natural gas leaks, Ready.gov states that "It is vital that all household members know how to shut off natural gas" and that property owners must ensure they have any special tools needed for their particular gas connections. Ready.gov also notes that "It is wise to teach all responsible household members where and how to shut off the electricity," cautioning that individual circuits should be shut off before the main circuit. Ready.gov further states that "It is vital that all household members learn how to shut off the water at the main house valve" and cautions that the possibility that rusty valves might require replacement.

Achieving Preparedness

Levels of preparedness generally remain low, despite attempts to increase public awareness.

Various methods exist to promote disaster preparedness, but they are rarely well documented and their efficacy is rarely tested. Hands on training, drills and face-to-face interaction have proven more successful at changing behaviour. Digital methods have also been used, including for examples educational videogames.

TORNADO PREPAREDNESS

The term "tornado preparedness" refers to safety precautions made before the arrival of and during a tornado. Historically, the steps taken have varied greatly, depending on location, or time remaining before a tornado was expected. For example, in rural areas, people might prepare to enter an external storm cellar, in case the main building collapses, and thereby allow exit without needing rescue from the main building as in urban areas. Because tropical storms have spawned many tornadoes, hurricane preparations also involve tornadoes. The term "tornado preparedness" has been used by government agencies, emergency response groups, schools, insurance companies, and others.

Understanding the Dangers

Preparedness involves knowing the major dangers to avoid. Some tornadoes are the most violent storms in nature. Tornadoes have varied in strength, and some tornadoes have been mostly invisible due to a lack of loose dirt or debris in the funnel cloud. Spawned from severe thunderstorms, tornadoes have caused fatalities and devastated neighborhoods within seconds of arrival.

A tornado operates as a rotating, funnel-shaped cloud that extends downward from a thunderstorm, to the ground, with swirling winds which have reached 300 miles per hour (480 km/h). The wind speed might be difficult to imagine: traveling the length of a U.S. football field within 1 second (over 130 meters or 430 feet per second). Damage paths have been in excess of one-mile wide (1.6 km) and 50 miles long (80 km).

Not all tornadoes are easily seen. A tornado funnel can be transparent until reaching an area with loose dirt and debris. Also, some tornadoes have been seen against sunlit areas, but rain or nearby low-hanging clouds has obscured other tornadoes. Occasionally, tornadoes have developed so suddenly, so rapidly, that little, if any, advance warning was possible.

Before a tornado strikes an area, the wind has been known to die down and the air to become very still. A cloud of debris has sometimes marked the bottom of a tornado even when the funnel was not visible. Tornadoes typically occur along the trailing edge of a thunderstorm.

The following is a summary of typical tornadoes:

- They may strike quickly, with little or no warning.
- They may appear nearly transparent until dust and debris are picked up or a cloud forms in the funnel.
- The average tornado moves Southwest to Northeast in the U.S., but tornadoes have been known to move in any direction.
- The average forward speed of a tornado is 30 miles per hour (48 km/h), but has varied from stationary to 70 mph (110 km/h).
- Tornadoes can also accompany tropical storms and hurricanes as they move onto land.
- Waterspouts are tornadoes that form over water.
- Tornadoes are most frequently reported east of the Rocky Mountains during spring and summer months.
- Peak tornado season in the southern U.S. states is March through May; in the northern states, it is late spring through early summer.
- Tornadoes are most likely to occur between 3 p.m. and 9 p.m. (local time), but have occurred at other times.

A tornado with no obvious funnel from the upper clouds, although the rotating dust cloud indicates strong winds at the surface.

Steps when Expecting Storms to Arrive

The U.S. Federal Emergency Management Agency (FEMA) has advised the following precautions before a storm reaches an area:

- Be alert to the changing weather conditions.
- Listen to NOAA Weather Radio and Skywarn, or to local commercial radio or television newscasts for the latest information.
- Watch various common danger signs, including:
  - Dark, often greenish-colored sky;
  - Large hail stones;

- A large, dark, low-lying cloud (particularly if rotating);
- Loud roar of wind, sounding similar to a freight train.

Upon seeing an approaching storm or noticing any of the danger signs, they were advised to prepare to take shelter immediately, such as moving to a safe room, internal stairway, or other safe-haven area.

All individuals and families should have a disaster preparedness kit made prior to tornado. According to FEMA the kit should include items needed to shelter in place in the event of a disaster such as a tornado for up to 72 hours following impact.

Example of a tornado emergency kit.

Actions taken during Tornadoes

During August 2010, FEMA advised people to perform the following actions when a tornado struck.

Location	Action taken
In a structure (e.g. residence, small building, school, nursing home, hospital, factory, shopping center, high-rise building,restaurant)	They were to enter a pre-designated shelter area such as a safe room, basement, storm cellar, or the lowest building level. If there was no basement, then to the center of an interior room on the lowest level (closet, interior hallway) away from corners, windows, doors, and outside walls. The goal has been to put as many walls as possible between there and the outside. They were advised to get under a sturdy table and use arms to protect head and neck, and not open windows.
In a vehicle, trailer, or mobile home	They were advised to leave immediately and enter the lowest floor of a sturdy, nearby building or a storm shelter. Mobile homes, even if tied down, offer little protection from tornadoes. If a car is flipped by high winds, there is also the danger of broken glass.
On the outside with no shelter	They were advised to lie flat in a nearby ditch or depression and cover head with their hands. Also, to beware of the potential for flooding there. They were advised to not stay under an overpass or bridge (where winds or debris might be funneled). It was safer to be in a low, flat location. The advice was to never try to outrun a tornado in urban or congested areas in a car or truck, but instead, to leave the vehicle immediately for safe shelter. Flying debris from tornadoes causes most fatalities and injuries.

Because some preparations vary, depending on location, people have been advised to consult their local area preparedness plans, rather than assume the plans are similar for all areas, such as which local buildings have been designated as storm shelters.

A 2012 study of tornado injuries found that wearing a helmet such as those used for American football or bicycling, is an effective way to reduce injuries and deaths from head trauma. As of 2012, the CDC endorsed only general head protection, but recommended that if helmets are to be used, they be kept close by to avoid wasting time searching for them.

After the 2013 Moore tornado, it became apparent that thousands of people attempt to flee major tornadoes, and this has been credited with reducing the death toll. However, during this event some people were killed as the tornado passed over the traffic jam caused by the impromptu evacuation. In addition to urban traffic, evacuation can also be hampered by flash flooding produced by associated thunderstorms, and the need to be certain about the position and direction of the tornado. Others who did not flee the Moore tornado were also killed because the buildings they were hiding in were completely destroyed, highlighting the need for storm shelters and safe rooms constructed specifically to withstand very high winds.

Long-Term Preparations

Depending on location, various safe-haven areas have been prepared. The goal has been to avoid outer walls which might collapse when a roof section becomes airborne and the walls below lose their upper support: many interior rooms resist collapse longer, due to smaller walls interconnected to each other, while outer walls deflect the force of the winds. Because mobile homes typically lack foundation anchors and present a large surface-area sail (to catch wind), the advice has been to seek a safe haven elsewhere, such as in a stronger nearby building. When a mobile home begins to roll, people have been injured by hitting objects inside, or being crushed when a trailer suddenly hits the ground and begins to collapse around them.

In a multi-story building, an internal stairway (away from broken windows) often acts as a safe haven, due to the stairs reinforcing the walls and blocking any major debris falling from above. If a stairway is lined with windows, then there would be the danger of flying glass, so an interior stairway, or small inner room, would be preferable.

In private homes, some similar stairway rooms have been used, or an interior room/closet kept clear to quickly allow entry when a storm is seen or heard approaching (the wind roar intensifies, sounding like a swift "freight train" coming nearer, louder). With weeks or months to prepare, an interior safe room can be constructed, with space for emergency water, food and flashlights, and a telephone to call for rescue if the exit becomes blocked by falling debris. Some above-ground safe rooms have been built with steel-rebar rods in cement-filled cinder blocks, to withstand winds of 250 miles per hour (400 km/h). Rural homes might have an outside storm cellar, or other external bunker, to avoid being trapped within a collapsing house. In rural homes, generators are also helpful to maintain power with enough fuel for a few days.

There were no building codes requiring tornado shelters nor specifically designed to prevent tornado damage until the 2011 Joplin tornado prompted a local ordinance requiring hurricane ties or similar fasteners. The state of Oklahoma adopted the minimum U.S. standard that year for the first time, but did not add high-wind protections like those in Florida designed to protect against hurricanes. Other states in Tornado Alley have no statewide building codes. The chance of any given location in Tornado Alley getting hit by an F-2 tornado (strong enough to do major structural damage and exceeding the 90 mph guideline for straightline winds) is about 1 every 4,000-5,000 years; in other areas the annual probability is one in several million. The most stringent building codes only require earthquake strengthening for a 1 in every 500-1,000 year probability.

The U.S. Federal Emergency Management Agency has spent tens millions of dollars subsidizing the construction of shelters and safe rooms in both private and public buildings. Many buildings in Tornado Alley do not have basements, because unlike in more northern areas, there is no need for a deep foundation to get below the frost line, in some places the water table is high, and expansion and contraction of clay-heavy soils can produce additional pressure on buildings that can cause leaks if not reinforced.

Medical Preparations

Having a first aid kit in the safe haven is advised to help victims recover from minor injuries. People needing prescription medications could have a medicine bag ready to take to shelter. Some people have reported their "ears popping" due to the change in air pressure, but those effects seem to be temporary. Covering people with mattresses or cushions has helped avoid injury from flying debris, as walls collapsed nearby.

Injuries sustained during a tornado vary in nature and in severity. The most common injuries experienced during a tornado are complex contaminated soft tissue wounds and account for more than 50% of the cases seen by emergency rooms following a tornado. These wounds will most likely be contaminated with soil and foreign bodies due to high wind speeds caused by tornadoes. Fractures are the second most common injury obtained after a tornado strikes and account for up to 30% of total injuries. Head injuries are also commonly reported during a tornado, but severe head injuries only account for less than 10% of the total. Even though only 10% of reported head injuries are severe, they are the most common cause of death following a tornado. Blunt trauma to the chest and abdomen are also injuries obtained following a tornado, but only account for less than 10% of overall injuries.

Tornado Drills

Students participate in a tornado drill, lining up along an interior wall and covering their heads.

Tornado drills are an important element in tornado preparedness. Like any other safety drills, they increase chances of correct response to a real tornado threat.

Most states in the midwestern and southern United States conduct a statewide tornado drill in late winter or early spring in preparation for the severe weather season. During these drills, the National Weather Service issues test tornado warnings, and local Emergency Alert Systems and/ or NOAA Weather Radio (normally as a Required Weekly Test or Required Monthly Test; Live Tornado Warning Codes can only be used if a waiver from the FCC is granted since "Live Code Testing" is prohibited per regulations) are activated along with outdoor warning sirens. Schools and businesses may also conduct a tornado drill simultaneously.

A tornado drill is a procedure of practicing to take cover in a specified location in the event that a tornado strikes an area. This safety drill is an important element of tornado preparedness.

Generally, a signal is given, such as a series of tones (ex. Continuous Tone), or a voice announcement. Upon receiving the signal, building occupants of schools, hospitals, factories, shopping centers, etc. proceed to a designated location, usually an interior room or corridor with no windows, and assume a protective position.

In homes and small buildings one must go to the basement or an interior room on the lowest floor (closet, bathroom), to stay away from glass.

Cars and mobile homes must be abandoned, if there is small chance to drive away.

In some jurisdictions, schools are required to conduct regular tornado drills, though generally less frequently than fire drills.

Tornado Drills by State

In many states tornado drills are part of the Severe Weather Awareness Week.

- Alabama
- Florida
- Georgia
- Indiana
- Iowa
- Ohio
- Michigan
- Minnesota
- Missouri
- Texas
- Virginia
- Wisconsin
- North Carolina

EMERGENCY EVACUATION

Emergency evacuation is the urgent immediate egress or escape of people away from an area that contains an imminent threat, an ongoing threat or a hazard to lives or property.

Examples range from the small-scale evacuation of a building due to a storm or fire to the large-scale evacuation of a city because of a flood, bombardment or approaching weather system. In situations involving hazardous materials or possible contamination, evacuees may be decontaminated prior to being transported out of the contaminated area.

Evacuees on Interstate 45 leaving Galveston, through Houston, during Hurricane Rita in 2005
Note how no south-bound lanes (right) were used as north contra-flow lanes for vehicles turning west.

Reasons for Evacuation

Special speed limit sign in the United States for evacuation routes, requiring drivers to maintain the maximum safe speed.

Evacuations may be carried out before, during or after disasters such as:

- Natural disasters
  - Eruptions of volcanoes
  - Tropical cyclones
  - Floods
  - Earthquakes
  - Tsunamis or
  - Wildfires/bushfires

Other reasons include:

- Industrial accidents
  - Chemical spill

  - Nuclear accident
- Transport
  - Road accidents
  - Train wreck
  - Emergency aircraft evacuation
- Fire
- Military attacks
  - Bombings
  - Terrorist attacks
  - Military battles
  - Imminent nuclear war
- Structural failure
- Viral outbreak

Planning

Emergency evacuation plans are developed to ensure the safest and most efficient evacuation time of all expected residents of a structure, city, or region. A benchmark "evacuation time" for different hazards and conditions is established. These benchmarks can be established through using best practices, regulations, or using simulations, such as modeling the flow of people in a building, to determine the benchmark. Proper planning will use multiple exits, contra-flow lanes, and special technologies to ensure full, fast and complete evacuation. Consideration for personal situations which may affect an individual's ability to evacuate is taken into account, including alarm signals that use both aural and visual alerts, and also evacuation equipment such as sleds, pads, and chairs for non-ambulatory people. Considering the persons with a disability during an emergency evacuation is important. This is because it is crucial that every user gets out of the building or to a safe place in the building, thus also the persons with disabilities or the non- ambulatory people. Regulations such as building codes can be used to minimize the negative consequences of the threat triggering the evacuation and optimize the need to self-evacuate without causing alarm. Proper planning, that covers designated actions to ensure safety of the users in emergencies, will implement an all-hazards approach so that plans can be reused for multiple hazards that could exist.

Therefore, key elements for emergency planning and preparedness are early warnings for the people inside the building by emergency helpers but also voice assistance, facilities to leave the building safe and fast, such as exit routes and good evacuation practices. The evacuation managing team must know that to do in emergency situations and which actions to take. Furthermore, the above-mentioned key elements are highly bounded with the human behavior types (like panic levels), awareness of the layout which is very crucial item in emergency evacuation for maritime transportation and also the prompt reactions of first respondents.

Evacuation Sequence

The sequence of an evacuation can be divided into the following phases:

- Detection,
- Decision,
- Alarm,
- Reaction,
- Movement to an area of refuge or an assembly station,
- Transportation.

The time for the first four phases is usually called pre-movement time.

The particular phases are different for different objects, e.g., for ships a distinction between assembly and embarkation (to boats or rafts) is made. These are separate from each other. The decision whether to enter the boats or rafts is thus usually made after assembly is completed.

Small Scale Evacuations

The strategy of individuals in evacuating buildings was investigated by John Abrahams in 1994. The independent variables were the complexity of the building and the movement ability of the individuals. With increasing complexity and decreasing motion ability, the strategy changes from "fast egress", through "slow egress" and "move to safe place inside building" (such as a staircase), to "stay in place and wait for help". The third strategy is the notion of using a designated "safe haven" on the floor. This is a section of the building that is reinforced to protect against specific hazards, such as fire, smoke or structural collapse. Some hazards may have safe havens on each floor, while a hazard such as a tornado, may have a single safe haven or safe room. Typically persons with limited mobility are requested to report to a safe haven for rescue by first responders. In most buildings, the safe haven will be in the stairwell.

By investing the strategy of individuals in evacuating buildings, the variable human reactions is a complex factor to take into account during an evacuation. This is a critical factor for escaping fast out of the building or to a "safe haven". During an emergency evacuation, people do not immediately react after hearing the alarm signal. This is because an evacuation drill is more common. Therefore, they will start evacuating when there is more information given about the degree of danger. During an evacuation, people often use the most known escape route, this is often the route through which they entered the building. Thereby, people mostly adapt the role follower in emergencies. These human reactions will determinate the strategy of individuals in evacuating buildings.

The most common equipment in buildings to facilitate emergency evacuations are fire alarms, exit signs, and emergency lights. Some structures need special emergency exits or fire escapes to ensure the availability of alternative escape paths. Commercial passenger vehicles such as buses, boats, and aircraft also often have evacuation lighting and signage, and in some cases windows or extra doors that function as emergency exits. Commercial emergency aircraft evacuation is also facilitated by evacuation slides and pre-flight safety briefings. Military aircraft are often equipped with ejection seats or parachutes. Water vessels and commercial aircraft that fly over water are equipped with personal flotation devices and life rafts.

Since the emergence of The Internet of Things technologies, new techniques are appearing, which involves new equipment. Most of them are wireless devices such as IDs scanner, beacons or back-scatter system. The new techniques are for example based on a communication protocol such as Wi-Fi, Bluetooth, UWB or RFID and the use of indoor positioning system. The use of The Internet of Things technologies in small scale evacuations can result in a faster evacuation time: Mostly by localizing the fire sources, analysing the fire spreading inside the building or finding people that are trapped inside the building. Some buildings can have a monitoring interface that provides all these kind of information to evacuate in the best way possible.

An exit sign in the United States, showing the way to the nearest exit, with two emergency lights for electrical failure.

ISO 7001 standard exit sign, used since 1982 in Japan.

Large Scale Evacuations

The evacuation of districts is part of disaster management. Many of the largest evacuations have been in the face of wartime military attacks. Modern large scale evacuations are usually the result of natural disasters. The largest peacetime evacuations in the United States to date occurred during Hurricane Gustav and the category-5 Hurricane Rita in a scare one month after the flood-deaths of Hurricane Katrina.

Hurricane Evacuation

Evacuation route marking near the Texas Gulf Coast.

Despite mandatory evacuation orders, many people did not leave New Orleans, United States, as Hurricane Katrina approached. Even after the city was flooded and uninhabitable, some people still refused to leave their homes.

The longer a person has lived in a coastal area, the less likely they are to evacuate. A hurricane's path is difficult to predict. Forecasters know about hurricanes days in advance, but their forecasts of where the storm will hit are only educated guesses. Hurricanes give a lot of warning time compared to most disasters humans experience. However, this allows forecasters and officials to "cry wolf," making people take evacuation orders less seriously. Hurricanes can be predicted to hit a coastal town many times without the town ever actually experiencing the brunt of a storm. If evacuation orders are given too early, the hurricane can change course and leave the evacuated area unscathed. People may think they have weathered hurricanes before, when in reality the hurricane didn't hit them directly, giving them false confidence. Those who have lived on the coast for ten or more years are the most resistant to evacuating.

Public Transportation

Since Hurricane Katrina, there has been an increase in evacuation planning. Current best practices include the need to use multi-modal transportation networks. Hurricane Gustav used military airlift resources to facilitate evacuating people out of the affected area. More complex evacuation planning is now being considered, such as using elementary schools as rally points for evacuation. In the United States, elementary schools are usually more numerous in a community than other public structures. Their locations and inherent design to accommodate bus transportation makes it an ideal evacuation point.

Registries

Most local communities maintain registries for special needs individuals. These opt-in registries help with planning, as those that need government evacuation assistance are identified before the disaster. Registries used after a disaster are being used to help reunite families that have become separated after a disaster.

Enforcing Evacuation Orders

In the United States, a person usually cannot be forced to evacuate. To facilitate voluntary compliance with mandatory evacuation orders first responders and disaster, management officials have used creative techniques such as asking people for the names and contact of their next-of-kin, writing their Social Security Numbers on their limbs and torso to enable identification of remains, and refusing to provide government services in the affected area, including emergency services.

Personal Evacuation Kits

In case of an emergency evacuation situation, it is important to have an individual emergency evacuation kit prepared and on hand prior to the emergency. An emergency evacuation kit is a container of food, clothing, water, and other supplies that can be used to sustain an individual during lag time. Lag time is the period between the actual occurrence of an emergency and when organized help becomes available, generally 72 hours, though this can vary from a few hours to several days. It may take this long for authorities to get evacuation shelters fully up and functional. During this time, evacuees may suffer fairly primitive conditions; no clean water, heat, lights, toilet facilities, or shelter. An emergency evacuation kit, or 72-hour kit, can help evacuees to endure the evacuation experience with dignity and a degree of comfort.

Cyber-Physical Systems

The development of digital infrastructure resources opened a new research area in the design of cyber-physical systems to provide the individual with safer options during an emergency evacuation.

EMERGENCY SANITATION

Emergency sanitation is the management and technical processes required to provide sanitation in emergency situations. This can include man-made or natural disasters. Emergency sanitation is also required during humanitarian relief operations for refugees and Internally Displaced Persons (IDPs).

Emergency situations are classified into three phases which are called the "immediate", "short-term" and "long-term" phases. In the immediate phase, the focus is on reducing open defecation. Toilets provided might include very basic latrines, pit latrines, bucket toilets, container-based toilets or chemical toilets.

Providing showers and handwashing facilities is also part of emergency sanitation during all phases. Fecal sludge management becomes a priority during the long-term emergency management phase.

Emergency toilet in Haiti, suitable for areas where digging pit latrines is not possible.

Methods

To address the problem of public health and the spread of dangerous diseases that come as a result of lack of sanitation and open defecation, humanitarian actors focus on the construction of, for example, pit latrines and the implementation of hygiene promotion programmes.

Emergency pit latrines with bathing shelters built in the Bidi Bidi refugee settlement in northern Uganda.

The supply of drinking water in an urban-setting emergency has been improved by the introduction of standardised, rapid deployment kits.

In the immediate emergency phase, the focus is on managing open defecation, and toilet technologies might include very basic trench latrines, pit latrines, bucket toilets, container-based toilets, chemical toilets. The short term phase might also involve technologies such as urine-diverting dry toilets, septic tanks, decentralized wastewater systems.

In urban emergencies, the main focus is usually on a quick rehabilitation and extension of existing services such as sewer-lines and waste-water treatment plants. This can also include the installation of sewerage pumping stations to improve or extend services.

Settings

The emergency response often has to differ greatly based on the setting it takes place.

Home Based

Home based settings where people choose to stay in or close to their homes (or those of their relatives, neighbours or friends). While this setting offers the quickest way to (self-) recovery, it also poses a high risk of sanitation related impacts due to the common lack of access to outside help and inadequate public-health monitoring.

Host Community

Host community settings with significant displacement into outside communities (usually urban) with existing but maybe also effected sanitation infrastructure in private homes.

Existing infrastructure in such settings is usually quickly overloaded due to the increase in population density and improvements/repair is often hindered by access- and space-limitations. Intra-community conflicts over the sanitation waste management are thus fairly common.

Mass Shelter

Mass shelter settings where the displaced population is housed in existing but often re-purposed building-complexes such as schools, community centres, places of worship, malls, warehouses and sport stadiums. In some disaster prone countries, dedicated large emergency shelters are build for this purpose.

Existing sanitation facilities are usually inadequate for full-time stay of a high number of people, and the non-emergency management structures are typically unable or unwilling to continue their services. Legal issues over the re-purposing are also fairly common, especially if occupation continues for a longer time.

Due to usually cramped living conditions there is a high risk of conflict and often also cases of sexual violence, both of which often are in some relation to the sanitation facilities.

Emergency Settlements

Emergency settlements (formal or informal) where previously sparsely populated areas are newly occupied by the displaced population in large numbers. Typically these are set up by governments, the UN and humanitarian aid organisations.

Due to the typically short time frame of arrivals and the non-existing infrastructure, these kind of encampments pose maybe the greatest challenge in regards to providing adequate emergency sanitation facilities.

Challenges

Emergency pit lining kits, suitable for areas with high water table.

The provision of sanitation programmes is usually more challenging than water supply as it provides a limited choice of technologies. This is exacerbated by the overwhelming and diverse needs of Wash.

Challenges with excreta disposal in emergencies include:

- Building Latrines in areas where pits cannot be dug, desludging latrines, no-toilet options and the final treatment or disposal of the fecal sludge.
- Weak community participation and finding hygiene promotion designs that are suitable for a given context to make the WASH interventions sustainable.
- Newly arriving IDP or refugee populations can usually only be settled in less than ideal areas, such as land that is prone to regular flooding or which is very dry and with rocky

ground. This makes the provision of safe sanitation facilities and other infrastructure very difficult.

- In long running emergencies, the safe decommissioning or desludging of previously quickly built sanitation facilities can also become a serious challenge.
- Humanitarian actors need to understand the importance of better preparation and resilience and the need for exit strategies and have consideration on the environment.

DISASTER MEDICINE

Disaster medicine is the area of medical specialization serving the dual areas of providing health care to disaster survivors and providing medically related disaster preparation, disaster planning, disaster response and disaster recovery leadership throughout the disaster life cycle. Disaster medicine specialists provide insight, guidance and expertise on the principles and practice of medicine both in the disaster impact area and healthcare evacuation receiving facilities to emergency management professionals, hospitals, healthcare facilities, communities and governments. The disaster medicine specialist is the liaison between and partner to the medical contingency planner, the emergency management professional, the incident command system, government and policy makers.

Disaster medicine is unique among the medical specialties in that unlike all other areas of specialization, the disaster medicine specialist does not practice the full scope of the specialty everyday but only in emergencies. Indeed, the disaster medicine specialist hopes to never practice the full scope of skills required for board certification. However, like specialists in public health, environmental medicine and occupational medicine, disaster medicine specialists engage in the development and modification of public and private policy, legislation, disaster planning and disaster recovery. Within the United States of America, the specialty of disaster medicine fulfils the requirements set for by Homeland Security Presidential Directives (HSPD), the National Response Plan (NRP), the National Incident Management System (NIMS), the National Resource Typing System (NRTS) and the NIMS Implementation Plan for Hospitals and Healthcare Facilities.

Ethics in Disaster Medicine

The Disaster Medicine practitioner must be well-versed in the ethical dilemmas that commonly arise in disaster settings. One of the most common dilemmas occurs when the aggregate medical need exceeds the ability to provide a normal standard of care for all patients.

Triage

In the event of a future pandemic, the number of patients that require additional respiratory support will outnumber the number of available ventilators. Although a hypothetical example, similar natural disasters have occurred in the past. Historically, the influenza pandemic of 1918-19 and the more recent SARS epidemic in 2003 led to resource scarcity and necessitated triage. One paper estimated that in the United States, the need for ventilators would be double the number available in the setting of an influenza pandemic similar to the scale of 1918. In other countries with fewer resources, shortages are postulated to be even more severe.

How, then, is a clinician to decide whom to offer this treatment? Examples of common approaches that guide triage include "saving the most lives", calling for care to be provided to "the sickest first" or alternatively a "first come, first served" approach may attempt to sidestep the difficult decision of triage. Emergency services often use their own triaging systems to be able to work through some of these challenging situations; however, these guidelines often assume no resource scarcity, and therefore, different triaging systems must be developed for resource-limited, disaster response settings. Useful ethical approaches to guide the development of such triaging protocols are often based on the principles of the theories of utilitarianism, egalitarianism and proceduralism.

Utilitarian Approach

The Utilitarian theory works on the premise that the responder shall 'maximise collective welfare'; or in other words, 'do the greatest good for the greatest numbers of people'. The utilitarian will necessarily need a measure by which to assess the outcome of the intervention. This could be thought of through various ways, for instance: the number of lives saved, or the number of years of life saved through the intervention. Thus, the utilitarian would prioritize saving the youngest of the patients over the elderly or those who are more likely to die despite an intervention, in order to 'maximise the collective years of life saved'. Commonly used metrics to quantify utility of health interventions include DALYs (Disability Adjusted Life Years) and QALYs (Quality Adjusted Life Years) which take into account the potential number of years of life lost due to disability and the quality of the life that has been saved, respectively, in order to quantify the utility of the intervention.

Egalitarian Approach

Principles of egalitarianism suggest the distribution of scarce resources amongst all those in need irrespective of likely outcome. The egalitarian will place some emphasis on equality, and the way that this is achieved might differ. The guiding factor is need rather than the ultimate benefit or utility of the intervention. Approaches based on egalitarian principles are complex guides in disaster settings. In the words of Eyal "Depending on the exact variant of egalitarianism, the resulting limited priority may go to patients whose contemporaneous prognosis is dire (because their medical prospects are now poor), to patients who have lived with serious disabilities for years (because their lifetime health is worse), to young patients (because dying now would make them short-lived), to socioeconomically disadvantaged patients (because their welfare prospects and resources are lower), or to those who queued up first (because first-come first-served may be thought to express equal concern."

Procedural Approach

The inherent difficulties in triage may lead practitioners to attempt to minimize active selection or prioritization of patients in face of scarcity of resources, and instead rely upon guidelines which do not take into account medical need or possibility of positive outcomes. In this approach, known as proceduralism, selection or prioritization may be based on patient's inclusion in a particular group (for example, by citizenship, or membership within an organization such as health insurance group). This approach prioritizes simplification of the triage and transparency, although there are significant ethical drawbacks, especially when procedures favor those who are part of socioeconomically advantaged groups (such as those with health insurance). Procedural systems of triage emphasize certain patterns of decision making based on preferred procedures. This can take place in the form of a fair lottery for instance; or establishing transparent criteria for entry into hospitals - based on non discriminatory conditions. This is not outcome driven; it is a process driven activity aimed at providing consistent frameworks upon which to base decisions.

These are by no means the only systems upon which decisions are made, but provide a basic framework to evaluate the ethical reasoning behind what are often difficult choices during disaster response and management.

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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.

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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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