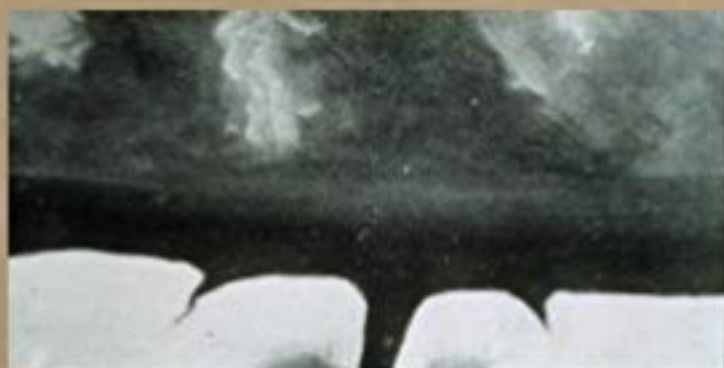
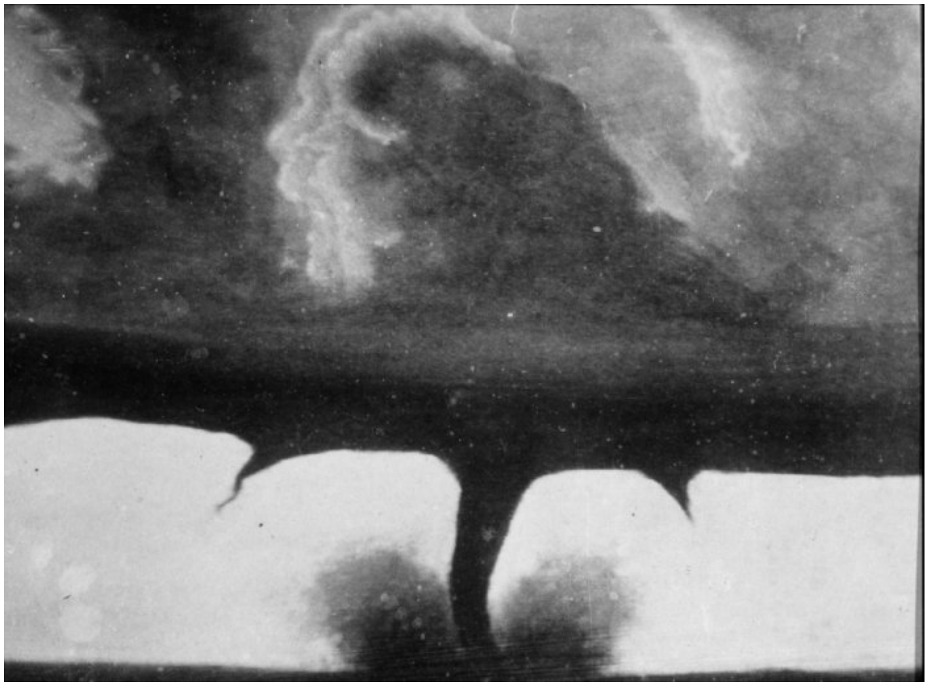
Weather Stricken



Anastasios Tsonis

Weather Stricken

Weather Stricken



Anastasios A. Tsonis
University of Wisconsin-Milwaukee

I have been teaching introductory (100-level) Atmospheric Sciences courses for over 25 years. I soon grew uneasy with the textbooks in the market that became too massive, too glitzy, and too expensive. Not to mention that every two or three years the publishers will produce a new edition, which will only be slightly different than the previous one, only to force students not to buy used previous (and cheaper) edition copies. During this time I was using my notes, which I finally developed into this textbook. This textbook is not a mainstream textbook. It is a new kind of textbook written to read like a novel while presenting historic scientific fact with every day examples.

Anastasios Tsonis
University of Wisconsin-Milwaukee

Table of Contents

Cover credit

Oldest known tornado picture

Imade ID: wea00206, Historic NWS Collection (albert.e.theberge.jr@noaa.gov)
Location: 22 miles southwest of Howard, South Dakota
Photo Date: 1884 August 28

Part I

Introduction

1. A weather-year in the life of the United States

Courtesy of NOAA

What follows is a slightly edited brief history of the main weather events that took place in 2004 reported by Jay Lawrimore of the National Climatic Data Center/National Oceanic and Atmospheric Administration (NCDC/NOAA).

"January 2004

An Arctic air mass encompassed much of eastern Canada and the U.S. Northeast during mid-month. Record daily low temperatures were set in U.S. cities such as Boston and Providence on the 14th, as temperatures plunged near or below zero degrees Fahrenheit. Three deaths in the United States were blamed on the cold weather. Weekly temperature anomalies during January 11-17 were more than 9°F below normal in the Northeast U.S.

A winter storm spread a blanket of snow and ice across a large area of the U.S. from the Plains to the Eastern Seaboard during the 24th-27th. At least 56 deaths were blamed on snow, ice and cold from Kansas to the East Coast, most from a severe ice storm in parts of the Carolinas.

In the Pacific Northwest of the United States, a parade of strong weather systems brought strong winds and wintry precipitation to areas of Washington and Oregon. Snow fell all the way to the Pacific Ocean, with Seattle and Portland reporting several inches of snow and ice. Snow accumulations across the higher terrain of the Cascade Mountains were well over a foot.

February 2004

Piedmont areas of the Carolinas received exceptionally heavy snow on February 26. Locally up to 20 inches of snow accumulated in the Charlotte metropolitan area. It was Charlotte's third largest snowstorm on record, with 13.2 inches observed at the airport.

March 2004

Thunderstorms that moved through Maryland caused the capsizing of a water taxi with 25 people aboard in Baltimore's inner harbor near Fort McHenry. Winds gusting to 50 knots (55 mph) struck the area as the thunderstorms moved through the region. Five people died as a result of the accident.

A late-season winter storm affected the northern Mid-Atlantic and into the Northeast United States on the 16th. Snowfall accumulations of 6-10 inches were common across areas of Pennsylvania, New York and into southern New England. Boston, MA reported just over 7 inches of snowfall from the storm.

April 2004

Record heat affected areas of California during April 26-27. Records broken for the month of April included 100°F at Yorba Linda on the 26th and 27th, 98°F at

Sacramento on the 26th and 99°F at Paso Robles on the 27th.

Severe thunderstorms spawned 52 tornadoes in the United States on the 20th, with the majority of these occurring in the states of Illinois and Indiana. Eight people were killed in Utica, Illinois as an F-3 tornado affected the downtown area.

An unusual late-season snow fell across parts of southern Indiana and the western parts of Kentucky and Tennessee on the 13th. In Jackson, TN, it was the latest measurable snowfall on record. In Kentucky, there were 6 fatalities in traffic accidents caused by slick driving conditions.

May 2004

The western wildfire season got off to an above average start by early May with fire danger at unprecedented high levels for early spring in parts of California. Several large fires affected the southwestern part of the state, where the Eagle and Cerrito fires charred more than 28,000 acres and destroyed more than a dozen houses.

Showers and thunderstorms brought torrential rains and flooding to parts of Texas during May 1-2. Flooding affected northern and coastal sections of the state, resulting in 6 deaths.

Heavy rains caused flooding in Texas and Oklahoma on the 14th. More than 17 inches of rain fell in nine hours placing 400 square miles of Robertson County, TX underwater. At least one person died in an automobile accident due to the heavy rains, and as many as 200 homes were damaged from the rising flood waters.

A significant outbreak of severe weather and tornadoes affected portions of the U.S. Great Plains during May 21-24, 2004. There were 179 reported tornadoes during this period, along with many reports of hail and wind damage. A strong tornado rated F-4 on the Fujita scale virtually destroyed the town of Hallam, Nebraska on the 22nd, and caused one fatality.

June 2004

Severe thunderstorms affected the Dallas-Fort Worth, TX area on June 1st, 2nd and 7th. Damaging winds and flooding accompanied each episode of severe weather. Approximately a half-million customers lost power from storms on the 1st-2nd.

July 2004

The multi-year drought throughout much of the western U.S. enhanced wildfire potential, with several large fires scattered across the region during July. Numerous large fires also charred parts of Alaska and the Yukon Territory in Canada.

Strong thunderstorms dumped upwards of a foot of rain on parts of north Texas during *the 28th-29th. In southern Dallas County, around 200 homes were damaged by high water in the suburb of Lancaster. One fatality was blamed on the flooding.*

In the Mid-Atlantic region, strong thunderstorms produced excessive rainfall and severe flooding during the 12th-13th. In central New Jersey, more than 10 inches of rain fell in less than 24 hours.

August 2004

Hurricane Alex developed off the southeast coast of the United States on July 31, reaching tropical storm strength by the 1st of August. Alex attained hurricane status by the 3rd and lashed the North Carolina Outer Banks as the eye passed just offshore. Winds on Ocracoke Island gusted as high as 120 mph, causing significant damage but no injuries. The storm continued to strengthen as it tracked away from land areas, and became the strongest recorded Atlantic hurricane at such high latitude (greater than 38 degrees north), with maximum sustained winds on the 5th of 120 mph at 40 degrees north latitude.

Tropical Storm Bonnie developed in the southern Gulf of Mexico on the 9th and came ashore just west of Appalachicola, FL on the 12th. Maximum sustained winds at the time of landfall were near 50-mph. Heavy rain and localized severe weather (including tornadoes) occurred well inland.

Hurricane Charley developed early in the month. Charley entered the southeastern Gulf of Mexico on the 13th, passing the Dry Tortugas by mid-morning. The hurricane intensified very rapidly just prior to a Florida landfall as it trekked northeastward into Charlotte Harbor and came ashore near Mangrove Point in the Port Charlotte/Punta Gorda area at category 4 intensity. At the time of landfall, maximum sustained winds were near 145 mph, causing massive damage to coastal areas and barrier islands in the path of the storm's eye. Charley continued northeastward as a hurricane, tracking directly over the Orlando and Daytona Beach areas during the evening of the 13th. Winds at the Orlando International Airport gusted to 105 mph, a new record wind gust for the city. In Florida, 25 of the state's 67 counties were declared federal disaster areas. Tens of thousands of buildings were damaged, 12,000 destroyed and more than 2 million customers were without electrical services at the conclusion of the storm. The Florida citrus crop sustained severe damage. It was the strongest hurricane to hit Florida's west coast since Donna in September 1960, and it was the strongest hurricane to affect the state of Florida or the United States coastline since Hurricane Andrew in August 1992. Estimated insured losses from Charley were $6.8 billion (USD). Charley was blamed for 22 deaths in Florida. After emerging off the east coast of Florida, Charley continued in a northeasterly direction, reaching the South Carolina coast south of Georgetown near Cape Romain on the morning of the 14th. Maximum sustained winds near the time of this landfall were near 75 mph. Heavy rainfall and gusty winds spread inland across eastern North Carolina and Virginia. Charley made a fourth and final landfall on Long Island as a tropical storm on the morning of the 15th with maximum sustained winds near 40 mph.

Hurricane Gaston developed off the southeast coast of the United States on the 27th, making landfall near McClellanville, South Carolina on the 29th just under hurricane strength, with maximum sustained winds near 75 mp). The storm moved northward, and dumped as much as 13 inches of rainfall on the city of Richmond, Virginia. This quantity of rainfall caused massive flooding in the city, and about 20 blocks of the downtown area were declared uninhabitable on the 31st. There were 7 fatalities in the greater Richmond area, and Virginia governor Mark Warner declared a state of emergency

September 2004

In the United States, preliminary numbers indicated a total of 247 tornadoes were reported during September 2004, breaking the record for the month. The old record was 139 tornadoes set in 1967. The unusually high number of tornadoes was blamed on land-falling hurricanes. Hurricane Frances produced 117 tornadoes, topping Hurricane Beulah's 115 tornadoes in September 1967. Hurricane Ivan produced 104 tornadoes, while Jeanne produced 16.

Hurricane Frances developed in the central tropical Atlantic Ocean on August 25, attaining hurricane intensity by the 26th. Frances then crossed onto the Florida peninsula near Sewall's Point early on September 5 with maximum sustained winds near 105 mph. In Florida, more than 1.8 million customers lost power and more than 90,000 people waited out the storm in over 300 storm shelters. The hurricane brought major flooding and some structural damage, and also dealt another significant blow to the citrus crop, which had been devastated by Hurricane Charley in August. Frances re-emerged into the northeast Gulf of Mexico late on the 5th and made a final landfall near St. Marks, Florida as a tropical storm on the 6th. The remnants of the storm then moved northward into the Appalachians, where major flooding resulted from rainfall accumulations of ~6-20 inches. Frances also spawned 117 tornadoes on its track through the southeast U.S. and a total of 23 fatalities were also blamed on the storm. Insured losses from Frances were estimated at $4.4 billion (USD).

Hurricane Ivan developed from a tropical wave that emerged off the African coast at the beginning of the month. Ivan made landfall along the Gulf Coast of the United States on the morning of the 16th, reaching the coastline near Gulf Shores, Alabama with maximum sustained winds near 130 mph. Significant damage from winds and storm surge was reported along the coastline of Mississippi, Alabama and the Florida panhandle, as offshore buoys measured wave heights of 15 meters (50 feet). Heavy rainfall and more than 100 tornadoes spread well inland into the interior Southeast, Tennessee Valley and Mid-Atlantic regions. In western North Carolina, around $200 million (USD) in damage was caused in Buncombe County from the combined effects of Frances and Ivan in the span of a two week period (Asheville Citizen-Times). At least 50 deaths in the United States were attributed to Ivan (Associated Press). The remnants of Ivan exited the Delmarva Peninsula and headed south, crossing Florida and re-emerging in the Gulf of Mexico. Ivan was reclassified as a Tropical Storm by the 23rd and made a final landfall just west of Cameron, Louisiana on the evening of the 23rd with maximum sustained winds near 45 mph. Estimated insured losses from Ivan were $6 billion (USD).

Hurricane Jeanne made landfall around midnight on the 26th (local time) near Stuart, Florida with maximum sustained winds near 120 mph. Strong winds and torrential rains from the hurricane caused severe damage as it tracked across Florida. Jeanne weakened but produced heavy rainfall as it moved across Georgia, the Carolinas and into the Mid-Atlantic states. Combined impacts of flooding and severe weather (tornadoes) resulted in at least 10 fatalities in the United States, with estimated insured lost totaling $3.2 billion (USD). In Florida, more than one out of every five houses received damage this season from the unprecedented impacts of four hurricanes (Charley, Frances, Ivan and Jeanne).

October 2004

The first significant storm system of the season for California brought heavy snowfall to the higher elevations of the Sierra Nevada Mountains, and heavy rainfall and mudslides to much of the state on the 19th. Rainfall amounts in the 1 to 4 inch range were common, with some record daily amounts reported.

Severe thunderstorms erupted in the U.S. Tennessee Valley region on the 18th, resulting in 28 reports of tornadoes in Arkansas, Missouri, Tennessee and Alabama. There were three fatalities in southeastern Missouri near the town of Cooter, while at least 118 buildings were damaged and 15 people injured in Arkansas from the storms.

Tropical Storm Matthew developed in the western Gulf of Mexico on the 8th and crossed the coast near Houma, Louisiana on the 10th with maximum sustained winds near 40 mph. The primary impact from Matthew was the heavy rainfall that accompanied the storm.

November 2004

Heavy rainfall in Texas during November 15-18 was blamed for at least 2 deaths. Areas of the Texas Hill Country received 10 inches of rainfall during this period, producing widespread flooding.

An outbreak of severe thunderstorms on the 23rd produced reports of 54 tornadoes across portions of Texas, Louisiana, Arkansas and Alabama. In Texas's Hardin County, one person was killed with three injured when a tornado struck during the afternoon.

December 2004

A major storm system affected parts of the western United States during December 27-29, bringing a variety of weather conditions to the region. Heavy rainfall broke daily precipitation records at some locations in California, with Los Angeles (downtown) breaking a daily rainfall record for the month of December (5.55 inches fell on the 28th). This was the third wettest calendar day in Los Angeles since records began in 1877. Very heavy snow fell across the Sierra Nevada Mountains, with some areas receiving several *feet of accumulation. Winds with this weather system gusted over 65 mph at some coastal and mountain locations in California.*

Snow fell on Christmas Day in Deep South Texas. In Corpus Christi, snow totaled 4.4 inches. It was only the second White Christmas ever in Corpus Christi. Farther north in Victoria, 12.5 inches of snow fell, making it the first White Christmas on record for Victoria.

In the United States, the first widespread, significant lake-effect snowfall event of the season occurred on December 14. Locally, 4-10 inches of snow fell downwind of the Great Lakes.

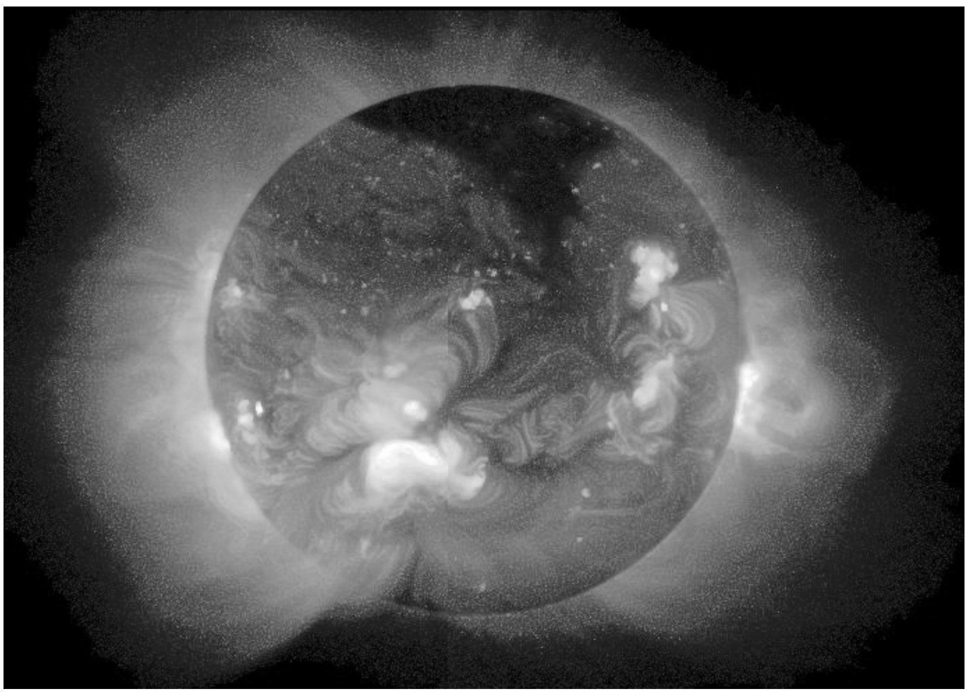
Heavy accumulations of snow and ice blanketed areas of Kentucky, Ohio, Indiana and Michigan on December 22nd and 23rd, breaking daily snowfall records in some locations. Accumulations exceeded 20 inches in parts of Kentucky and Indiana."

If you think that 2004 was an exceptionally brutal year when it comes to the U.S. weather, think again. I could go on and on reporting the weather events year after year and the picture will look very similar. Extreme cold spells, heat waves, heavy rainfall and snowfall, flooding, severe droughts, tornados, hurricanes, wildfires, killer storms, hail damage, lightning deaths, you name it. The United States experience it all and not just every once in a while. Such weather events are simply every day life. Why, you may wonder is our weather so temperate? Well, this is a long but interesting story.

Part II

Getting to know weather

2. The supreme factor



http://rsd.gsfc.nasa.gov/rsd/images/

In ancient Egypt he was called Ra. He was depicted as a human with the head of a hawk, wearing a fiery disk on his head. Ra was believed to be the creator and overseer of the universe. He came out of an egg, which rose out of water in the beginning of time. He had two children who became the atmosphere and clouds. One day Ra cried and from his tears the humans were born.

In ancient Persia he was called Mithra. In the sacred Zoroastrian writings he is considered as good spirit and as the ruler of all. According to the myth, all animals and plants sprang from the body of the divine bull, which Mithra killed.

In ancient Greece his name was Helios. He was the son of the Titans Hyperion and Thea and his daily activity was to ride his golden and fiery chariot across the heavens, providing light and warmth to humans and to the Gods of Olympus. He was the only one who could control the untamed horses that drew his chariot. When his son Phaethon tried to ride the chariot he fell and was killed. In later times he is identified with Apollo, the god of logic and reason who was also a great musician, healer and foreteller of future.

In the Aztec religion he was called Huitzilopochtli. The name means "blue hummingbird on the left". It was believed that the earth goddess Coatlicue magically conceived him after she kept in her bosom a ball of hummingbird feathers, which signify the soul of a slain warrior. He was born anew every morning and according to the myth he led the Aztecs to the promised land, the Valley of Mexico, from their storied homeland of Aztlan.

In early Japan (which literally means the 'origin of the day' and often translated as 'rising sun'), her name was Amaterasu. According to the oldest Japanese religion called Shinto, Amaterasu was born from the left eye of Izanagi, the first being. After mistreated by her brother Susanowo, she ran to the cave of heaven and closed the entrance with a huge rock. After that, darkness reigned and evil spirits began their domination of the world. In order for the gods to bring Amaterasu out of the cave they organized a loud party outside the cave with the goddess of laughter, Uzume, performing an exotic dance. They also placed a big mirror outside the cave's entrance. Amaterasu became curious and carefully tried to see what the fuss was all about. When she saw her brilliant reflection in the mirror she came out of the cave. Since then her light filled the world with warmth and color.

In ancient Sumeria his name was Shamash. According to Sumerian mythology, every morning, the scorpion-men of the East Mountain would open a gate and let Shamash out. He would ride the sky in a chariot and at the end of the day he would enter the West Mountain to begin his journey through the underworld. This cycle would be repeated every day. In Babylon, the symbol of Shamash was the solar disk with a four-pointed star inside it.

For the Fon people who still live in West Africa his name was Liza. He was regarded as harsh and powerful. He was inseparable from his partner Manu, who was associated with the moon. They were both born by the creator of the universe, Nana Buluku. Manu had her home in the west whereas Liza in the East. When there was an eclipse people believed that Liza and Manu were mating. Their unity represented the order that is found in the universe.

For the Inca people living in ancient Peru, his name was Inti. Inti's wife was Pachamama, the Earth goddess. According to the myth Inti instructed his son Manco Capac and his daughter Mama Ocollo to go to Earth and provide mankind with the foundations of civilization.

In the Hindu pantheon his name is Surya. He is one of the twelve Adityas, whose responsibility is to guard the twelve months. He is depicted as a red man with four hands and three eyes riding a chariot drawn by seven horses and driven by Aruna who represents the dawn. Surya is caring, capable of healing people and bringing good fortune.

The native North American tribe of Natchez worshiped him by keeping ceaseless fire in their temples and having class ranks named after him. For the Navajo Indians of North America his name was Tsohanoai. He appears as human and he carries the sun on his back across the sky every day. At night he rests after hanging the sun on a pin on the west wall of his house.

For the Inuit people leaving in Greenland his name was Malina. In the Norse mythology he was Freyr. For the Celts he was Lugh (the modern city of Lyon derives from his name). The Amazon Indian tribe Mamaiurans called him Kuat. In the Polynesian mythology his name was Maui. The ancient Chinese people believed that ten of them existed, one for each day of the Chinese ten-day week. To the Aborigines, she was a woman. She would ascent every morning from the east, she would light a fire and she would then carry a torch across the sky. In the early and late hours she would color herself red and in this process she would spill red shades in the sky and clouds. Once she reaches the west she would become her underground return to the east. The torch, which is still going, provides heat to the earth, which maintains plant growth.

Different cultures, different name, same god. The sun god. There is hardly any ancient culture that did not deify our shining star. While other celestial objects were deified (the moon, lightning, wind, etc), the sun was undeniably the major actor in the play of ancient gods. This apotheosis only signifies the importance that the ancient people attributed to the sun; an importance that has not diminished in time simply because if it were not for the sun, there would be no life on this planet. It is the sun that provides the light that is used to convert carbon dioxide and water into sugar glucose, which is the basic energy source of most organisms. This process, which is called photosynthesis, also produces oxygen, on which most life forms depend for existence. It is thus not an exaggeration to say that all life depends on the sun.

But it is not just life that depends on the sun. Even in planets without life other forms of activity take place. A great example is weather. As with life, if it were not for the solar radiation there would be no weather at all. All will be still, there will be no changes and deep freeze will reign. Weather begins with and ends with the sun and its light. Since weather is the subject of this book it is obvious what our starting point should be.

By the 19th century it was well understood that light has properties of waves. This was clear because light will form patterns that waves do. These patterns are called diffraction and interference patterns. A wave is a sequence of crests and troughs and the distance between any two crests or any two troughs defines the wavelength. Diffraction is a property of all waves and results when waves spread as they pass through small openings. It is more pronounced when the opening is comparable in size to the wavelength of the wave. For example, diffraction patterns are often observed with ocean waves that are channeled and then pass through narrow harbor mouths (figure 1).

Figure 1: Wave diffraction at an Eastbourne beach, New Zealand (courtesy of Winton Clitheroe, New Zealand Physics Teacher's Resource Bank).

Interference patterns form when waves from two sources collide. When two waves collide, if two crests arrive at a point at the same time they combine to form a higher crest. Similarly, if two troughs arrive at a point at the same time they superimpose to form a deeper trough. Such interference is called constructive interference. If a crest and a trough arrive at a point at the same time then they cancel each other out and they form a flat region. This is called destructive interference (figure 2). A simple experiment to visualize all these is to drop two stones into a pond. The resulted pattern is one of propagating rings that correspond to regions of constructive interference. The flat regions between the rings correspond to regions of destructive interference. If we drop just one stone we see a simple diffraction.

Figure 2: Wave interference at an Eastbourne beach, New Zealand (courtesy of Winton Clitheroe, New Zealand Physics Teacher's Resource Bank).

Light creates similar interference patterns. When light passes through a slit whose opening is comparable to the wavelength of the light, the light will diffract or spread out in waves. Projected on a screen this diffraction appears as a pattern of alternating concentric bands of light and darkness much like a target. If light is passed through an apparatus with two slits the two diffracted waves interact and constructive and destructive interference occurs that creates a series of bright and dark fringes, the brightest of which is at a point midway between the two slits (figure 3).

The advantage of something being carried on a wave is that it can be carried in many different ways. Since any number can define a wavelength, in principle we can have an infinite number of different waves. We can have long waves where the wavelength is large and short waves where the wavelength is small. The light that is coming from the sun is made up of many different waves (or types of radiation), which constitute the electromagnetic spectrum of the sun. And this fact is what is going to make all the difference in the world, what is going to support life on earth, and what is going to sustain a hospitable climate for this life. But let's take one thing at a time.

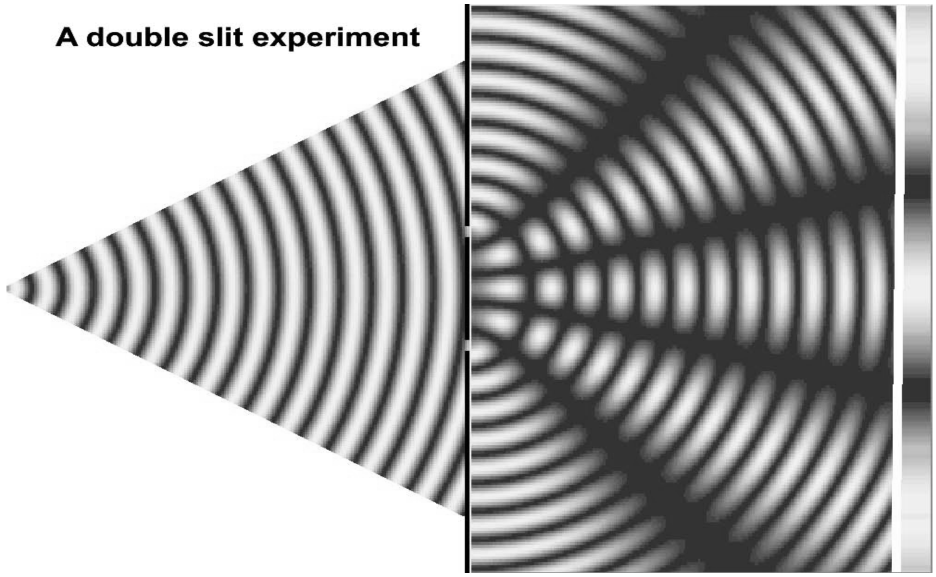


Figure 3: Diffraction and interference of light.

In general, solar radiation consists of (from very short to very long waves) x-rays, gamma rays, ultraviolet (UV) light, visible light, infrared radiation, microwave radiation, television waves and radio waves (figure 4). These different waves are not represented equally in a sample of pure solar radiation. Forty four percent is visible light, 37% is near infrared radiation (close to red in the visible light), 11% percent is far infrared radiation and seven percent is ultraviolet light. The remaining 1% is due to all other waves.

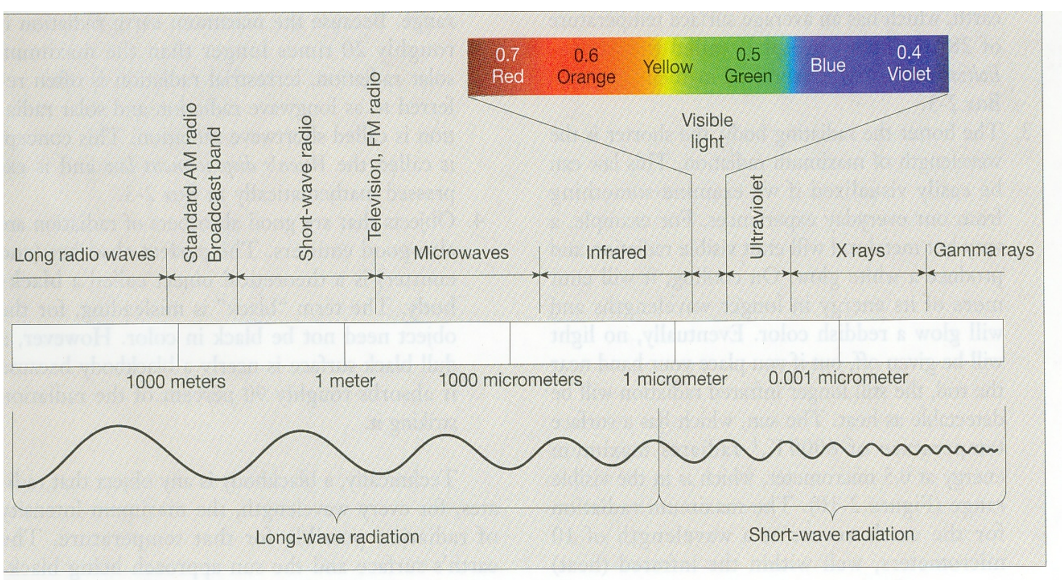


Figure 4: The electromagnetic spectrum of solar radiation.

Different waves have different properties. For example, only certain waves can be seen by the human eye (the visible light). The visible light appears white but it is the result of the mixing of several monochromatic (single color) waves (from shorter to longer waves these colors are purple, blue, green, yellow, orange and red). Also, shorter waves carry more energy. Imagine that you and a friend hold the two ends of a rope. If you shake the rope up and down you will create a wave. If you shake it very fast you will generate a short wave and when you shake it very slow you will make a long wave. Since when you shake the rope very fast you need to do more work, the short waves must carry more energy than the long waves. The fact that very short waves carry a lot of energy makes them dangerous to our health. X-rays, gamma rays as well as UV light are harmful to living things.

Different waves will interact with matter differently. Solar radiation can interact with matter in two different ways. It can be scattered by matter or it can be absorbed. First let's deal with scattering. Imagine that you are sailing in a nice boat in a water body of your preference. The wind is light, the temperature is comfortable and the wine is chilled. The waves are small and when they encounter the boat they break and change direction. They are scattered at some angle and present no threat to the boat or to you. Now imagine you are watching the movie *The Perfect Storm* where a few fishermen in a small boat find themselves in the middle of a stirred up ocean forming huge waves. The waves are so much bigger than the boat that it is impossible for the boat to 'break' the waves. The waves simply go their way uninterrupted sweeping in their path the small boat. The lesson we learn from these two examples is that the relationship between the size of the boat (matter) and the size of the wave (wavelength) determines whether the wave will be scattered or not. If the wavelength is smaller than the size of the object encountered, then the object scatters the wave. Otherwise, the wave goes through as if the object were transparent.

Now we can see what will happen when the streaming into space solar radiation encounters the top of our atmosphere and begins its trek toward the surface of the planet. The atmosphere consists of billions upon billions particles, which will provide the objects that will scatter or not scatter the solar radiation. Most of these particles are bigger than the very short waves (x-rays, gamma rays). Because of this, these waves are continually scattered by the particles and never find their way to the surface of the planet. In a sense, the very short waves are filtered out. If clouds are present they scatter and reflect visible light (that is why clouds appear white). The rest of the sun's radiation is not affected so much by scattering. It may, however, be affected by absorption.

Imagine that in a dark room a friend is holding a flashlight in front of your face. The yellowish-white light is similar to the visible light from the sun. What would you observe? First, your face would be illuminated as it reflects (scatters back) some of this light. Second, your face would begin to warm up. Why does your face get warmer? Since it was not getting warmer before the flashlight was turned on, it means that your face is getting warmer because of the light emitted by the flashlight. This in turn means that some of the energy carried by the light is used to warm your face. This describes the process of absorption, whereby the intercepting object retains a portion of an incident radiation. Now let's turn the flashlight off. What would happen next? Obviously, your face will cool. But why?

To answer this question, it may be helpful to think of what would happen to an object if the source of heat is never removed. As the object keeps on absorbing more and more of the incident radiation its temperature is increasing. This would lead to a non-physical situation where the temperature would become so high that the object will explode or evaporate. Nature does not like situations like that. As a result once an object absorbs some radiation and gets warmer, a counter radiation is generated by the object, which removes some of the heat. Thus, when the flashlight is turned off, your face cools because it emits radiation. In other words, your face cools because you are loosing heat. This example demonstrates a very important point with implication to climate. The radiation responsible warming your face was visible light. However, when your face cools by emitting radiation, your face does not glow in the dark! Thus, your face is not emitting visible light. What type of radiation does it emit? Obviously, the radiation emitted must be of a wavelength different than the incident radiation. We call the emitted radiation infrared radiation. All objects emit infrared radiation. The amount of infrared radiation, as you may have guessed, depends on the temperature of the object. The warmer the object the more the infrared radiation it emits. This principle is used to see at night. A soldier in the dark, for example, equipped with heat-sensing goggles can differentiate a human from a tree because the human body temperature is around 98 degrees Fahrenheit, whereas the temperature of the tree is much less. Similarly, a submarine can be detected even when it is submerged because the heat coming out of the engines corresponds to higher temperature that that of the surrounding ocean.

Absorption does not depend on the relation between the size of the object and the wavelength of the intercepted radiation. Rather, absorption depends on the chemical properties of the object. This introduces the so-called selective absorbers. Certain types of radiation can only be absorbed by certain gases only. Thus, while the fate of the x-rays and gamma rays is determined by scattering, the fate of the remaining radiation will be determined by absorption. Ozone (O_3), a gas in the atmosphere, is a selective absorber that absorbs only ultraviolet (UV) radiation. In fact, even though it exists in extremely small amounts it absorbs almost all the ultraviolet radiation from the sun. Ultraviolet radiation is a short wave that is harmful to humans. When we are exposed to UV light the body's defense mechanism reacts by producing melanin, which absorbs UV radiation. It is this process that gives us a tan. If, however, our body does not produce enough melanin (and this is the case with people with pale skin), then the natural protection is absent and we run the risk of developing skin cancer. About 90% of skin cancer cases are attributed to prolonged exposure to UV light. Plant life and other organisms are also vulnerable to this radiation. The responses of plants to UV irradiation include physiological, biochemical, morphological and anatomical changes. UV light affects plant growth by reducing leaf size and limiting the area available for energy capture. Thus, ozone constitutes a shield that protects life on our planet from dangerous rays.

Another selective absorber, but in the infrared region of the electromagnetic spectrum, is carbon dioxide (CO_2). Together with water vapor and some other gases, it absorbs infrared radiation. Thus, during the day it absorbs some of the sun's infrared radiation. This energy is then used to operate the 'atmosphere engine'. Since the UV light is taken care by the ozone, this leaves the visible light as the main radiation responsible for warming the surface of the planet. Once the planet warms up it begins to radiate back, but now this radiation is infrared radiation. A good part of this infrared radiation is also absorbed by carbon dioxide thereby keeping some of this warmth close to the surface. This way we remain relatively warm at night. If it were not for carbon dioxide and water vapor the planet's *average* surface temperature will be zero degrees Fahrenheit, which is fifty nine degrees Fahrenheit lower than today's average temperature. Such frigid conditions would not have fostered life in this planet. This effect is popularly known as the *greenhouse effect*. This association to the glass structures used to grow plants and vegetables all year around is, strictly speaking, not very accurate. The air does not warm simply because glass allows the visible light to go through and warm the air inside and then does not allow heat to escape. The air inside a greenhouse remains warm because it cannot circulate and mix with cold air outside. In other words, glass is not exactly acting like carbon dioxide in the atmosphere. Be this as it may, the terminology is now established and we will refer to this effect as the greenhouse effect.

As we will see later, despite their major roles, both ozone and carbon dioxide exist in the atmosphere in very little amounts. This is not a problem as long as the fine balance that they maintain in our atmosphere is not disturbed. And unfortunately, exactly because their amounts are very small they can either be depleted or multiplied without much effort. How can this happen? One way is from anthropogenic effects, or in plain words, from man-made pollution. It is now well known that certain chemicals introduced into the atmosphere can find their way to the stratosphere and there they can break the ozone. These chemicals are called chloro-fluoro-carbons or CFCs and are produced from aerosol propellants (used in spray cans, such as deodorants and hairsprays), cleaning solvents, refrigerants and plastic blowing agents. Back in seventies, F. Sherwood Rowland and Mario Molina, two chemists from the University of California at Irvine and Paul Crutzen of the Max-Planck-Institute in Mainz, Germany were presenting results suggesting how CFCs will break down ozone in the stratosphere. Indeed, later studies and measurements of chlorine levels confirmed that in the eighties and nineties ozone concentration had decreased dramatically over Antarctica. This observation came to be known as the ozone hole. For their efforts these three atmospheric scientists were awarded the Nobel price in chemistry in 1995. They were the first and only atmospheric scientists to be awarded a Nobel price. The naturally present ozone in the stratosphere should not be confused with ozone produced near the surface from chemical reactions involving pollutants, such as nitrogen oxides. This ozone has an unpleasant odor and irritates the eyes and the respiratory system. As a result, people suffering from asthma and bronchitis are often affected during ozone alert days when concentrations near the surface are increased.

Equally important consequences ensue when the amount of carbon dioxide increases. The burning of fossil fuels (gasoline, for example) produces large amounts of carbon dioxide. In fact, carbon dioxide concentrations are on the rise in last 50 years or so, or since industry and cars became an important part of our lives (figure 5).

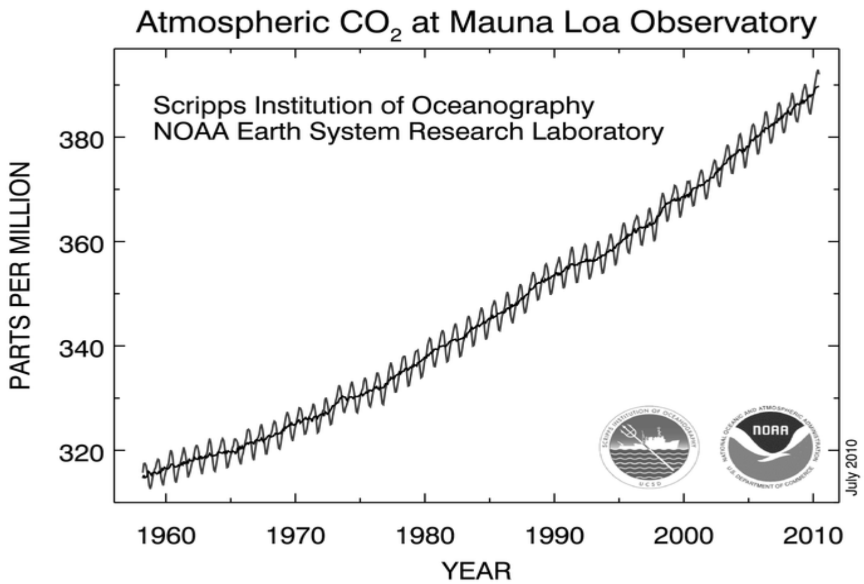


Figure 5: Carbon dioxide amounts on the rise in the last 50 years.

As we discussed a few paragraphs earlier, carbon dioxide helps keeping the air near the surface warm. In a sense it acts like a blanket keeping us warm at night. Therefore, if we increase the amount of carbon dioxide in the air, we effectively throw another blanket over us. Thus, increased amounts of carbon dioxide in the air will enhance the greenhouse effect. As a result, more heat will be trapped near the surface and the temperature will increase. We will then have a warmer planet. Atmospheric scientists have documented that since the mid 19^{th} century the average air temperature of the planet near the surface is increasing, with this tendency being very pronounced in the last in the interval 1980-2000. This warming is known as *global warming* (figure 6).

Given that carbon dioxide levels are also on the rise, we are all faced now with the possibility that we are causing this warming of our planet. Global warming has become one of the most important issues in atmospheric science and in politics. It is a sensitive issue, because as usual, when there is a problem there is at least two theories. On the one hand it is straightforward that, in theory, increased amounts of carbon dioxide will enhance the greenhouse effect. On the other hand, a global warming is not necessarily associated with an enhanced greenhouse effect. Climate is naturally variable and in the past the planet was as warm without the presence of man-made pollution. The issue is far from over. For example, a key factor is the oceans. The oceans are believed to absorb carbon dioxide from the atmosphere. Exactly, how much and how fast, however, is still an open question. There are those who believe that the ocean can take care of the billions of tons of carbon dioxide thrown in the atmosphere every year. Others, however, are much more cautious. They argue (rightly) that man-made pollution is disturbing the natural balance in nature and the results are not only unpredictable but they may be disastrous.

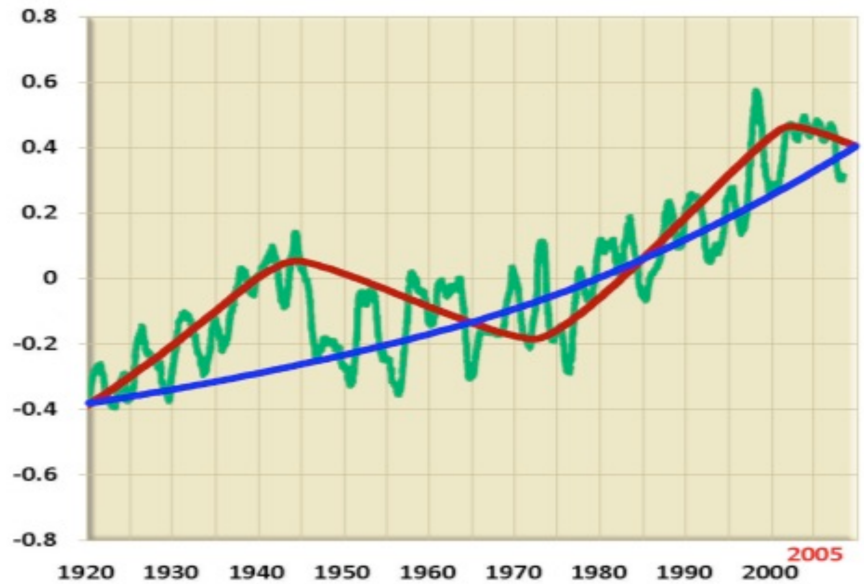


Figure 6: The yearly global temperature record (green). Red is a smoothed version and blue represents the low-frequency signal (or overall trend) often referred to as 'global warming'.

We now know the fate of the solar radiation as it travels through the atmosphere. Some of it (the x-rays and gamma rays) will be filtered out, some of it (the ultraviolet radiation and portions of infrared radiation) will be absorbed by ozone and some of it will be absorbed by the other gases in the atmosphere. Clouds will also scatter and reflect visible light and absorb infrared radiation. On the average, only 50% of the total amount on the top of the atmosphere (mostly the visible light) will be available to warm the planet during the day. 30% is lost back into space and 20% is retained by the atmosphere (figure 7). The 30% lost into space defines the *albedo* of the planet. By definition *albedo* is the percentage of incident radiation reflected back.

A final note: Any type of radiation would warm up an object. The fact that the visible light is the radiation responsible for warming the planet does not mean that other types would not have warmed the planet had they been present in large concentrations or had they not been absorbed before they reached the surface. Any type of radiation in adequate concentration would heat up an object. Thus, microwave ovens can warm food because they generate high concentrations of microwave radiation. In fact, they are more efficient than warming food than visible light. For example, you may warm your food by placing it under a light, but it will take much longer than sticking it in the microwave oven.

So, the sun will warm the surface of the planet. What is next? How is the atmosphere going to react? I guess this is a good point to introduce the atmosphere in greater detail.

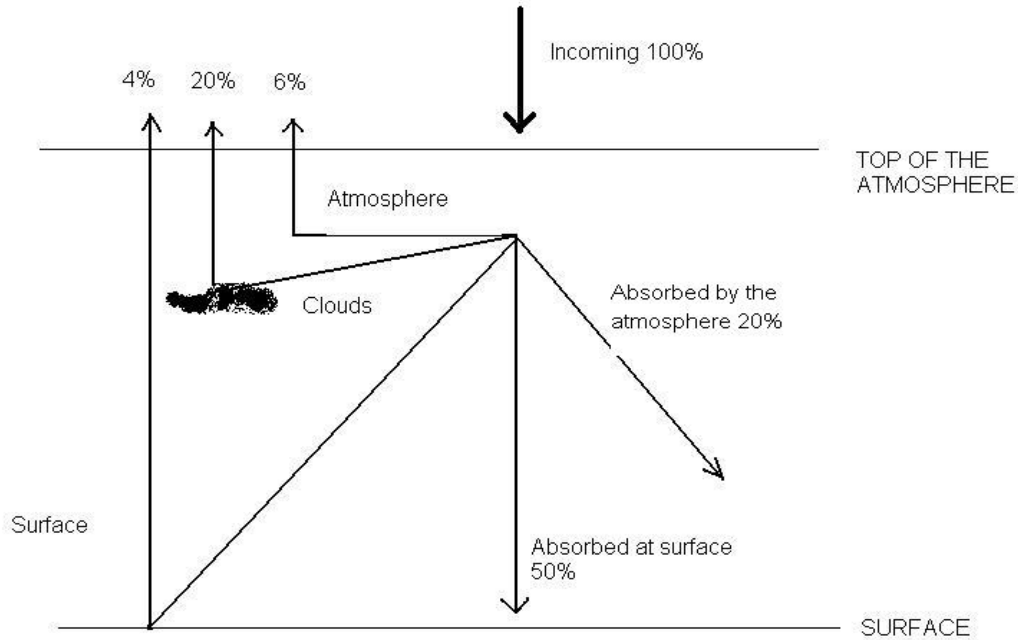
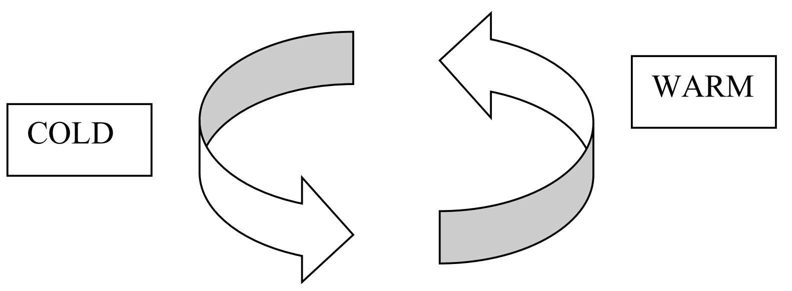


Figure 7: The average radiation budget of the atmosphere.

3. Atmosphere reacts to surface heating



Are you interested to do a little experiment right now? If you are close to the kitchen, pour some water in a pot and turn the heat on. While water is warming up, cut small pieces of paper, crumble them and throw them in the pot. Wait until water begins to boil and observe what happens. The pieces of paper are caught in circular vertical motions that sink them to the bottom and then raise them to the top. These motions which are called *convection* appear to be everywhere. Every piece of paper is trapped in one of them. This simple process is of paramount importance to the atmosphere and weather. Let's see why and how it occurs in the atmosphere and what its consequences are.

Our atmosphere has not remained the same in time. Early in its history, the atmosphere consisted of hydrogen and helium, which were probably supplied by the solar wind carrying them from the sun to our planet. Later, when the planet developed a differentiated core (solid inner/liquid outer core), the earth's magnetic field was established, which deflects solar wind. This cut off the supply of hydrogen and helium. At that time increased volcanic activity introduced many other gases such as water vapor, nitrogen, carbon dioxide, ammonia, methane, etc. Condensation of water vapor produced liquid water, which filled the oceans and photosynthesis (a chemical reaction between carbon dioxide and solar radiation) produced organic compounds and oxygen.

The various constituents of the atmosphere have different atomic weight. Because of the planet's gravity, all objects much smaller than the earth will accelerate toward the Earth's center of mass (toward the Earth's core). Because the gases in the atmosphere are not able to go through the earth's crust, the majority of them are compressed near the earth's surface. This is why the atmosphere is most dense in the low levels of the atmosphere and very thin at high levels (figure 8). In addition, heavier elements are pulled more and are thus found closer to the surface. Light elements on the contrary are found at higher altitudes. This divides the atmosphere into two regions the lower region (below 50 miles) called the *homosphere* and the upper region called the *heterosphere*. These two regions are then arranged into four layers (figure 9). The lowest layer (the one closest to the surface) is called the *troposphere*. The word derives from the Greek words *τρόπος* and *σφαίρα*, meaning behavior and sphere, respectively.

This is the layer where weather expresses itself or shows its behavior. It is the layer where all weather (rain, snow, wind, storms, tornadoes, hurricanes, etc.) takes place. It contains 75% of the atmosphere and 99% of water vapor. No weather is observed above the troposphere. Next is the stratosphere. Stratosphere derives from the words *stratum* and *sphere*. Stratum in Latin means uniform. The name very clearly characterizes this layer as it is a layer where there is hardly any movement of air. This is where airplanes prefer to fly, so that they are not exposed to head wind. In the stratosphere it is very dry (too far from the source of water vapor which is water evaporating from the surface) and it is there where we find the important gas ozone. Above the stratosphere is the *mesosphere* (from the Greek word *μεσαίο* meaning middle). The upper and final layer is called the *thermosphere*. As the name suggests, thermosphere is a very hot place. This is because this layer being the outer layer intercepts the complete and un-shortened (from scattering and/or absorption) radiation. It thus has more energy available to warm up.

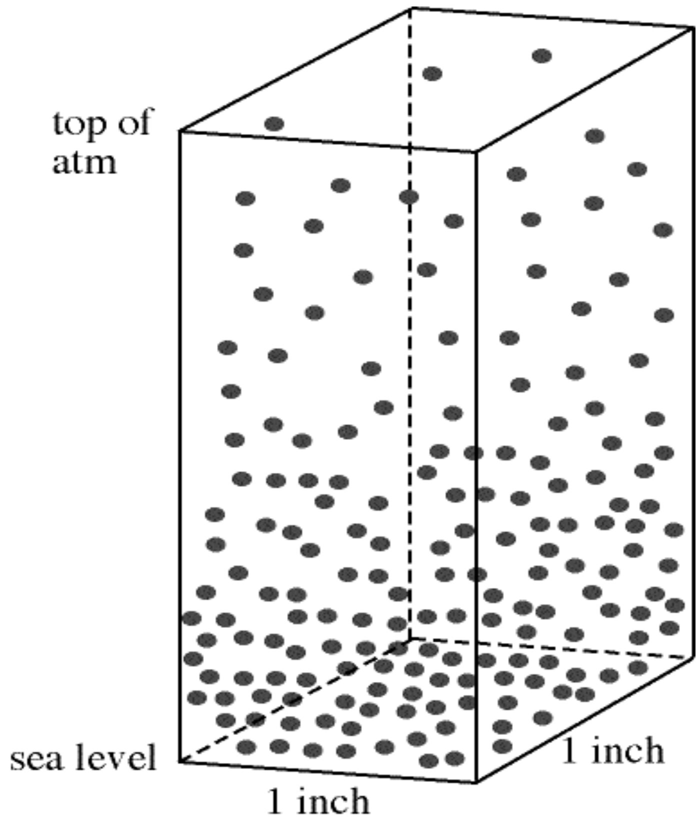


Figure 8: Distribution of particles with height. Because of gravity the atmosphere is denser close to the surface. As we go higher density decreases.

Since the air is very thin there, the total mass is small and even small amounts of radiation absorbed result in high temperatures. In addition this is the area where the very energetic x-rays and gamma rays are being scattered. Their high energy strips the atoms of their electrons thereby producing a lot of ions (positively charged atoms and negatively charge electrons; in the past this part of the atmosphere was called the *ionosphere*). This process is associated with heat release, which also helps warming the thermosphere.

In the homosphere, our atmosphere is mostly nitrogen and oxygen (figure 10). Seventy eight percent of the atmosphere is nitrogen and 21% percent is oxygen. All other gases sum up to the remaining 1% with argon claiming 93% of that one percent (i.e. 0.93 % of the total atmosphere). Another gas that is found in the atmosphere is water vapor. Water vapor is not a permanent gas. It is introduced in the air through evaporation of water and then it is removed via precipitation. We all appreciate the importance of oxygen. Apart for keeping us alive, it is a major constituent of water, of most rocks and minerals and of the human body. Nitrogen is as important since it helps dilute oxygen in burning and respiration processes. Also, bacteria in the soil use nitrogen to produce nitrates, which are then absorbed by plants. What, however, we may not appreciate as much is that in that remaining one percent are included two gases without which life may have not developed on this planet. They are (not in order of importance) carbon dioxide and ozone (a relative of oxygen). Carbon dioxide makes up of about 4% of the last one percent (0.04% of the total atmosphere). Ozone is found in even smaller amounts. It is only 0.000004% of the total atmosphere. As we discussed earlier, both these gases play a very vital role in the atmosphere.

As we discussed earlier, because of gravity, the air density (the amount of mass per unit volume) decreases as we go higher. Individually, each molecule or particle in the atmosphere has very little weight but all together result in a considerable weight. Believe it or not, the total weight of the atmosphere is 5600 trillion tons. Assuming that the area of the top of your head is about 35 square inches, then the weight of the atmosphere in a

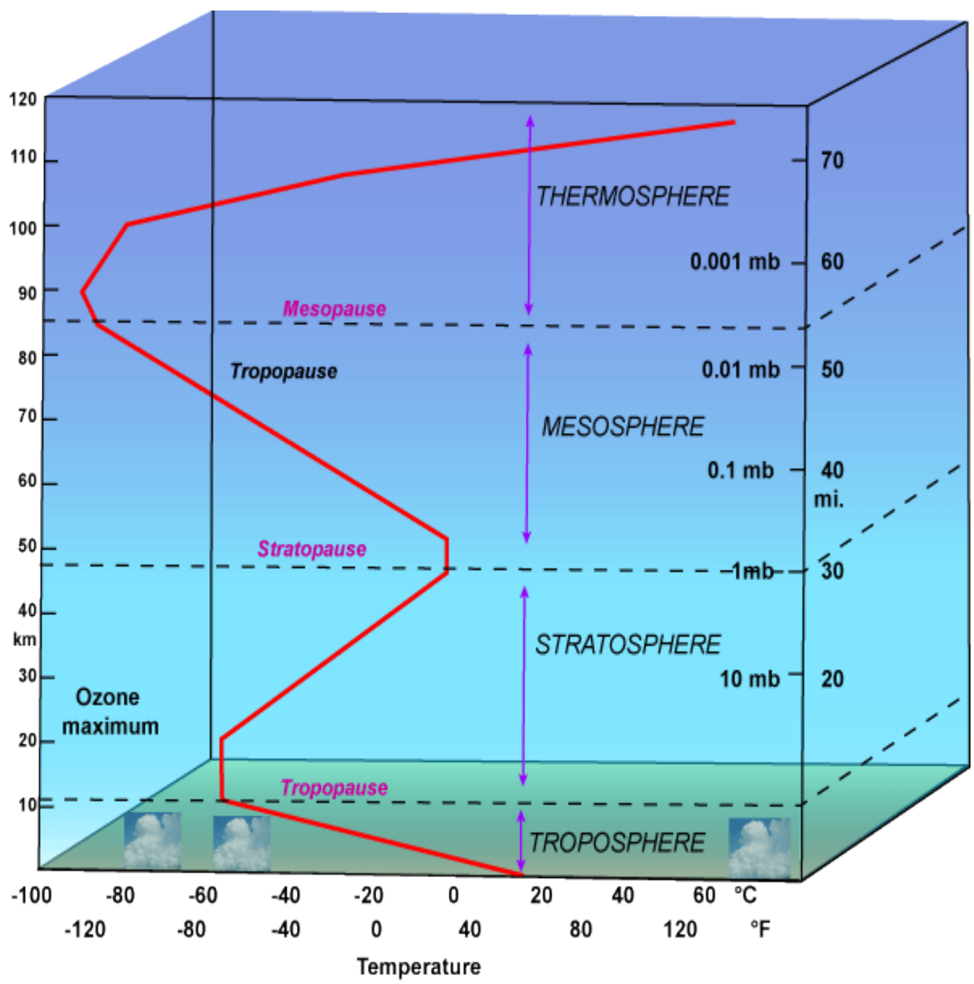


Figure 9: The vertical structure of the atmosphere. The red line shows how temperature changes with height and it will be discussed in detail later.

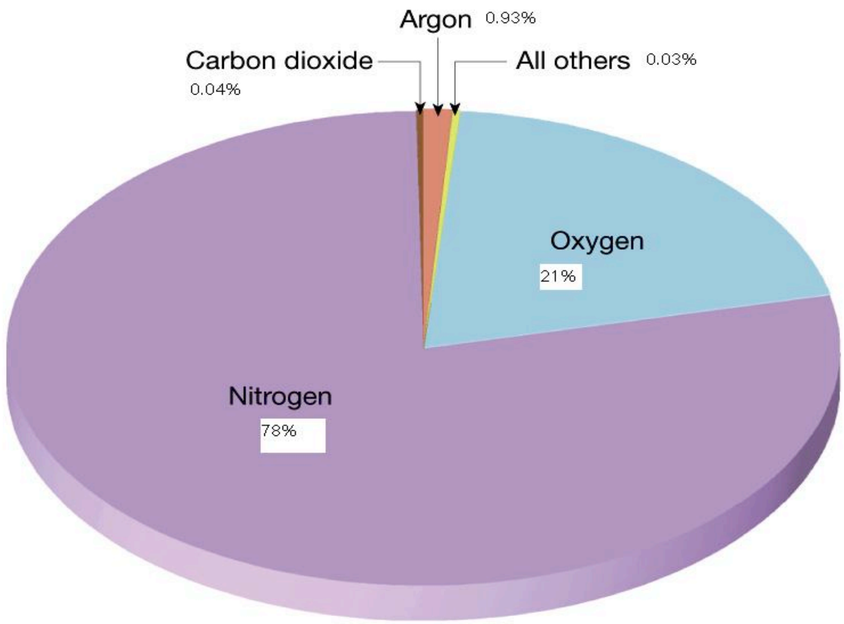


Figure 10: The composition of the atmosphere in the lower 50 miles (80 kilometers).

column having as base the top of your head and extending from sea level to the top of the atmosphere is about 500 pounds. Thus, not only air has weight, it actually is quite heavy. This weight acts as a force upon the earth. When this force is divided by the area, we get the pressure that the atmosphere exerts on that area. This pressure is called *atmospheric pressure*. It is one of the most important variables in weather. As you climb a mountain there is less and less atmosphere on the top of your head, therefore the atmospheric pressure decreases with altitude. This means that at a fixed level in the horizontal the pressure is the same everywhere and also that the pressure at the surface of the planet (1000 mb on the average) is much higher than the pressure near the top of the atmosphere (where it is zero). Does this create a problem? Imagine that you are pushing on one end of a table and a much bigger fellow is pushing from the opposite and. Which way will the table move? The answer is clear. The table will move toward you. The bigger fellow, because he is bigger exerts more pressure than you. Therefore, on one end we have high pressure and on the other end we have low pressure. The net result: movement from high pressure to low pressure. Every time we establish a high and a low pressure there is movement. The difference in pressure creates a force called the *pressure gradient force*, which provides the initial impulse that starts the air movement. Thus, straightforward reasoning will tell us that the atmosphere should rush from the high pressure at the surface off into space. Of course we know that this is not case. The reason is that this particular force in the atmosphere (the vertical pressure gradient force) is balanced by the force of gravity. This balance is called *hydrostatic balance*. Over large scales this balance is always maintained and the atmosphere stays where it is. However, as we will see later, in small scales motions in the vertical will be allowed.

High and low pressure areas can form in the horizontal as well. The atmospheric pressure at a given level (for example, surface) is not necessarily always the same. Imagine that you have two identical rooms next to each other, each one equipped with two identical pieces of furniture. Because the pieces of furniture are identical, they weigh the same and exert the same pressure (P) on the two floors (figure 11). If we take one piece from room 2 and move it to room 1, then the pressure on the floor in room 1 will increase (P1>P), whereas the pressure on the floor in room 2 will drop (P2<P). Similarly, in the atmosphere, if air is transported from some other area over to your area your pressure will increase. As we will see later, changes in pressure are always associated with changes in weather. Incidentally, while changes in pressure in the vertical will create air movement in the vertical and changes of pressure in the horizontal will generate movement in the horizontal, it is only the horizontal movement that is called *wind*.

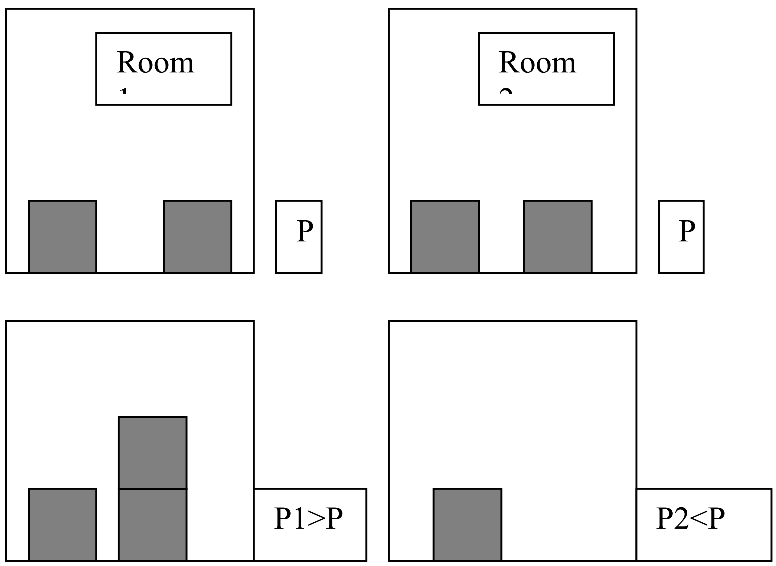


Figure 11: See text for details.

Density and pressure must be related. Density is defined as the amount of mass per unit volume. After moving the piece of furniture to room 1, there is more mass in that room. Since the size of the room (volume) is fixed, this means that the density in room two increases as well. Given their definition, both density and pressure decrease as we climb the atmosphere.

Another variable related to density and pressure is temperature. We take temperature for granted, but exactly what is temperature? Defining temperature can be very frustrating. If you search the web for definitions of temperature you will soon get lost. Qualitatively speaking, we can describe the temperature of an object as that which determines the sensation we fell when we touch it. Technically speaking, however, the definition of temperature varies. We discussed how an object will absorb energy and become warmer, but exactly what happens when the temperature increases? To answer this question we have to see what happens to the molecules of this object after they receive energy. Because of the extra energy, the molecules get excited and move faster. This speed is what defines temperature. The faster the molecules go the higher the temperature of the object. Similarly, if the molecules slow down (for example, by loosing heat), the temperature drops. This is one way to define temperature. As far as this book goes, this definition will be adequate. Based on this definition we can explain how temperature relates to density and pressure. If we imagine that the molecules occupy some 'box' before they are heated, then this volume will expand (like the air in a balloon expands when is heated). Since now we have the same amount of molecules inside a larger volume, the density will decrease. What about pressure? Will it increase or decrease? The answer to this question can be understood if we, for a moment, assume that the 'box' is solid (like a closed room) and that the heated air is not able to push the walls aside. In this case the density remains the same even though the temperature increases. However, the molecules are now moving faster and as a result the chance to collide with the walls and floor increases. This 'banging' on the walls and floor increases the pressure exerted by the molecules. Thus, just because the density remains the same it does not mean that the pressure will remain the same. This would be the case only if the temperature remained constant. Thus, changes in pressure can come about from changes in density and from changes in temperature. The relationship between pressure, density and temperature is expressed by the *ideal gas law*, which states that the pressure of a gas is proportional to density and proportional to temperature. More specifically:

pressure = temperature x density x a constant

This will indicate that if density (temperature) changes in some way while temperature (density) is held constant, then pressure changes in the same way. If both temperature and density increase (decrease) then pressure increases (decreases). However, if density increases and temperature decreases (or vice-versa), then the effect on pressure will be determined by the one which changes more. The ideal gas law was derived in the 1800s by combining experiments performed by the French scientist Joseph Louis Gay-Lussac (1778-1850) and observations made by the English scientist Robert Boyle (1627-1691) almost a century earlier. It is one of the most fundamental laws in meteorology. The ideal gas law also implies that if the pressure remains constant while the temperature increases, then, in order to maintain the equality between the right and left hand side of the equation, density must decrease. It follows that when the air warms at a constant pressure level (for example surface), it must become lighter (because density must decrease). *Thus, air that gets warmer than its surroundings is lighter and as a consequence it will rise.*

Is there anything else that will make the air even lighter?

To answer this question we have to bring water into the play. Seventy percent of our planet's surface is covered by water. Water is found in three phases: vapor, liquid and solid. At the surface of the planet the phase in which water is found depends on temperature. When the temperature is relatively low, water exists as ice because in this case the molecules move at very low speeds and they cannot overcome the chemical bonds from their neighboring particles. As a result the molecules are held together in a rigid pattern. As the temperature increases the molecules move faster. Now they are not bound to the neighboring molecules so rigidly, but they are still bound strong enough not to be able to escape. This way water becomes liquid. At relatively high temperatures all the bonds are broken and the molecules are free to move as they like, thereby becoming gas. This free motion allows a gas to expand and fill the room provided to it. As we all know if we wish to melt ice or to evaporate liquid water, we have to provide ice or liquid water with heat. When these changes take place on a cook top, the burners provide the heat. When they take place in the atmosphere, the heat is borrowed from the environment. Therefore, melting or evaporation cools the environment. They are, in other words, cooling processes. That is why when you come out from the sea or your shower you feel cold; water on your skin evaporates using heat from your body. Nature is very beautiful and wise but it is unforgiving. Thus, if it lends you some energy for a change of phase (say, liquid to vapor), then when the opposite happens (i.e. vapor to liquid) this energy must be given back. It follows that condensation and freezing release heat into the environment; in other words they are warming processes. These "hidden" heats are called *latent* heats of evaporation, of melting and so on and are very important in weather and climate. Try to remember this for later.

Now, what do you think happens when water vapor in introduced into dry air? A common misconception is that now the air has more 'stuff' in it and thus it should be heavier. This, however, is not true at all. In fact, the air is going to become lighter.

Back in the early 1800s, Lorenzo Romano Amedeo Carlo Avogadro (1776-1856), a lawyer turned scientist, discovered that a mole of any gas at a fixed pressure and temperature will always have the same number of molecules regardless the type of the gas. In other words, if we were to introduce some extra molecules in that fixed volume, then an equal amount of molecules will have to leave the volume (of course this requires that the fixed volume is not rigid as, for example, a closed room but 'open' like a cubic foot of air in the atmosphere). This number is extremely large. To get an idea of how large it is imagine the following. If a molecule were of the size of un-popped popcorn kernel and you covered the United States with one mole worth of them, then the country will be covered in popcorn to a depth of nine miles. If you were able to count one million molecules per second it will take more than the age of the universe to count all the molecules in one mole. When the air is dry it mainly contains oxygen and nitrogen. Accordingly, when water vapor is evaporating in the atmosphere, some nitrogen and oxygen molecules have to be moved elsewhere. The molecular weight of dry air is determined by the molecular weight of nitrogen and oxygen. Nitrogen's molecular weight is 28 (two atoms with atomic weight of 14). That of oxygen's is 32 (two atoms with atomic weight of 16). Given that 78% of dry air is nitrogen and 21% is oxygen, it turns out that the molecular weight of dry air is about 29. The molecular weight of water is 18 (two atoms of hydrogen with atomic weight of 1 and one atom of oxygen). Thus, water vapor is lighter than dry air, which means that when some dry air is replaced by water vapor to produce moist air, the molecular weight of air decreases.

What we have learned up to this point is that warm dry air is lighter than cold dry air and that moist air is lighter than dry air. It follows that warm moist air will be much lighter than cold dry air. This bottom line is of paramount importance to weather. Baseball players who find it easier to score home runs in hot humid days than in cool dry days, know this fact very well. Less dense air provides less resistance for the ball, which means it travels farther.

Speaking of heat and temperature, don't you get frustrated of how unevenly microwave ovens heat up different types of food? For example, meat and potatoes will not heat up evenly even though they are exposed to the same amount of radiation. Why is this happening? Apparently meat does not have the same ability to increase its temperature than potatoes. This differential heating is due to the so-called *heat capacity*, which also plays an extremely important role in weather and climate. By definition heat capacity is the amount of heat need to raise the temperature of an object by one degree Celsius (1.8 degrees Fahrenheit). Not all substances have the same heat capacity. Water, for example, has a high heat capacity and as a result requires large amounts of heat to increase its temperature significantly. On the other hand, land has a lower heat capacity, which means that it requires less heat to raise it temperature. Accordingly, water does not get as warm as land or it takes much longer to warm up. This explains why during summer, sea or lake water is always cooler than land. We can reverse the argument and state that when objects lose heat they also lose it at a slower rate when their heat capacity is high. This explains why Lake Michigan is warmer than the surrounding land in winter. Similar arguments can be made for sand and grass. Grass has a higher heat capacity compared to sand and it is cooler during the day but warmer at night.

Now consider the surface of our planet with its oceans, the forests, the snow on the ground, the deserts, the bare ground, etc. Like the planet as a whole, each different type of terrain has its own albedo. For example, snow on the ground has an albedo of 70% as it reflects 70 % of the radiation reaching the ground and absorbs only 30% (figure 12). Depending on how reflective they are and what is their heat capacity will determine how warm they are going to get. One thing is for sure. They will not all get warm similarly. Different types of surface will heat up differently thereby creating a mosaic of temperatures. And, over warmer regions the air in contact with the underlying surface will get warmer, like our hand gets warmer when we touch a source of heat. This way of heat transferring is called *conduction*. Warmer air is lighter and because of that it will rise, thereby transferring the heat from the surface to higher levels.

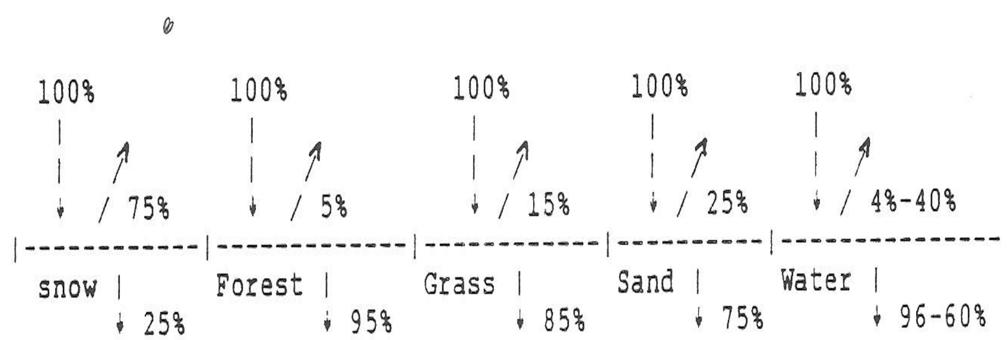


Figure 12: Albedos of various types of surface

As warm air begins to rise, what are the changes occurring in the neighborhood?

To construct the changes when warm air begins to rise, we need to recall the definition of pressure. At a given level the atmospheric pressure over a fixed area is given by the amount of the air included in a cylinder having the fixed area as base and extending from the given level to the top of the atmosphere. Imagine two identical two-story houses adjacent to each other (top of figure 13). In each floor of each house we place two objects of equal mass of one unit. If we ignore the weight of the walls and floors, then the pressure at the bottom in each house will be 4 units and the pressure on the second floor in each house will be 2 units. In this arrangement pressure is *stratified*. It decreases with height and at any given level the pressure in the horizontal is the same. Now imagine that we take one object from the house on the right from the first floor and we move it in the second floor (bottom of figure 13). Will the base of the house experience a change in pressure? Since the total pressure is the number of objects above the base, the pressure is still 4 units. However, the pressure on the second floor is not anymore 2 units. It has increased to 3 units. At the same time the pressure distribution in the house to the left has remained unchanged. In this case pressure still decrease with height but it is not stratified. At the level of the second floor pressure is higher on the right house and lower on the left. Now replace the houses with two adjacent areas (area 1 and area 2) on earth's surface and assume that initially the pressure is stratified. In other words, initially the pressure decreases with height but at any given level it is the same in the horizontal direction. Also, replace the unit objects with air. Then, from the above example it follows that when the air begins to rise over area 1, the pressure at the surface will not change, but the pressure at a higher level will increase compared to the pressure at the same level over the adjacent area 2. So now we are at a level above the surface and we have created an area of higher pressure and an area of lower pressure. What is going to happen next?

As we discussed previously, once a high and a low pressure area are established, a motion of air from the high pressure toward the low pressure ensues. In effect, this represents a removal of some air for area 1 and a deposit of air over area 2. Thus, the pressure at the *surface* in area 1 drops whereas the pressure at the *surface* in area 2 increases. This in turn causes the air at the surface to move from high to low to replace the rising air. At the same time over area 2 the air sinks to replace the air removed at the surface, thereby closing a vertical circulation between the two areas (indicated with the arrows in figure 13). Therefore, as the air over an area rises, it soon is replaced with colder air. The final result is to modify the pressure at the surface; pressure drops where the air is rising and increases where the air is sinking. Thus, rising air is associated with lower pressure and sinking air with higher pressure.

Such circulations happen very often in the atmosphere. Consider for example what happens in the summer in Milwaukee or any other place close to a water body. During the day land warms faster than water and thus the air over land gets warmer compared to the air over Lake Michigan. So, the air begins to rise over Milwaukee. Soon after that cooler air from the lake flows to replace the warm air, thereby closing a circulation that we all know as *lake* or *sea breeze*. Later in the day, the situation reverses. As we begin to

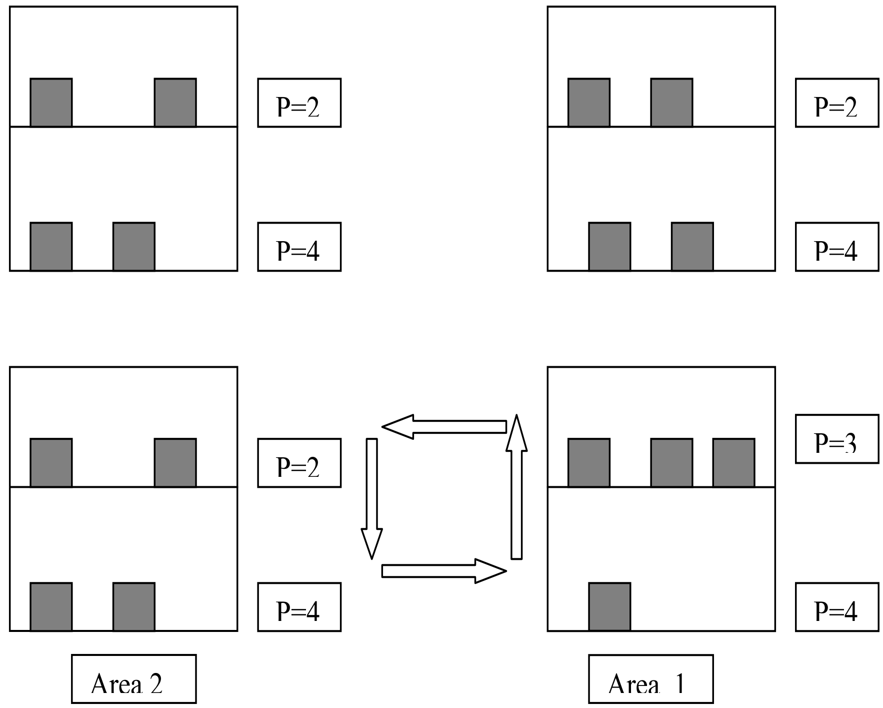


Figure 13: See text for details.

cool down, land cools faster than water and now the air will rise over the lake and this air will be replaced by a flow of air from the west. This circulation pattern is known as the *land breeze*. Similar circulations develop along mountain slopes where we get *valley* and *mountain breezes*. The circulating pattern of warm and cold currents is called *convection*, and is responsible for mixing and re-distribution of heat in the atmosphere. It is another way of transferring heat together with radiation and conduction. Because temperature contrasts can occur at small as well as at large scales, these motions will take place at all scales, even at hemispheric scales.

Because the planet is a sphere, the angle formed between the incident solar radiation and the tangent at any latitude is not constant. In general, equatorial regions intercept solar radiation more directly than Polar Regions. On the average the tropics receive more than the Polar Regions. This means that the atmosphere close to the surface will be warmer near the tropics and colder near the poles. This differential heating will cause a convection pattern of planetary proportions. The air around the equator will rise creating higher pressure aloft over the equatorial region and lower pressure aloft over the polar regions. Thus, as with the lake or land breeze, the air in the upper levels will move toward the lower pressure regions, i.e. the poles. This removal of air from the equatorial region and deposition in the Polar Regions decreases the pressure at the surface at the equator and increases it at the surface at the poles. The result: a movement of surface cold air from the north and south toward the equator and establishment of two simple circulation cells (one in each hemisphere) that will move the whole atmosphere (figure 14).

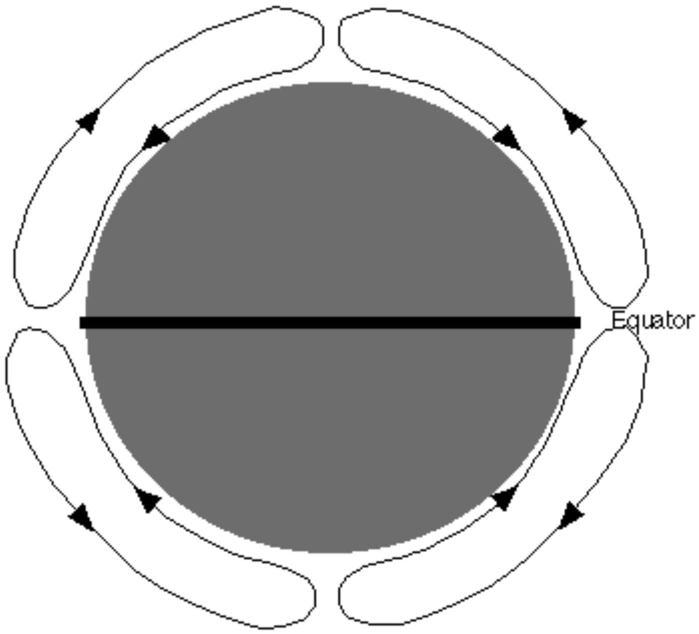


Figure 14: The Hadley circulation cells. Courtesy of John Cortinas Jr. (john.cortinas@noaa.gov)

This simple atmospheric circulation is called the Hadley circulation in honor of the eighteen-century English meteorologist George Hadley who proposed this idea. It looks though as if Hadley had some help from the writings of Aristotle some 2,500 years earlier. According to this simple circulation, at the surface the air rushes from the North Pole in the northern hemisphere and from the South Pole in the southern hemisphere. This will make the surface winds in the northern hemisphere mostly north winds and in the southern hemisphere mostly south winds. In Μετεωρολογικά (Meteorology, Book II) Aristotle states that most winds are north in the northern hemisphere or south in the southern hemisphere. He goes on to argue that this is due to the fact that the north and the south are the only regions the sun does not visit. Even though his complete explanation includes some inaccuracies, his insight that the north and south receives less radiation is astonishing.

Embedded in each Hadley cell will be found all smaller scale convection currents created by temperature contrasts at the earth's surface. Our atmosphere can then be thought as little whirls within bigger whirls within even bigger whirls; one huge mass of circuitous elements of all sizes.

A last topic to discuss before we move on to the next chapter is the vertical distribution of temperature in the atmosphere (red line in figure 9). As we discussed earlier both pressure and temperature decrease as we go higher. How does temperature vary with height? If we follow what we have discussed so far and use our logic, we will decide that temperature must increase with height because as the solar radiation travels through the atmosphere is been scattered and absorbed, which mean less and less radiation remains as it streams toward the surface of the planet. Compounding on this is the fact that closer to the surface the density is higher and therefore there is more mass to be warmed with less radiation available than at higher levels where there is less mass. Clearly then temperature must increase as we climb the atmosphere. Well, not really! This theoretical expectation does not happen. The temperature distribution of the atmosphere is rather complicated. It decreases with height in the troposphere, it increases in the stratosphere, it decreases in the mesosphere and it increases in the thermosphere. Let' see why.

To be consistent with the scientific terminology, at this point I would like to adopt the notion of a *parcel of air*. A parcel of air is meant to represent a sample of air that we can follow as it moves. We can picture it as a cube of any size in the atmosphere. As this cube moves it will experience many changes.

First let's consider what will happen to our parcel if it begins to rise (figure 15). To start with, we can imagine the cube of volume V1 sitting at the surface with its faces exposed to the pressure at the surface (P1). As the cube rises it goes into areas of lower pressure. This is because the pressure in the atmosphere decreases with altitude For example P2<P1). Thus, as the parcel rises the pressure of its surroundings lessens. Since now less pressure is squeezing the parcel, it is free to expand (V2>V1). Expansion means that the parcel is pushing away its surroundings, in the same way as the surface of an inflating balloon pushes the air around it. When we blow a balloon we do some work, isn't it? Well, similarly the parcel has to do some work during the expansion. Doing work means we spend energy. Thus, the expansion of the parcel is followed by a reduction in its energy.

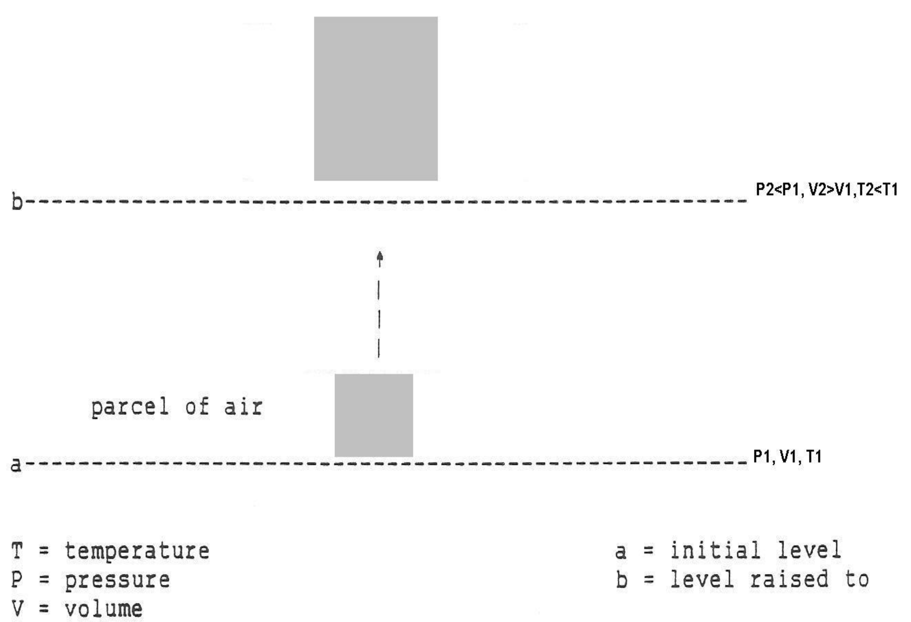


Figure 15: As the parcel of air rises it expands and eventually cools (see text for details).

Now, what is the source of energy in the parcel?

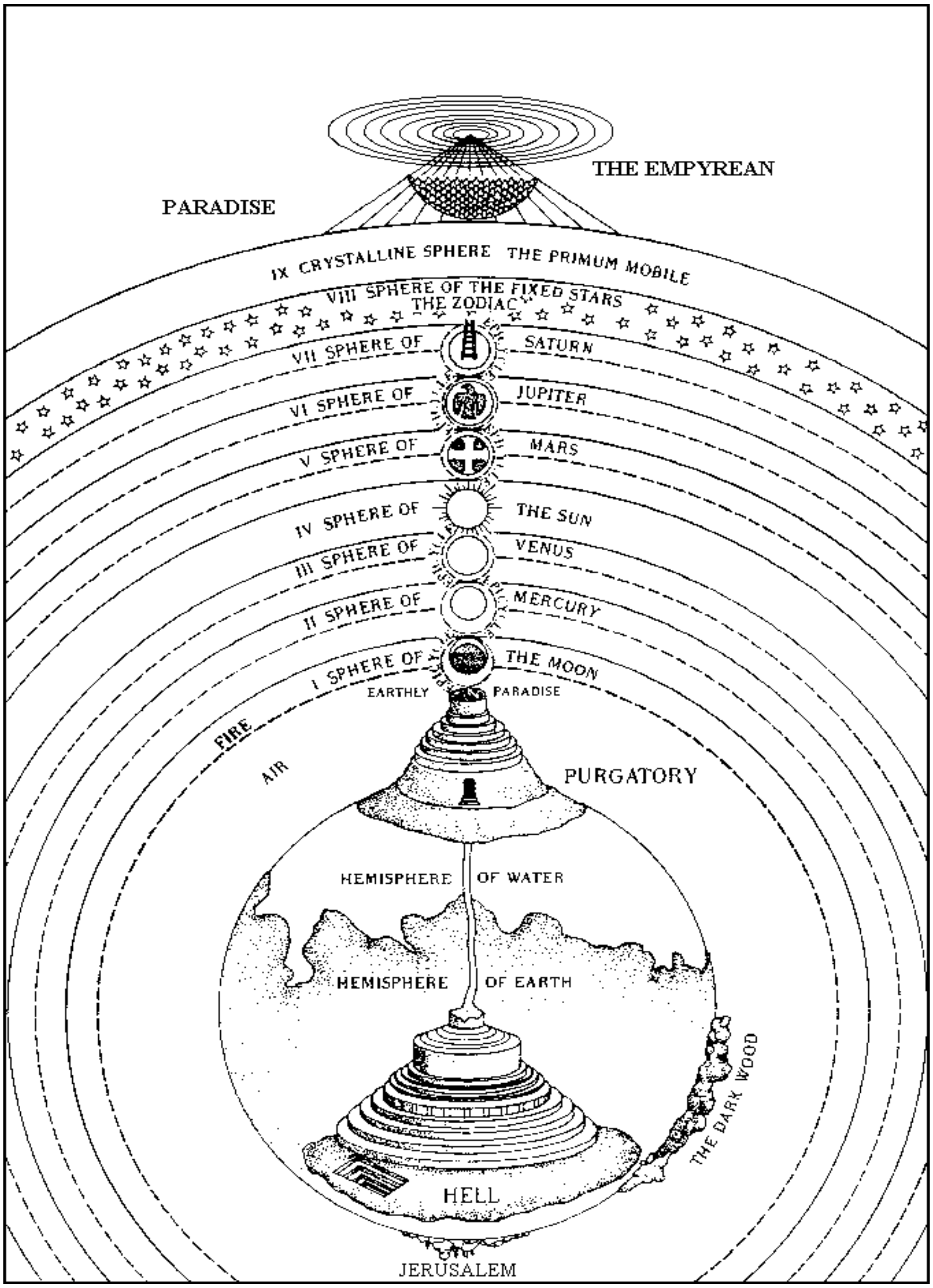
Discussing energy can take us into some troubled waters, but let's give it a try. My favorite definition of energy is the ability to do damage. Imagine a stone on a porcelain plate placed on the ground. The stone is doing no damage to the plate, which means it has no energy. If we raise the stone and then let it fall it will break the plate into many pieces. Since the stone did damage it must have had some energy. If we repeat this thought experiment but lifting to and letting the stone fall from a greater height, we can imagine that now the damage to the plate will be greater. This will indicate that the parcel had more energy when it was higher. Somehow this energy must relate to how far an object is from the surface of the planet. This energy is called *potential* energy and is due to the gravity of the planet. For the stone to get this energy, we must lift it off the ground. In other words, we must do work. In this case we say that we do work on the stone. Once the stone begins to fall the potential energy is transformed into *kinetic* energy. When it approaches the ground almost all its potential energy is transformed into kinetic energy, which is released to the ground upon impact. When a parcel of air is at the ground it has no potential energy to transform into kinetic energy. As such, it will not move unless some energy is provided to it. For example, when a car is set in motion it is the chemical energy of the fuel that is transformed into kinetic energy. When it comes to a parcel of air, motion can be achieved by absorption of radiant energy from the sun or through conduction with a warm area; the parcel warms and begins to rise. We can thus see that while in general energy is the ability to do work, this ability comes in many forms.

Let's go now back to the rising parcel. Since the parcel is pushing the surroundings, it is doing work on the surroundings, thus it is transferring some of its energy to its environment. As a result some of the parcel's kinetic energy is spent. Less kinetic energy means slower motion and, according to the definition of temperature, slower motion means lower temperature. *Therefore, as the parcel rises it cools* ($T2<T1$). To reach this conclusion we have to assume that as the parcel rises and expands, it does mix with the environment. In a sense, we assume that its hypothetical boundaries can stretch bur they hold the air inside them and do not allow it to interact with the air outside, like the air inside a balloon. Of course, we know that in the atmosphere this cannot be true, but for some applications this is an acceptable assumption. Because of this assumption, this cooling is called *adiabatic cooling* from the word *αδιάβατος*. This Greek word refers to an area or place or object, which has not been walked upon. It signifies the fact that there has been no interaction with outsiders. If we reverse the arguments and now consider a sinking parcel, we will conclude that as air sinks from higher level, its temperature increases (i.e. higher temperature at lower levels than at higher levels). This is called adiabatic warming. Adiabatic cooling and warming are of paramount importance in meteorology. They are responsible for the cooling of the air's temperature as we climb the lower atmosphere. The air close to the surface gets warm, rises and sets off convection patterns of rising and sinking motions. As long as convection takes place in the atmosphere the temperature of the air will decrease with height. However, there are limits to this. As we discussed above, when the parcels rise and cool they also slow down. Thus, at some point they will have no more kinetic energy and they will be to cold

(and heavy) to move any higher. At this point the rising motions will cease. This boundary marks the end of the lower layer of the atmosphere (the troposphere), where all weather takes place and it is called the *tropopause*. Its average height is about 12 Km (8 miles).

Above the tropopause there are no rising and sinking motions thus the effect of convection is gone and temperature is now going to do what we expect from theory. In the stratosphere temperature begins to increase with height. Helping here is ozone, which is found in the stratosphere and as we discussed earlier absorbs most of the ultraviolet part of solar radiation. This increase in temperature continues up to about 50 Km and at that level the air is warm and thin enough to be able rise again. This is similar to what is happening in the troposphere and again it results in a steady decrease in temperature with height for up to about 90 km where it becomes too cold for rising motions. From that level on temperature increases again with height and actually it increases very rapidly. We are now in the thermosphere. This rapid increase is as we mentioned earlier compounded by the striping of electrons from the very energetic x-rays and gamma rays which creates ions and releases heat in the environment. As with the tropopause the boundary separating the stratosphere from the mesosphere is called the stratopause and the boundary separating the mesosphere from the thermosphere is called the mesopause.

4. The motion of the planet and its effects on the atmosphere



Aristotle's view of the universe lasted for 2,000 years and had far reaching consequences. From the edition by Thomas Digges of his father's *A Prognostication everlasting…*, published in 1576 in London (By permission of the Royal Society).

Up to now we have considered our planet as standing still and receiving solar radiation. This, as we all know, is not true. The planet moves and its motion will greatly affect the organization of the atmosphere. The motion of the planet has been hotly debated since the ancient times.

It may not be an exaggeration to say that ever since the humans were able to put one plus one together, they have been fascinated with the 'heavens'. The sun, the stars, the moon, the eclipses, raised their curiosity to the maximum. They needed to explain all these celestial objects and phenomena. To them these objects represented the heavens where the gods reigned. They needed to know their gods better.

While many ancient cultures like the Sumerians and Babylonians observed and recorded the movement of celestial objects, it was the Greeks in the mid first millennium B.C. who really advanced astronomy. As early as 500 B.C. Anaximander in order to explain the effects of horizon suggested that the planet was round. Both Plato and Aristotle advanced this idea. Aristotle's model was that each of the planets, the sun, and the moon were on a crystalline sphere. The spheres were concentric with earth at the center. The stars were placed on a sphere, which surrounded all other spheres. The outermost sphere was, according to Aristotle, the domain of the 'Prime Mover'. The Prime Mover propelled this outermost sphere into a rotation that was passed on from sphere to sphere causing the whole universe to rotate.

The Greeks preferred such a model (called the geocentric model) because they did not believe that the earth was moving. This belief was based on the available observations at that time. For example, the heavens were out there and earth was not part of them. The heavens showed little change. The stars were at the same place every night. In contrast, earth was always changing. They attributed this to a regularity of the heavens, which could never be observed in corruptible earth. How can then earth be part of the heavens? In addition, objects in the sky were luminous whereas earth was not glowing. How can earth be similar to the heavens? Finally, they observed that in the atmosphere clouds were not left behind, as they should if the planet were in motion. They also argued that when you jump you land on the same spot. How can this be so if the plate is moving? Today we understand all these observations, but at that time they presented indisputable evidence that the earth was motionless. Thus, earth must be the center of the universe with everything else moving around it in perfect circles.

The Aristotelian model, however, could not explain the so-called retrograde motion of the outer planets. This motion occurs when the earth catches up and overtakes an outer planet. This phenomenon can be explained very easily if the sun is at the center and the planets revolve around it (heliocentric model). Because the orbits of earth is smaller than that of the outer planets, as we go around the sun the planet catches up with and passes the outer planets, which now appear as if they move backwards. Interestingly, a student of Plato, Aristarchus of Samos (often referred to as the Copernicus of antiquity), was the first to propose a heliocentric model of the universe in the early third century B.C. His model, however, was dismissed at that time. Unfortunately, the great popularity of the geocentric model did not foster such new and revolutionary ideas. Rather, in order to explain these backward motions and to fit the observations, astronomers proposed complicated additions to the geocentric model. Ptolemy, who lived from 85 to 165 A.D., revised the model by assuming that as a planet goes around earth, it is not going along a circle with earth on its center. Rather, it revolves on a smaller circle (the epicycle) whose center goes along the circle with earth on the center (figure 16).

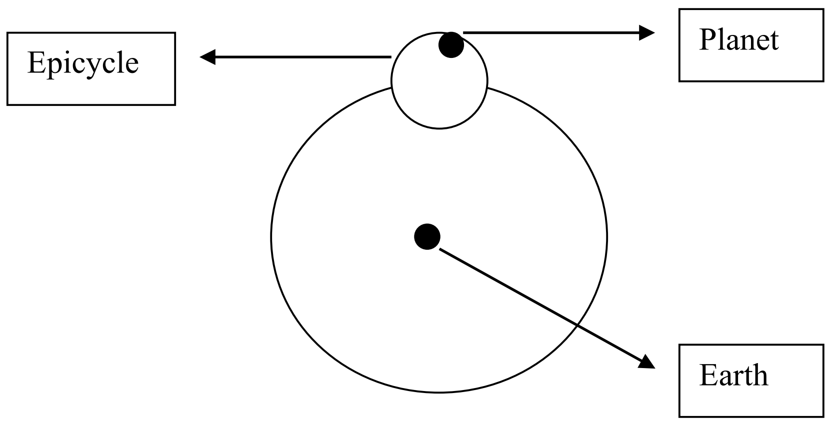


Figure 16: Ptolemy's model to explain the retrograde motion of planets.

This model fitted the data at that time well, but as more data were gathered more corrections and more epicycles had to be added. Nevertheless, the geocentric model lasted for nearly 1,500 years. Then around the mid second millennium, the Polish astronomer Nicolaus Copernicus (1473-1543), reasoned that a complicated universe cannot represent the elegance and wisdom of God. Copernicus was a Neo-Platonist who believed that God not only was the creator but he was a wise creator who would have not made a complicated universe. He also believed that because the sun provides warmth and light (necessary ingredients for life), it is a copy of God. Thus, the sun must be at the center of all. Motivated by his belief, he adopted Aristarchus' heliocentric model. He also found that the farther the planet from the sun the slower its motion and he was thus able to explain the retrograde motion without the need of the annoying epicycles.

Copernicus' model, however, would not go well with the Church. At that time the Christian leaders were firm believers of the Aristotelian view of the universe with its imperfect earth and perfect heavens. The Prime Mover had been identified with God and his crystalline sphere with the Christian Heaven. Going away from the center meant perfection, more control, somebody to watch over you. The Church's paradigm, that Man is God's special creation of the physical universe and earth the center of a wonderfully planned universe, was not compatible with Copernicus model. Copernicus new this and that is why he delayed publication of his model until 1543, the year of his death.

A few decades later came Galileo (1564-1642) who with the help of the telescope made new and improved observations, which clearly demonstrated the validity of the heliocentric model. He also ran into troubles with the Church. He was summoned and to save his life he was forced to give up his work and recant his theories.

But the tides had changed. Once a theory is solidly demonstrated there is very little the Church or any other organization can do. Today, there is no educated person who thinks otherwise. In fact, today we know that at any given time, earth is involved in six different motions. First, it revolves around the sun. This motion takes 365.25 days to complete. That is why every four years we have to add an extra day (February 29; leap year). At the same time, the planet spins on its axis. A complete spin takes 24 hours (a day) to complete. As the planet spins on its axis it wobbles like a spinning top. This wobble is called the *precession* of the earth's axis. This third motion has a cycle of about 23,000 years. The fourth motion relates to the tilt of the axis and is called the *obliquity*. This motion, which will be discussed in more detail shortly, has a cycle of about 41,000 years. The fifth motion of the planet is due to the fact that it is a member of the Milky Way (our galaxy), which also rotates. Finally, like all celestial objects, our planet expands with the universe. The last four motions are associated with very long time scales. Because of that, these motions do not affect the day to day weather phenomena. They might affect phenomena that take very long time to occur, such as climate changes, but weather the way we know it is affected only by the two first motions. Let's consider these two motions in detail.

The orbit around the sun is not a circle. Rather it is an ellipse with the sun as one of its foci. This means that the planet is not at the same distance from the sun at all times. Some times it is closer and some times it is farther (figure 17). Since we get warmer the closer we are to a heat source, one may argue that the elliptical orbit will cause the seasons. This is partly correct. For example, our planet is the closest to the sun at the *perihelion*, which is reached around the end of December and the farthest from the sun at the *aphelion*, which is reached around the end of June. These times coincide with summer and winter, respectively, in the southern hemisphere, but not with summer and winter in the northern hemisphere. In fact, summer in the northern hemisphere occurs when the planet is at the farthest point from the sun.

To explain this discrepancy, imagine that you are in front of a fireplace and you face the fire directly. The closer you are to the fireplace the warmer your face will get. At any fixed distance from the fireplace your face will reach a uniform temperature. If you then tilt your head backwards, your forehead will cool whereas your chin will get warmer. The reason for that is that when you face away from the fire your forehead does not intercept the heat directly whereas the chin intercepts heat more directly than before. In fact, if you experiment with this, you will find out that the cooling of your forehead when you tilt your heat is greater than what it would have been if you simply moved a bit farther from the fireplace without tilting your head. So, if the fireplace is the sun, your head is the planet, your forehead is the northern hemisphere and the chin is the southern hemisphere, then the fact that the northern hemisphere winter occurs when the planet is the closest to the sun could be explained if the planet is tilted as it revolves around the sun. And this is true. The orbit the planet traces as it goes around the sun defines a plane, which is called the plane of the ecliptic (figure 18). Just think of it as an ellipse drawn on a flat table. The axis of rotation is not perpendicular to that plane but it "pierces" it at an angle of about 23.5^0 (figure 18). Because of this tilt, when the planet is closest to the sun the northern

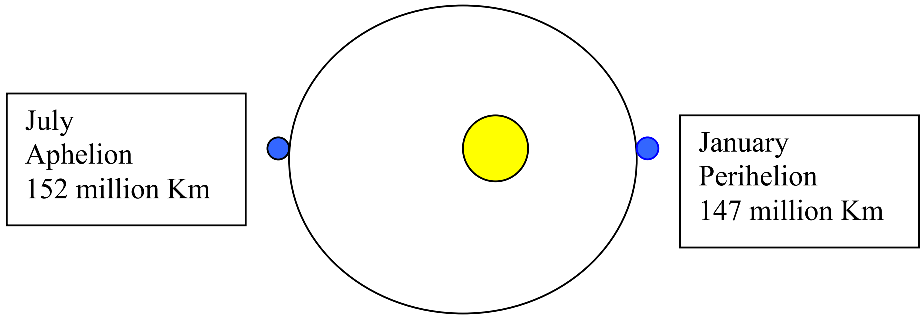


Figure 17: The elliptic orbit of earth.

Hemisphere is tilted away from the sun whereas the southern hemisphere is tilted toward the sun. At this position the northern hemisphere does not intercept the solar radiation directly, and thus it does not get very warm. This is the position when the northern hemisphere winter (winter solstice) and the southern hemisphere summer begin. As the planet revolves around the sun and spins on its axis, when it is at its farthest point from the sun, it is the northern hemisphere that is tilted toward the sun whereas the southern hemisphere is facing away from the sun. This is the position where the northern hemisphere intercepts solar radiation most directly[1]. Now the seasons reverse and the northern hemisphere begins its summer (summer solstice) while the southern hemisphere begins its winter. In between we have the vernal equinox (start of spring) and the autumnal equinox (start of autumn).

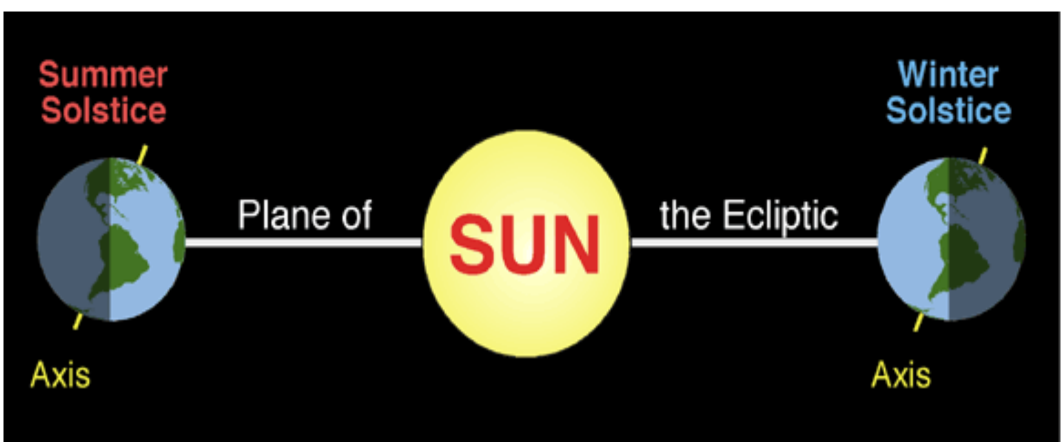


Figure 18: Courtesy of Dr. Michael Pidwirny (mpidwirny@ouc.bc.ca)

[1] As we all know even though the northern hemisphere intercepts solar radiation most directly at the end of June it is not until mid August that the maximum temperature of the summer will occur. This difference in time is called the *seasonal lag*. For an explanation see Appendix 1.

It follows that both the ecliptic orbit and the tilt of the axis cause the seasons and their timing. Now here is a good question: Since the southern hemisphere summer occurs when the planet is closest to the sun and the northern hemisphere summer when the planet is the farthest for the sun, does it mean that the southern hemisphere summers are warmer (and by extension the northern hemisphere winters are warmer)? This is a very legitimate question and it makes sense to think that way. However, there is a fundamental difference between the two hemispheres, which will not allow this to happen. A quick look at a globe will show us that the southern hemisphere's surface is mostly covered by water whereas the northern hemisphere's is covered by land. As we discussed previously, due to the ever-important heat capacity, water needs more heat to become as warm as land. As such, even though the southern hemisphere is closer to the sun during its summer, it does not get as warm as the northern hemisphere gets during its summer. Similarly, because water will take longer to loose its heat than land, the northern hemisphere's winters are much colder. Owing to water's large heat capacity, the temperature of water increases and decreases slowly. As a result water temperature does not tend to extremes throughout a year. Because of that the contrast between summer and winter in the northern hemisphere is larger compared to southern hemisphere.

Apart from affecting how direct a place is intercepting radiation, the tilt also determines the length of day and night. If there were no tilt (left panel in figure 19) then half of the northern hemisphere and half of the southern hemisphere will intercept radiation at any given time. The other halves would be dark. Thus the length of day and night would have been the same at all places on earth. The tilt changes that. During summer solstice, more than half of the northern hemisphere is intercepting radiation (right panel). Thus, days are longer than nights in the summer. At the same time less than half of the southern hemisphere is illuminated. Since this is wintertime down there, it follows that nights are longer in winter. In addition, as the figure illustrates, because of the tilt there are two regions (north of the Arctic Circle or 66.5^0 N and south of the Antarctic Circle or 66.5^0 S) where during summer the sun never sets and during winter the sun never rises. Consider this if you are planning to retire in northern Alaska!

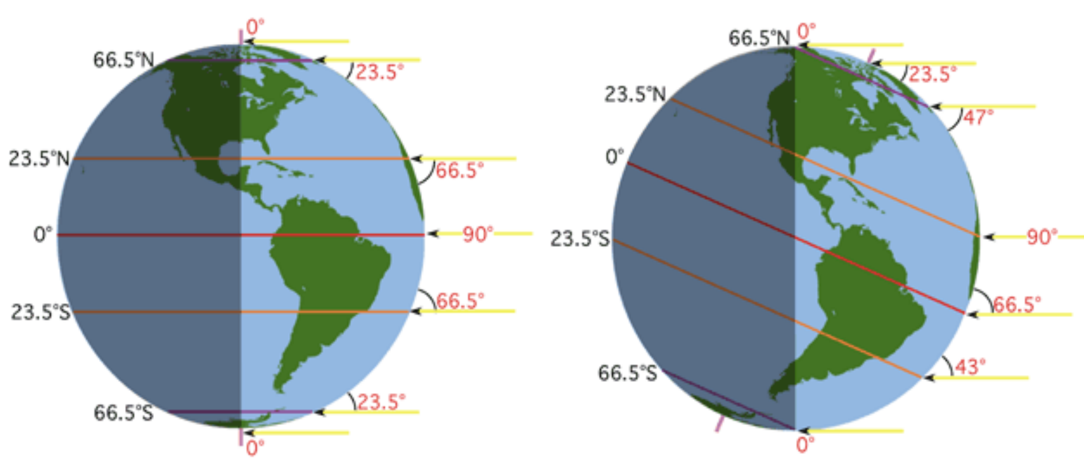


Figure 19: Courtesy of Dr. Michael Pidwirny (mpidwirny@ouc.bc.ca)

We can now see how changes in the tilt will affect the seasons and climate. If the tilt were to increase, then at the perihelion the northern hemisphere would be facing even more away from the sun whereas the southern hemisphere would be facing even more directly. This means that winters in northern hemisphere would become colder and summers in southern hemispheres would become warmer. By extension, at the aphelion the northern hemisphere would be now facing more directly the sun and the southern hemisphere would be facing more away from the sun. Thus, summers in northern Hemisphere would become warmer and winters in southern hemisphere would become colder. We may conclude that if the tilt becomes greater than 23.5^0, then the difference between the seasons will be accentuated. Following the same steps but now considering that the tilt decreases, we will conclude that when the tilt becomes less than 23.5^0, the difference between the seasons will be smoothed, as we will now experience colder summers and warmer winters. Tilt variations do not affect the weather, as we know it, because the change is very slow. As we will see later, however, changes in the tilt may flip the climate state from today's state to that of the ice ages. However, the fact that the earth is tilted and that it orbits around the sun, determines the seasons and the length of day and night, which in turn determine the amount of heat received at a place, which in turn determines local weather and develops convection patterns. But we still have not seen how the other relevant to weather motion (the spin on the axis) will affect and modify this picture.

As the story goes, Napoleon's military trainers observed that the new long-range cannons were always missing their target to the right. The apparent deflection of the cannon balls from the straight path between the cannons and target was explained by the French scientist Gustave Gaspard Coriolis. Coriolis, who was born in 1792, suggested that this was due to the movement of the earth while the cannon ball was in flight. According to Coriolis, the spinning of the planet on its axis introduces a force (later named after him), which deflects everything that moves in the northern hemisphere to the right and everything that moves in the southern hemisphere to the left. Exactly at the equator there is no deflection. Let's try to reason through this.

Imagine that you are standing exactly at the equator as the planet spins on its axis. The motion of your body is a simple revolution around the axis of rotation. Your body does not spin at all. In effect, the spin is not apparent to you. Now imagine yourself at the North Pole. In this case the axis goes through your body. You don't anymore revolve around the axis. You are the axis. This means that now the motion of your body is a spinning motion. In any place between the equator and the poles your body has a motion which combines both revolution and spinning. Since the spinning of the axis is not apparent at the equator, exactly at the equator the Coriolis force is zero. As you move to higher latitudes the effect of the spin becomes more and more pronounced becoming maximum at the poles. Thus, moving objects are deflected more at higher latitudes. The fact that the deflection is opposite in the two hemispheres can be explained as follows. If you are standing at the North Pole looking south toward the equator, you will observe that the equator rotates counterclockwise. If you are standing at the South Pole you will observe the opposite. This relative rotation with respect to the equator is why the effect is opposite in the two hemispheres. Thus, the Coriolis force is proportional to the rate of rotations (the greater the rate of rotation the greater the deflection), and proportional to the latitude (the higher the latitude the greater the deflection; in mathematical term it is proportional to the cosine of latitude). Also for some reasons that we will not get into details here the Coriolis force is also proportional to the wind speed (the faster the motion the greater the deflection).

Coriolis force = rate of rotation x cosine of latitude x speed

There have been many misunderstandings regarding the Coriolis force and its effect. The most common one, usually introduced early in the minds of middle school students, is that the Coriolis effect will cause water going down the drain or flashed down the toilet to rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. This is an unfortunate myth, which we have to dispel. The planet rotates on its axis once a day. This rotation is much slower than rotations, which we experience in every day life, for example, rotation of tires, or rotation of water as it goes down the drain. Sinking rotating water makes one rotation in about one or two seconds. A day has 24x60x60=86,400 seconds. This means that compared to the rate of rotation of the planet, water rotates tens of thousands times faster. Thus, the Coriolis force (a result of one rotation per day) is orders of magnitude smaller than the forces operating in these fast rotations. Thus, the Coriolis force cannot possibly affect these motions. The direction of the rotation of water flashed in a toilet depends simply on the way the water just under the rim is squirted into the bowl when it is flushed.

In the same way, the Coriolis force will not affect the way winds swirl in the corner of buildings, or how tornados spin, which rotate much faster than the rotation of the planet. It will, however, affect the way slow moving, long lasting vortices such as low pressure systems and hurricanes rotate. It will also affect the slow moving ocean currents, thereby modifying their path. We will discuss this later, but first we will see how the Coriolis force will modify the general circulation of the simple Hadley cell (see figure 14).

The simple one cell circulation is unstable. There are many reasons for it being unstable. First, the planet's surface is not uniform. The distribution of land and water is not homogeneous. Second, it is subject to the earth's rotation, which will twist it differently at lower and higher latitudes. The net result is that each single Hadley cell will break into three smaller circulations. As before, the warm air at the equator will rise. But now in the northern hemisphere the upper current will not sink at the pole but at about 30 N. At about 60 N the air will also rise. At some level part of this rising air will move northward and part will move southward. The southward moving current will join the equatorial air and will sink with it at about 30 N. The northward moving current will sink at the North Pole. Similar motion will be established in the southern hemisphere. The equatorial cells are still called Hadley cells. The polar cells are called just that and the middle cells are called Ferrel cells, to honor the American meteorologist William Ferrel.

If for simplicity consider only the northern hemisphere, we can examine what will happen to the sinking air at 30 N and at the North Pole as it hits the surface. Some of the air at 30 N will flow north and some south. Since the direction of the wind is defined from where the wind is coming, this will mean that the initial tendency will be to establish north winds at the surface in the latitude belt 0-30 N and south winds in the latitude belt 30-60 N. As the air begins to move, however, the Coriolis force is activated, which deflects everything to the right. As a result rather than having a surface north wind in the latitude belt 0-30 N, we end up with an easterly flow. This easterly flow established in this belt is called the *trade winds*, as this wind was necessary for the ships of the Europeans trying to reach the newly discovered America to trade. The air that sinks in the North Pole will rush to the south. It, too, will be deflected to the right and as a result another easterly surface flow will be established in the latitude belt 60-90 N. This flow is called the *Polar easterlies*. In the latitude belt 30-60 N, the would-be south flow is also deflected to the right thereby becoming a westerly flow. We call this flow the *prevailing westerlies*. Those who live in the United States or other countries in that belt know that most of the times their weather comes from the west.

As we discussed before, sinking air is associated with high pressure at the surface and rising air with low pressure at the surface. If we look at the situation now, it follows that at 30 N and at the North Pole this atmospheric circulation will establish permanent high pressure areas at the equator and around 60 N it will establish low pressure areas. Since at the equator, at the pole, at 30 N and 60 N the motion is mostly vertical (either rising or sinking), at those locations there is very little horizontal movement. As a result at those locations the winds are very calm. Remember that wind is the horizontal movement of air. Vertical motion (sinking or rising) alone do not constitute a wind. The calm winds at the equator are known as the *Doldrums*.

The boundary between these the trade winds and the prevailing westerlies (the 30 N latitude) is called the *Horse* latitude. Its name derives from a very sad fact. Back in the times when traveling between Europe and America was done by sea, if the wind were not favorable, ships could get stuck in the middle of the ocean for a long time. Because of the trade winds and the prevailing westerlies, a sail ship coming from Europe should be traveling in the 0-30 N belt. When returning, it should be traveling in the 30-60 N belt. At that time, the general circulation of the atmosphere was not understood and often ships will get stuck around the 30 N latitude where the wind was calm. In order to save food and water, the sailors will throw the horses to the ocean. Floating dead horses were seen often in the Atlantic waters in the vicinity of the 30 N latitude.

A final feature of the circulation in the northern hemisphere is the polar front. The polar front is defined as the boundary between the prevailing westerlies and the polar easterlies (around 60^0 latitude). At this boundary warm air from the south converges with cold air from the north. This spells a lot of trouble because as we know cold air is heavier. At this boundary, therefore, there will be action as cold air will try to outmuscle the lighter warm air. This action will create disturbances in the atmosphere, which, as we will explain later, will lead to the creation of storms.

A similar three-cell circulation will be established in the southern hemisphere, where the westerlies are not called prevailing but *roaring*. The place at the equator where the two easterly flows merge is called the *Inter Tropical Convergence Zone* (ITCZ). Even though at the ITCZ air from the north converges with air from the south, the ITCZ is not like the polar front. The temperature contrast between the converging air masses at the equator is non-existent. Thus we should not expect here disturbances and storm formation similar to those at the polar front. However, this zone is critical in the formation of hurricanes. We will discuss this important issue in more detail later.

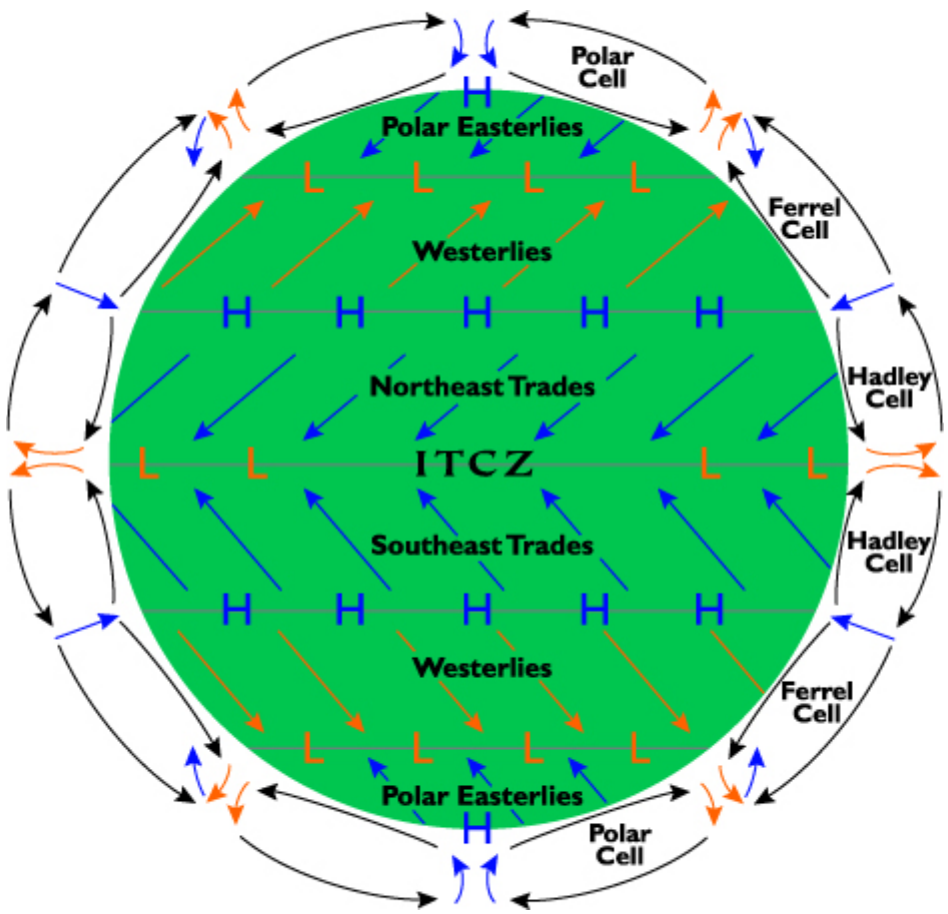


Figure 20: General circulation of earth's atmosphere (www.newmediastudio.org).

Thus, the spinning of the planet will modify the general circulation to six distinct flows close to the surface. These six flows may not always remain in their zonal (east-west or west-east) state. Because the planet's surface is not uniform and homogeneous, the zonal flow may become unstable and break into wavy patterns, which often make the flow meridional rather than zonal. This is similar to what happens to the flow of the smoke coming out of a chimney. The sculptured by the chimney flow breaks into a complicated pattern once it comes in contact with the "noisy" atmosphere. When the circulation has a strong meridional component it is possible for polar air to dip south or tropical air to travel north. Thus, air is always replaced thereby creating a 'mosaic' of high and low pressure systems. Next we will discuss the structure of the pressure field in the atmosphere.

When there are no rising or sinking motions the pressure field is stratified. Stratification means that pressure decreases with height but at a given level in the horizontal pressure is the same (figure 21, top). However, this will not last long. Rising motions and other movement of air and weather systems will create low and high pressure areas. Let's consider the situation described in the middle of figure 21. In this example at the surface the area to the right has a higher pressure (1000 mb) than its adjacent area to the left, which has a pressure of 900 mb. Note that these numbers are used here in order to keep things simple. Pressure at the surface is never below 950 mb (unless we are dealing with a hurricane) or above1050 mb. For simplicity again we also assume a linear decrease with height. As shown in that figure, if we were to reach a given pressure level, say the 600 mb level, then we have to reach a height h' over the low pressure area and a height h'' over the high pressure area. We thus see that high pressure at the surface corresponds to higher heights of a given pressure level. Much like topographic relief maps, which are represented by contours of equal elevations, the pressure field is represented by contours that represent equal pressure. These contours are called *isobars* and are drawn by connecting points of equal pressure. Indeed, as the above example shows, the pressure field will look like mountains and valleys with high pressure systems corresponding to mountains and low pressure systems corresponding to valleys. The bottom panel of figure21 is similar to the middle panel but now we have made the high pressure even higher (1100 mb). In this case the height of the 600mb level over the low pressure area is the same as before (h') but over the high pressure area it is h''' (with h''' > h'' > h'). It follows that within the high pressure system the higher the height the higher the pressure. Thus, since a high pressure system looks like a mountain, the highest pressure will correspond to the highest height; i.e. at the center. On the other hand within a low pressure system (a valley) the lowest pressure (lowest height) will be at the center. Since we cannot see the inner details in a three-dimensional structure, we "slice" the pressure filed at given levels, thereby producing maps in the horizontal. In those maps low and high pressure systems are delineated as concentric closed curves with pressure being the lowest at the center and increasing going outwards in a low pressure system, and highest at the center and decreasing going outwards in a high pressure system (figure 22).

The next question to ask is how the air moves within these low and high pressure systems. Let's consider first a high pressure system. As is illustrated in figure 23 (top) since the pressure is highest at the center and decreases outward then the pressure gradient force will tend to move the air from the center outward in all directions. However, as the motion is activated the Coriolis force will deflect it to the right (in the northern hemisphere), thereby establishing a clockwise (or anti-cyclonic) rotation. On the other hand, with a low pressure system where pressure is lowest at the center and increases outward the pressure gradient force will tend to move the air toward the center from all directions. As is illustrated in figure 23 (bottom) in this case the Coriolis force will cause the air to rotate counterclockwise (or cyclonic). Since in the southern hemisphere the Coriolis Effect is opposite the reverse is established there. The following table summarizes the type of rotation in the two hemispheres

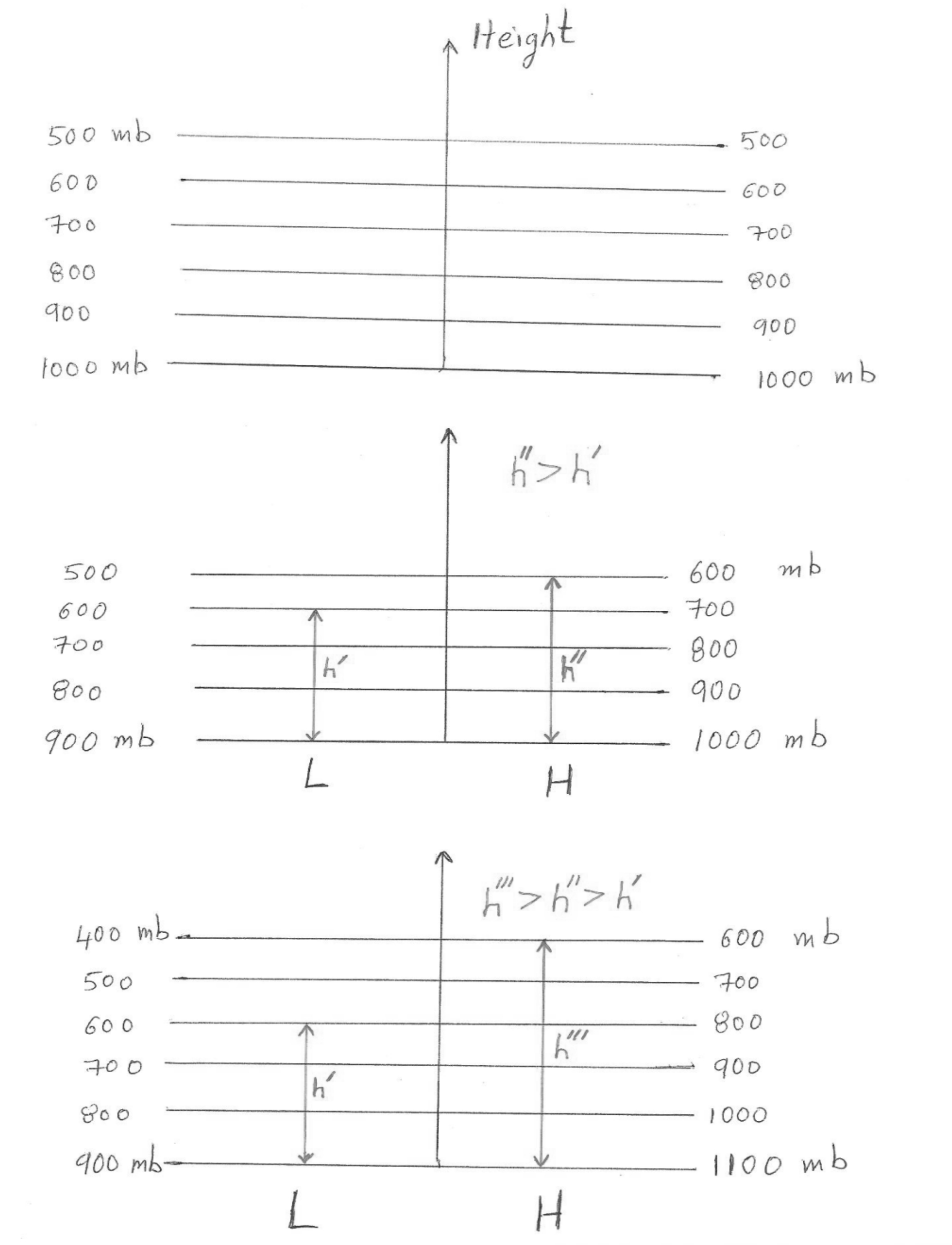


Figure 21: The height of a given pressure level is higher over a high pressure area than over a low pressure area.

	Northern Hemisphere	Southern Hemisphere
High pressure system	Anti-cyclonic	Cyclonic
Low pressure system	Cyclonic	Anti-cyclonic

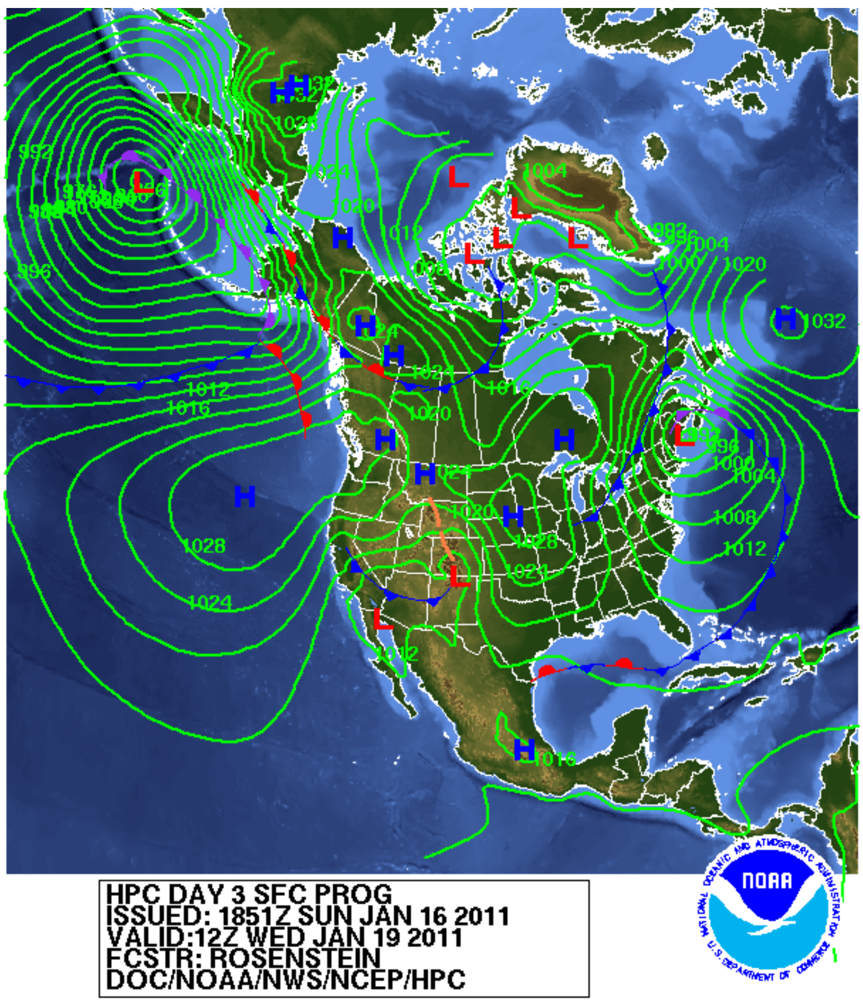
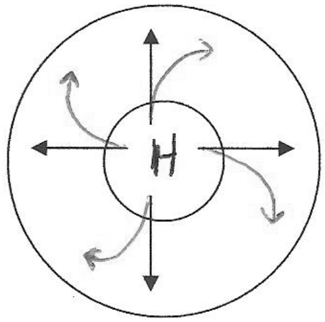


Figure 22: A horizontal cross-section of the atmospheric pressure field. High and low pressure systems are represented by co-centric contours with the pressure being highest at the center of the high pressure systems (and decreasing outward) and lowest at the center of the low pressure systems (and increasing outward).



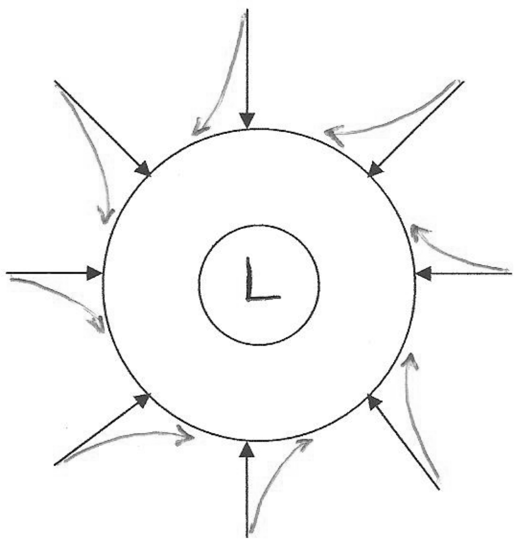


Figure 23: The effect of the Coriolis force on the circulation of air in a high pressure system (top) and a low pressure system (bottom) in the northern hemisphere. The situation is reversed in the southern hemisphere.

Having in place the general circulation of the atmosphere with all its low and high pressure systems and all its horizontal and vertical motions intertwined, many weather phenomena will now develop. Next we are going to construct, piece by piece, all these phenomena, and show how, without even one exception, all possible weather phenomena not only will affect the United States but they will cause a constant headache of immense proportions. We will start with the formation of clouds and precipitation.

5. How clouds and precipitation form.

Selections from a German cloud atlas In: "Wolken und andere Erscheinungen....", Thomas Forster, 1819 Figure 5

Image ID: wea00003, Historic NWS Collection

Clouds are the ‘symptoms’ of weather. When the weather is good a certain type of clouds can be seen in the sky. When the weather is turning gloomy different types will be developing. Most weather calamities are associated, in one way or another, with clouds and precipitation. For this reason we have to discuss the processes that underlie the development of clouds and precipitation.

We have already discussed that when a parcel of air rises it expands, is doing work on the environment, it spends some of this kinetic energy, and is cooling. Cooling, however, is not the only change the rising parcel will experience. In order to describe what else is taking place inside the parcel, we have to introduce the definition of humidity and relative humidity. We have already seen that water vapor is introduced into the air through evaporation of water from the surface of the planet. We have also established that when water vapor is introduced in dry air, it replaces some of the nitrogen and oxygen molecules and that this modifies the weight of the air; it makes it lighter. The amount of water vapor in the air defines the humidity. Usually it is expressed as grams of water vapor in one kilogram of air. Unfortunately, humidity is often confused in weather reports on television, where humidity is given as a percent (for example, 70%, 90%, etc). This practice is incorrect and I am not sure why it is practiced as such. The percent refers to relative humidity, which has a different meaning. Let me explain. Consider a lecture room with a capacity of N seats. At any given lecture the number of occupied seats may vary. In other words, the number of occupied seats may not always be equal to the capacity of the room. When all the seats are occupied the room has reached its capacity. If we now think of the occupied seats as water vapor molecules and the capacity as maximum number of water vapor molecules a parcel can hold, we can clarify the difference between humidity and relative humidity. While humidity is the amount of water vapor in the air, relative humidity (RH) is the amount of water vapor in the air divided by the amount the air can hold. Thus, the relative humidity is a fraction whose numerator is humidity and the denominator is capacity.

Relative humidity = Humidity/capacity

In the lecture room example the capacity N is determined by the size of the room. In the atmosphere temperature determines the capacity; the warmer the air the greater the capacity for water vapor. It follows, that the relative humidity could be high even if the numerator (amount of water vapor molecules in the air) is small, provided that the denominator is also small (which means cold temperatures). In other words, we don’t get high relative humidity only in the summer when the temperature is high but also during winter.

The above definition of relative humidity suggests two possible ways of increasing the relative humidity. The first way is to keep the temperature fixed (like in a room with a thermostat) and evaporate water in it (for example, with a humidifier). This provides water vapor in the air, thereby increasing its humidity. Since the temperature is steady, the capacity remains the same. Thus the numerator increases and the denominator stays the same. The final result will be an increase in the value of their fraction (relative humidity). When the amount of water vapor reaches the amount the air can hold at that fixed temperature the relative humidity becomes 100%. At this point the air is saturated with water vapor. Now, what do you think is going to happen if more water vapor is added to the air? One might temped to say that the relative humidity will keep on increasing, but this is not what will happen. Once the air reaches its capacity it cannot hold more water vapor. So, if we keep on supplying the air with extra water vapor this extra water vapor condenses and the resulted *liquid* water leaves the air, thereby returning the air to saturated conditions. It is important to stress here that just because there is condensation it does not mean that there is no more water vapor in the parcel. Only an amount of water vapor equal to the increase of relative humidity above 100% is condensed. In a room this condensation takes place on objects in the room, for example drapes, walls etc. That is why, if we over humidify, the room becomes damp.

The second way to increase the relative humidity is the inverse. We can keep the amount of water vapor the same (numerator stays constant) but lower the temperature. This decrease the capacity (i.e. the denominator) and results in an increase in relative humidity. In winter, this will be equivalent to opening the windows. Here again, after the air has cooled enough it will reach saturation. A further cooling will cause the relative humidity to rise above 100%, but as we discussed above this is not allowed. In this case again the extra vapor condenses to form liquid water.

While the first way is the way people increase the relative humidity in dry places, in the atmosphere (in lieu of humidifiers or dehumidifiers) the relative humidity changes because temperature changes. The air at a location may arrive from various sources. For example, if you leave in the Midwest the air today may have originated in the south or in the north. If it were originated in the Gulf of Mexico it will have picked more water vapor than it would have if it were originated in northern Canada. Whichever is the case, as long as we are dealing with the same air mass, it is reasonable to assume that the amount of water vapor in the air does not change throughout a day. Then we should expect the relative humidity to decrease as the temperature increases and to increase as the temperature drops. Indeed, we usually register the lowest relative humidity at the time of maximum temperature (around 3 p.m.) and the highest relative humidity when the temperature is the lowest (just before sunrise). If the cooling during the night is strong enough, then the air might reach saturation and with a further cooling the extra vapor will condenses at the surface to produce dew. This is why the temperature to which you have to cool the air to become saturated is called the *dew point temperature*, T_{dew}, (if this temperature is below 32 degrees Fahrenheit, then we might get frost rather than dew and it is called the *frost point temperature*). It should not be surprising then, to usually observe dew forming during cool nights. It follows that the dew point temperature is always lower than the actual temperature except when the air is saturated. In this case dew point temperature and actual temperature are equal.

Aristotle (again in his Meteorology, Book I), states “Both dew and frost are found when the sky is clear and there is no wind”. Was he right? Well, let’s see. The surface cools at night because heat is emitted from the surface into the atmosphere. If the sky is clear this heat escapes more rapidly than if it is cloudy. Thus, the surface and the air in contact with the surface will get cooler faster in clear nights. This increases the possibility of getting dew or frost. So, the first part of Aristotle's statement is correct. How about the second? For dew or frost to form at the surface the air at the surface should be the coldest. When the surface is cooling it is reasonable to assume that the air close to the surface will be the coldest because the air above receives some of the escaping heat and absorbs it. If, however, there is a strong wind, then there is mixing and the coldest air may not be at the surface. Aristotle was right on the money on this one as well.

Speaking of it, the dew point temperature is one other number the weather reports on television give you. If you are puzzled as to why this information is given, you are not alone. Definitely, it is not given because we care much if dew is going to from. As we will discuss next, knowing it can help us do a little weather forecasting ourselves.

In the discussion above, the changes in relative humidity are taking place at the surface. Now, consider a parcel of air, which has a certain amount of mass and a certain amount of water vapor. This defines humidity. If we know the temperature of the parcel, then we know its capacity and therefore we know its relative humidity. Let's assume that to start with the parcel is unsaturated (say, RH=70%). Then the dew point temperature of the parcel's air is lower than its temperature. If the parcel begins to rise, then its temperature goes down. Because we assume that the parcel is adiabatic, as it rises it does not mix with the environment, therefore its mass and water vapor remain the same. Thus, its humidity does not change. However, because its temperature goes down, its capacity decreases and therefore its relative humidity increases and the parcel's temperature approaches the dew point temperature. If the parcel's rising motion is strong, there will be a level where the temperature will be cold enough for the parcel to reach saturation. At that level the temperature of the parcel has become equal to the dew point temperature of the parcel at its initial level (figure 24).

What's next? Just because the rising parcel reached saturation it does not mean that is going to stop rising and cooling. Accordingly, the relative humidity of the parcel will keep on increasing. But, we have seen that when the relative humidity jumps above 100%, the extra vapor condenses into liquid water. Thus, just above the saturation level we will observe condensation and the formation of tiny water droplets. A cloud now begins to form.

Here is a good place to introduce the *equilibrium vapor pressure*. The equilibrium vapor pressure refers to the amount of vapor over a water or ice surface when the water or ice is at equilibrium with the vapor over it. For example, assume that you have a pan full of water in a room. If the air in the room is not saturated with water vapor, then water evaporates and supplies the air with vapor molecules. Once the air reaches saturation evaporation stops. The water left in the pan and the vapor in the air are now at equilibrium. The amount of water vapor in the air at this point has a certain weight given by the sum of all the water vapor molecules. This weight is pressing the surface of water in the pan. This defines a pressure, which we call equilibrium vapor pressure.

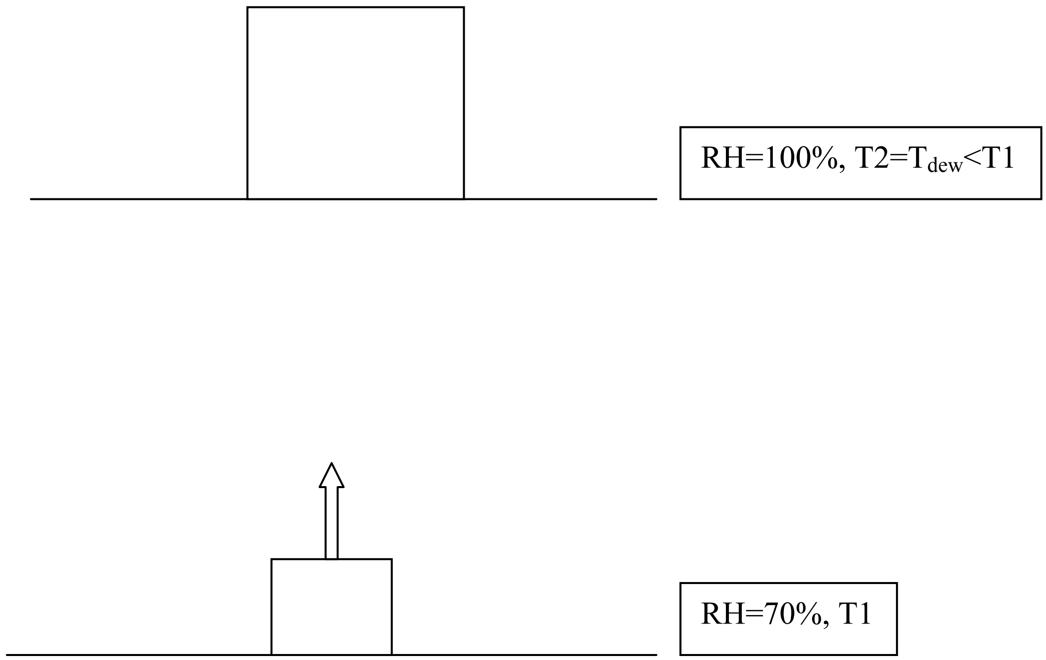


Figure 24: As the parcel rises it cools and its relative humidity increases. The temperature of the parcel when the relative humidity becomes 100% is the dew point temperature of the parcel at the initial level.

It follows, that the cloud bases occur just about where the parcel's initial temperature is lowered to match its dew point temperature. We can now reason that, if the initial difference between the temperature and the dew point temperature were great, then the required cooling will also be great and as a result the cloud bases will occur at high levels. Otherwise, the cloud bases will form at low levels. Thus, the smaller the difference between temperature and dew point temperature, the lower the cloud bases. In fact, if the difference is zero (i.e. the temperature at the surface equals the dew point temperature), then the cloud bases will form near the ground and we will get fog. It is also fair to say, that the lower the cloud base, the greater the possibility will be for the cloud to grow, simply because there is more room to grow. Consequently, the greater the development of the cloud, the greater the chance it will form precipitation. We are going to come back to this, but for now remember that when you see a small difference between temperature and dew point temperature, you may want to consider carrying an umbrella with you.

We can then conclude that clouds form when the air is cooled below its saturation point. What's next? Let's try to imagine this rising motion in terms of a movie frames (figure 25). Frame #1 shows the cloud base forming. At this point the extra water vapor has condensed into cloud droplets and the air's relative humidity has gone back to 100%. Here we will keep it simple and assume that the temperature remains above freezing as the parcel rises. Then, inside the parcel the two phases of water (vapor; small circles and liquid cloud droplets; large shaded circles) coexist and are in equilibrium with each other. Here this equilibrium is expressed as five water vapor molecules for every cloud droplet.

(in other words the equilibrium vapor pressure is five pressure units). Equilibrium here means that if no more changes occur in the parcel, water vapor and liquid water will coexist without increases or decreases in their amounts.

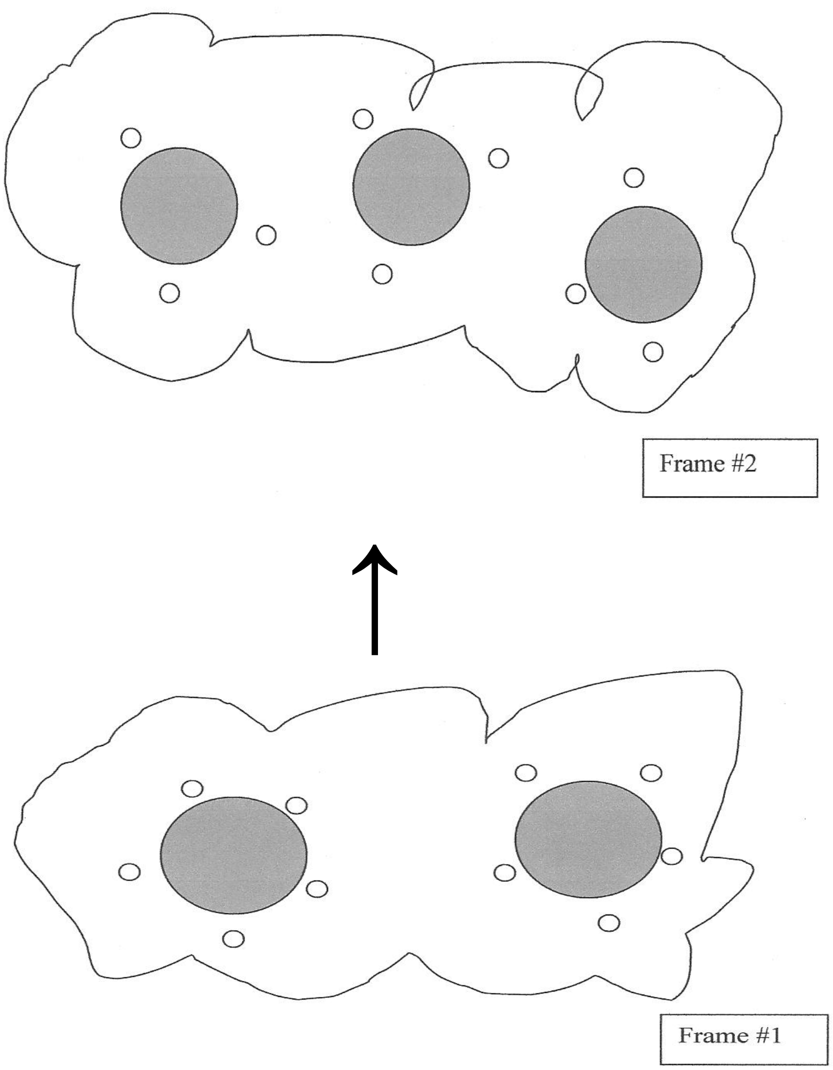


Figure 25: An illustration of how a cloud grows when the air that has reached saturation rises

In frame #2 the parcel rises infinitesimally. Then, because of adiabatic cooling, its temperature decreases[2] and its relative humidity increases. Thus, its relative humidity

[2] Note that because of the heat release due to condensation the parcel receives some heat. This does not mean that now the parcel will be warming as it rises but that the cooling rate will be lower than that when it was not saturated. When the parcels are dry (unsaturated) the cooling rate is 10 ^{0}C/Km and when they become saturated (moist) the rate is 6.5 ^{0}C/Km. This difference as is shown in Appendix 2 has significant effect in modifying local climate.

jumps above 100% again. Because of the cooling, the parcel's capacity decreases and the parcel does not need the entire vapor it had in frame #1 in order to be saturated (or at equilibrium with the liquid phase). Let's, say that this new equilibrium requires three water vapor molecules for one cloud droplet. Because of that, the extra vapor condenses and the cloud keeps on developing. The same process occurs in all consequent frames. The continuous rising motion keeps the temperature of the parcel falling, which keeps its capacity for water vapor falling, which keeps its relative humidity jumping above 100%, which sustains condensation, thereby developing the cloud.

Will this procedure ever develop precipitation? When water vapor condenses in your room or at the ground, it condenses onto some surface. In your room this surface can be a wall or a drape or your clothes, etc. In the atmosphere this surface is provided by very tiny particles called *condensation nuclei*. These nuclei can be salt from the oceans, dust, smoke, and other particles introduced naturally and from man made pollution into the atmosphere. For vapor to condense without such surface is practically impossible, as it would require relative humidities much higher than 100%, which are not easily attained in the atmosphere. If it were not for these nuclei, precipitation would rarely form in our atmosphere. The size of the condensation nuclei varies from 0.2 μm (microns) to 6 μm.

One micron is one millionth of a meter. Thus, condensation nuclei are very small and have very small surface. This is very important because water freezes at 32 F only if an adequate surface exists. As a consequence, water may form on them even at temperatures well below the freezing point (32 F). These droplets are called *supercooled*. In addition, there are two kinds of nuclei: The water seeking and the ice seeking nuclei, with the water seeking nuclei being more abundant than the ice nuclei. These two facts do not allow too many ice crystals to form and as a result, even at temperatures as low as -30 F, water droplets are more numerous than ice crystals. Ice crystals dominate the cloud at very high levels where the temperature is -40 F or lower.

The typical size of a cloud droplet is about 20 μm and the typical size of a rain drop is 2,000 μm. This means that a cloud droplet has to grow its volume one million times before it becomes a rain drop. At this rate it is estimated than rain formation will take days. Observations, however, indicate that a cloud can develop and produce rain in about one hour. Something else must be then responsible for rain formation.

A cloud can be either a warm cloud (having above freezing temperatures at all levels) or cold clouds (extending to levels where temperature is below freezing). In warm cloud only cloud droplets and water vapor exist in the cloud. Our understanding about rain formation in warm clouds is that cloud droplets grow by a mechanism, which involves collision between cloud droplets. When cloud droplets form, they don't all have the same size. Local fluctuations in water vapor and variations in the size of nuclei result in a non-uniform droplet size distribution. The larger droplets fall faster and overtake and collide with smaller droplets. In many of these collisions the smaller droplets merge with the bigger droplets thereby causing the bigger droplets to become even bigger, which in turn through the same mechanism increase their chance to grow even further and become raindrops. When the drops are big enough they may overcome the updrafts (rising motion) inside the cloud the fall out as rain. When these updrafts are very strong, the drops remain in the cloud longer and as result they grow bigger. This explains why the raindrops are larger when the clouds are big.

In cold clouds the situation is very different and more interesting. In cold clouds, as we discussed above, all three phases coexist. Cloud droplets and ice crystals will now compete for vapor. Which one will win? Let’s consider the situation frame by frame again shown in figure 26. In frame #1 the cloud base has just formed. At this point the extra water vapor has condensed into cloud droplets and ice crystals and the air’s relative humidity has gone back to 100%. Inside the parcel the three phases of water (vapor, liquid and solid ice) coexist and are in equilibrium with each other. If we now zoom (frame #2) into this frame we will observe something very interesting. Even though the three phases are at equilibrium with each other, the distribution of vapor is not uniform inside the developing cloud. The presence of ice crystals causes the distribution of water vapor to become uneven. There are more water vapor molecules around the droplets than around the ice crystals. The reason for this ‘unfairness’ is the equilibrium vapor pressure. Physics dictates that the equilibrium vapor pressure over ice is less than that over liquid water. The number of water vapor molecules required in order for the ice and the water vapor in the air to be at equilibrium is less. This fact will result in a picture inside the cloud where the water vapor molecules are arranged so that there is more vapor molecules around the droplets than around the ice crystals. This in turn will create ‘mini’ high pressures (H) around the droplets and ‘mini’ low pressures (L) over the ice crystals.

Recall now happens when a high and a low pressure are formed. Always in this case there is motion from high to low pressure. The same is going to happen inside the cloud between the “mini” high and low pressures. Accordingly, in frame #2 we will observe that water vapor molecules are swept from around the droplets (high pressures) towards the ice crystals (low pressures). Since the ice crystals are receiving water vapor molecules, they now have more than they need to be at equilibrium, whereas the droplets have less than they need. Thus, in frame #3 we will notice that the ice crystals use the extra vapor to grow, whereas the droplets evaporate to return to equilibrium with the air around them. This process continues and the ice crystals grow at the expense of the surrounding liquid droplets. Interestingly, even though there are much less ice crystals than droplets in the air, the crystals win. This process is called the ice-crystal process or the Bergeron process in honor of the Swedish meteorologist Tor Bergeron who suggested this mechanism.

Ice is a crystal made of water vapor molecules arranged on a hexagonal lattice. Because of that the most basic ice-crystal shape is the hexagonal prism, which includes two hexagonal basal facets and six rectangular prism facets (figure 27). As the crystal is blown through the cloud, water vapor molecules from around diffuse on it. Because the corners of the crystal stick out a bit more than the other points, water vapor molecules have a greater chance to diffuse to the corners. This causes the corners to grow faster and to stick out even more, which causes more water vapor molecules to stick on them. This positive feedback is called *branching instability* and it causes corners to grow into branches and random bumps in the branches to grow into side-branches. The final result is a beautiful and complex structure: the snowflake. The branching instability and random motion of the water vapor molecules cause each snowflake to be different from any other snowflake (figure 28).

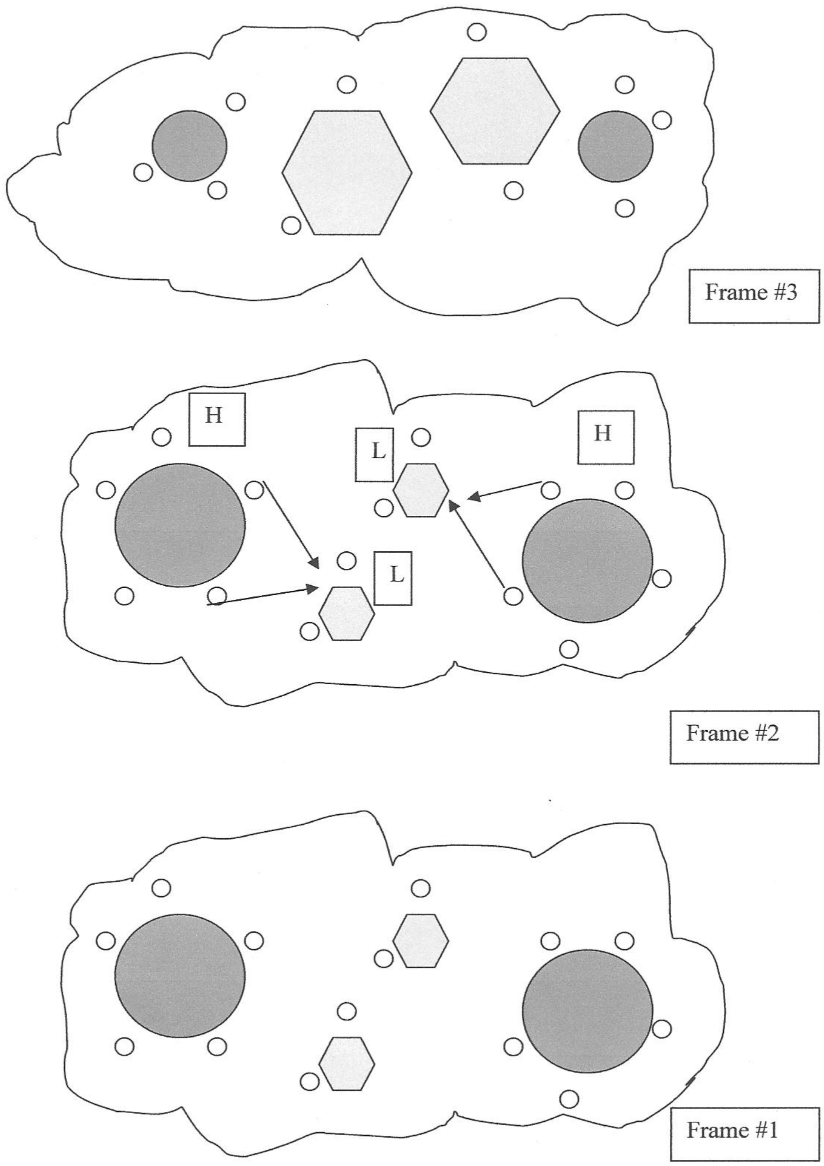


Figure 26: Illustration of the ice-crystal process.

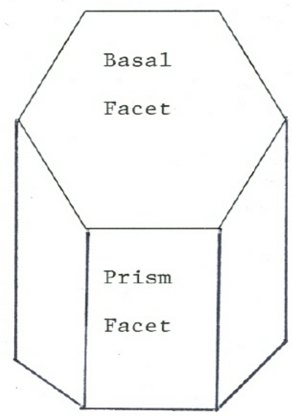


Figure 27: The basic geometry of an ice crystal.

Other possibilities exist. For example, ice crystals may collide with the supercooled droplets. In contact, the supercooled water losses energy and freezes, thereby sticking to the ice crystal. This icy structure is called graupel or ice pellet. However, whatever forms in cold clouds may by the time it reaches the ground become rain, if below the cloud the temperature is sufficiently high to melt the icy products. Thus, even though the ice-crystal process may initially produce snow, it often delivers rain on the ground. Of course, depending on the vertical structure of temperature at a given day, many types of precipitation may occur. For example (figure 29), assume that snow forms in the upper levels and begins to fall through a melting layer. Depending on how deep this layer is, some or all of it may melt. If below this melting layer and close to the surface there is a freezing layer, some of the rain may freeze to give ice pellets, rain and snow on the ground. Depending on the depth of this freezing layer, the rain may not freeze but may cool enough to freeze on impact with the ground. In this case, freezing rain may be added to the menu. There are days (usually February or March) that in several locations in the United States such vertical temperature structures (a freezing layer close to the surface and a melting layer above it) do occur. Those are the days when a mixed bag of products ranging form snow to ice pellets, to rain and freezing rain may precipitate. As I advise all my friends, those are the days to stay home and avoid driving!

We now know that clouds will form when the air rises and is cooled below its saturation point. And we have already described the simplest way for the air to rise. Just warm an area more than its adjacent areas. It is easy to visualize that a vertical (rising) motion will cause a cloud to develop in the vertical. If the rising motion is not very strong, the cloud that will form will not have a great vertical extend. These clouds are called *cumulus* clouds and are often observed forming early in the day even when it is cold (because there is always some warming at the surface). They look like cauliflower or cotton balls, and they tend to persist for many hours. If, however, the rising motion is strong then these cumulus clouds keep on growing and merging with each other, building a huge vertical development cloud called *cumulonimbus*. The word nimbus means in Latin, rain. Cumulonimbus clouds may be huge in the vertical but they are not large in the horizontal.

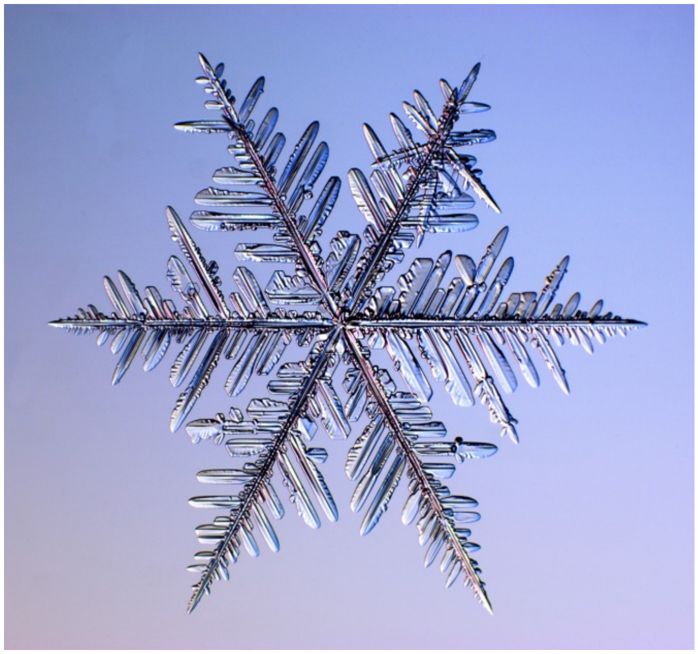


Figure 28: A snowflake. Notice the randomness superimposed on the hexagonal symmetry.

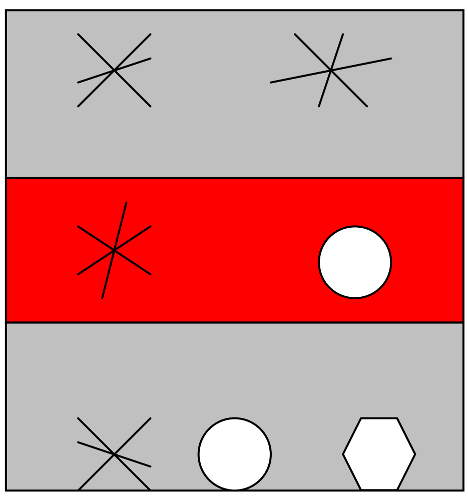


Figure 29: All or some of the snow formed in the upper cold layer may melt if it travels through a middle, melting layer. Then some raindrops may freeze going through the lower freezing layer thereby bringing a mixture of types of precipitation on the ground.

Because of their small horizontal extend they pass over an area quickly. Thus, they tend to rain heavily but for a short time. This is often referred to as a 'shower'.

Rising the air, however, is not the only way to cool the air. Air can also cool if it flows from a warmer surface to a colder surface. As the air travels over colder regions it may, by *conduction* with the colder surface, cool below its saturation point. In this case, the cloud forms in the horizontal. This process produces clouds that are low level clouds, uniform and which cover most of the sky. They are known as *stratus* clouds. If a stratus cloud finds itself in an environment, which supports growth, then it may become a *nimbostratus* cloud. Nimbostratus clouds look like status but they are thicker and precipitate steadily. Because of their large extend they take a long time to move out of an area. For this reason they deliver large amounts of rain or snow in their path. Other clouds may form from the combination of vertical and horizontal motions. They are, from higher to lower base, *cirrus*, *cirrocumulus*, *cirrostratus*, *altocumulus*, *altostratus*, and *stratocumulus* (see photographs and description of clouds in Appendix 3). In general, only nimbostratus and cumulonimbus cloud precipitate (some times light precipitation may be produced in stratus cloud). Figure 30 shows the 10 major types of clouds. Apart from cumulus and cumulonimbus, which are classified as vertical development clouds, the rest are classified as high level clouds (bases at or above 6 Km), middle level cloud (bases between 2-6 Km), and low level clouds (cases below 2 Km). When the cooling of the surface at night is too strong, the air in contact with the surface may be cooled below its saturation point. In this case a cloud may form just above the surface. This way of cooling the air below its saturation point is called *radiation cooling* and it results in the formation of fog, which is basically a stratus cloud very close to the surface. It is interesting here to come back to lake (or sea) and land breeze and their effect on local cloud patterns. As we have described earlier, during a lake breeze (which takes place from late morning to late afternoon) the air rises over land and sinks over lake. The opposite happens during a land breeze (which begins later in the day). Thus, one should expect that cloud from over land and around the lake (sea) shore during the day and over the lake during the evening. A beautiful picture showing the cloud formation during a lake breeze over Milwaukee, WI is shown in Appendix 3.

Before we close this chapter, I think it is proper to discuss another form of precipitation that is not rain or snow or a byproduct of them. This third and distinct form of precipitation is *hail*. A necessary ingredient in the formation of hail is a cloud with very strong updrafts (rising motion) in the lower part of the cloud. Initially, as the cloud develops to levels where the temperature falls below 5 ^{0}F, ice particles begin to form. As these ice particles fall they accrete supercooled liquid droplets and grow to become graupel. This graupel will serve as an *embryo* on which a hailstone will grow. Under normal conditions this graupel will either fall out of the cloud as ice pellets or snow. When, however, the updrafts at the lower part of the cloud are very strong they force the graupel back to higher altitudes where the process of growing by collecting supercooled water is repeated and graupel particles grow rapidly to hail size. While in the updraft motion the growing hailstone may reach a size that balances the opposition of the rising motion. At this point the hailstone ‘floats’ in the updraft. This provides the hailstone with extra time to grow into larger sizes. When the stone grows enough to overcome the updraft it falls out of the cloud. The growth of hailstones is characterized by two regimes; the dry and the wet growth regimes. In the dry regime, as the supercooled drops freezes at the surface of the hailstone it releases heat (in the same way as condensation releases heat). If during this action, the surface of the stone remains below 32 ^{0}F, then the accreted supercooled liquid remains frozen and the growth is dry. On the other hand if the stone’s

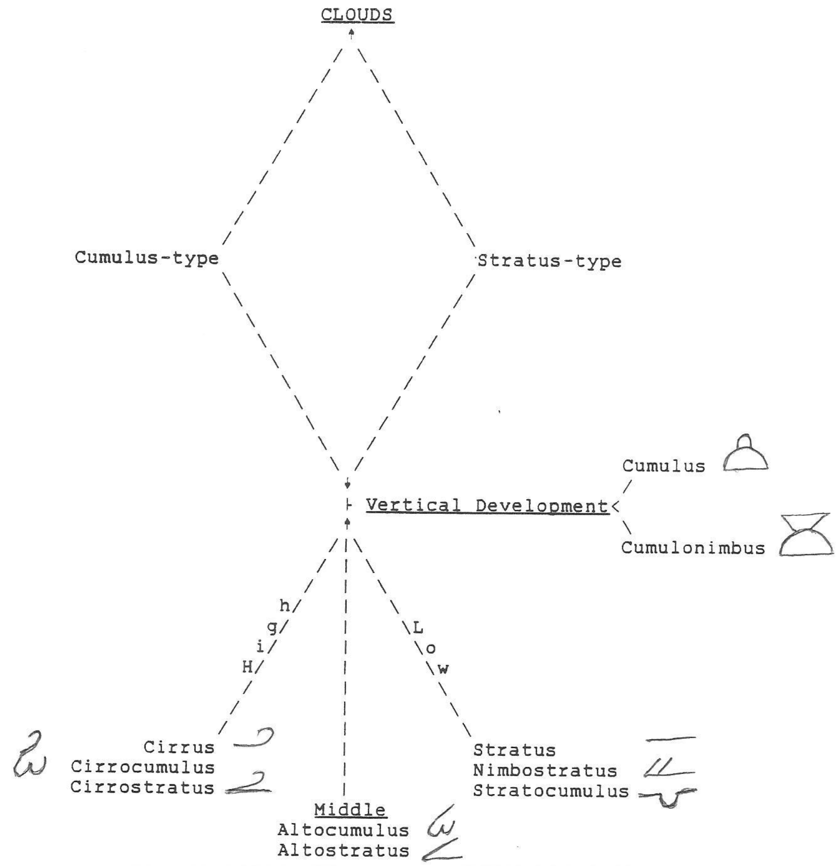
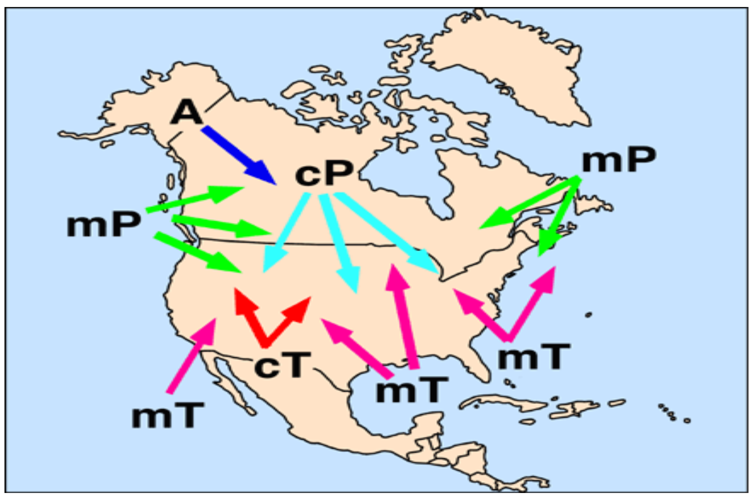


Figure 30: Types of common clouds and their symbols.

surface temperature rises above 32 ^{0}F, the accreted liquid does not freeze. In this case water diffuses into the porous regions of the stone. The hailstone still grows but now the growth is a wet growth. Inside hailstone producing clouds, the turbulent motion and inhomogeneous distribution of liquid cause the hailstones to collect supercooled water at varying rates. Thus, it is possible that both regimes may take place during the formation of hail. In this case the hail may acquire a layered structure (similar to that of an onion), each layer representing a change from the dry to wet growth regime. According to NOAA the largest hailstone ever recorded in the United States, in terms of diameter and weight, was produced by a raging thunderstorm on July 23, 2010 and fell in Vivian, South Dakota. It measured 8-inch in diameter, 1 lb and 15 oz in weight, and had a circumference of 18.62 inches.

6. Air Masses

Open to attack from all sides



Courtesy of Dr. Michael Pidwirny (mpidwirny@ouc.bc.ca)

MAJOR ARCTIC OUTBREAK THREATENS WESTERN AND CENTRAL UNITED STATES

A severe Arctic cold outbreak is poised to sweep through the western and central United States, endangering large portions of the country, according to NOAA's National Weather Service.

Abnormally cold temperatures are expected to reach the west and central parts of the United States beginning December 9 and persist for at least a week. Widespread areas of snow and icy precipitation will potentially move into the Plateau, Rockies, and northern and central Great Plains early next week, following close on the heels of several fast moving winter snow systems, and creating dangerous conditions west of the Mississippi Valley and the western Great Lakes.

The system will likely reach much of California and Arizona the following week, adding to state officials' concerns over an ongoing shortage of electricity. California officials have declared a stage two electrical power emergency eight times in the past three weeks, and are urging conservation of electricity. A stage-two emergency is declared when power reserves fall, or are expected to fall, below 5 percent. California has never had a statewide stage-three emergency, which indicates reserves have fallen below 1.5 percent.

Damaging frost and freezes are also possible, and farmers should stay tuned to forecasts from the local National Weather Service offices for freeze warnings.

As the cold outbreak advances, areas west of the Mississippi River may receive sleet and freezing rain. The eastern and southeastern United States will experience above normal temperatures next week, before increasingly cold temperatures move into the northeast by the middle of December.

The above is a National and Oceanic Administration Agency (NOAA) news release 2000-086 dated December 12, 2000, one of many regularly issued by the Administration. It warns about the impeding arrival of bitter cold, which is predicted to affect a large area of the country and thousands of people. During summer times it is not unusual to receive for the same areas warnings not for bitter cold but for extreme heat. Cold spells in the winter, heat waves in the summer. How can a region be vulnerable to such extremes? Is it bad luck or is there a reason?

As we have seen once the atmospheric circulation is set in motion, air can move around. Thus the air over a given area may have originated at various places, which has come into equilibrium with the underlying surface. This equilibrium ‘stratifies’ the air mass in the vertical so that at any level in the horizontal the temperature and relative humidity are uniform. For this to happen we need to have flat surfaces and light winds (ragged areas and strong winds mix the air in the vertical thereby destroying the vertical stratification. Thus, the best candidates for the source surface will be water bodies, deserts, and steppes in areas where permanent high pressure systems exist (for example around 30^0 N and close to the North Pole; see figure 20). The source surface will cause the air to acquire certain characteristics. An *air mass* is formally defined as a body of air with distinct characteristics in temperature and moisture. If the source of origin is a land region in the north then the air mass is cold and dry. The ice and snow covered area of northern Canada or Siberia are examples of such regions. These air masses are called *continental Polar* (cP). Some people like to divide the polar air masses to continental Polar and to continental Arctic (cA or simply A); we will not make this distinction here. If the source region is tropical land, then the air mass is warm and dry and it is called *continental Tropical* (cT). Deserts are typical sources of origin for these air masses. If the source region is a tropical ocean, the air mass will be moist and warm. If the source region is cold water, then the air mass is moist and cold. In the last two cases, the air masses are called *maritime Tropical* (mT) and *maritime Polar* (mP), respectively. The tropical Atlantic and the Caribbean are good sources for maritime tropical air masses, whereas the north Pacific and Atlantic waters are good sources for maritime polar air masses.

At their source an air mass can be stable or unstable. An air mass is called stable if rising motions are not allowed within it and unstable otherwise. Thus, if an air mass is heated from below (in other words its source surface is warm), then it is unstable. When an air mass is unstable and rising motions are encouraged, clouds and precipitation may form. Thus, unstable air masses bring changes in weather, whereas stable air masses do not. In general at their source all but the continental polar air masses are unstable. As the air masses begin to move around they may be modified. As such the changes that they may bring on the areas they invade depend on if and how they will be modified.

Take for example a polar air mass creeping down from the cold and dry regions of northern Canada to the warmer surface of the United States. At the source this air mass is stable. No rising motions can develop, which means no clouds and precipitation will form either. The skies are beautifully clear and crispy cold. As the air mass travels over the warmer surface of the United States (it is warmer simply because it is south of the air mass' source surface), air in contact with the surface may get warm and rise. In this case, however, because the air mass is very dry, one should not expect big clouds and precipitation to form. Small cumulus clouds may develop, but they don't bring with them any significant changes. However, if the air mass passes over a large body of water (such as the Great Lakes), it may pick up enough water vapor to develop clouds and snow. This snow falls in the leeward side of the lake and is known as *lake-effect snow*. Areas such as Buffalo, NY receive much more snow than areas in the windward side of the lake due to this effect. In the period from 24 to 28 of December 2001, Buffalo was buried by a total of about 80 inches of snow. The 1996 Veteran's Day snowstorm of 9-14 November dumped 70 inches of snow in Cleveland, Ohio and left 160,000 people without power. On November 15, 1900, 45 inches of lake effect snow fell in Watertown, New York in just 24 hours.

The lake-effect snow, however, is the least trouble an arctic air mass can cause. In many instances, arctic air masses bring bitter cold over the United States that not only persists but can spread as south as Florida and the Gulf of Mexico. This is often referred to as the *Siberian Express or Siberian Pipeline*, but in North America it also called the *Norther*, the *Blue Norther*, and the *Barber*. In times like these, temperature drops to very low levels. Take for example the arctic air outbreak of February 1899. Even though many other such outbreaks have occurred in the United States, this one is hailed as the "greatest arctic air outbreak in history". This arctic spell blanketed the entire area east of the Rockies bringing record low temperatures at many places. For example, Washington D.C. registered a temperature of -15 F, the coldest ever recorded in the capital. Ice formed in the Mississippi river flowed into the Gulf of Mexico; an event that has happened only one more time in recent history. The loss of livestock and crops was unprecedented. In the cold outbreaks of 1983 and 1985 Florida citrus growers lost a combined $6.5 billion. The severity of these air masses affects most of the United States. Temperatures as low as -65 F may be recorded in regions of Montana. Cities like Boston or Chicago can easily experience temperatures around -30 F. In the arctic outbreak on February 13, 1899, Tallahassee, Florida registered a record low of -2 F and New Orleans fell to -1 F. Couple this with windy conditions (which make the temperature feel even colder), and the situation becomes critical and life threatening. In such cases most of the nation can be paralyzed from frigid conditions.

Let's now consider that it is summer and a maritime tropical air mass is flowing from the Caribbean to Florida or from the Gulf of Mexico to Louisiana, Texas and other states to their the north. This air mass has originated over water, which in the summer does not get as warm as the land. Thus, the air traveling over Florida or Texas can be thought as colder air traveling over warmer surface (figure 31). In this case, the colder air in contact with the warmer surface will heat up and rise. In the summer, when the heating at the surface is strong, the rising motion is strong enough to develop daily cumulonimbus clouds and rain showers.

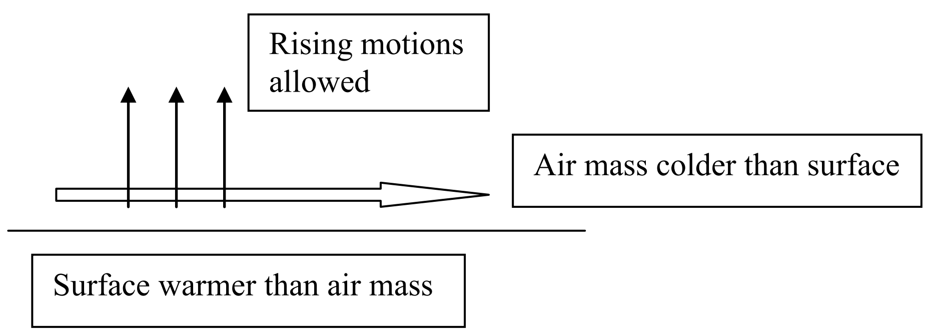


Figure 31: An air mass travelling over a warmer surface is unstable.

The same air mass will not bring the same whether in winter, however. In winter the surface of the ocean is not colder but warmer than land. As a result the situation reverses. Now a warmer air mass is traveling over colder surface. The warmer air in contact with a colder surface, cools, gets heavier and cannot rise (figure 32). In this case, clouds do not form in the vertical. Clouds, however, may form in the horizontal. If the cooling is strong, it may cool the air below it saturation point, thereby making clouds of horizontal extend close to the ground. These clouds, however, do not grow enough to develop any serious weather. This explains why tourists favor Florida in the winter rather than summer. The weather is more stable in winter.

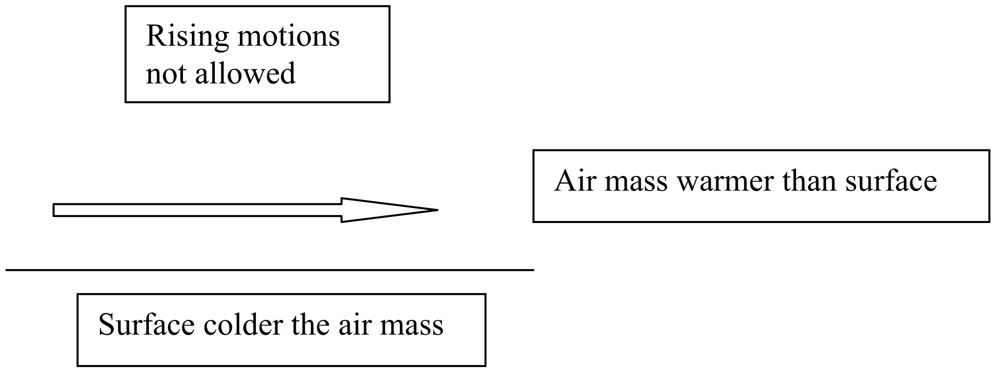


Figure 32: An air mass travelling over colder surface is stable.

These maritime air masses can bring serious problems as well: They are often a key ingredient to *heat waves*. Heat waves occur in the summer when the polar air has retreated well to the north. Then, warm and moist surface air from the south can advance to the north. When the conditions are right, sinking upper air may be act as stabilizing factor, which together with strong heating at the surface causes the warm humid conditions to persist. The effect of a heat wave can be exaggerated if prior to the movement of the air mass over an area precipitation was falling regularly. This makes the surface moisture high, which supplies the air mass with even more moisture than it already has. When the temperature is high and the relative humidity is high, then it feels even warmer. Evaporation is reduced and the body cannot cool easily. This creates a considerable stress for the human body. Such were the conditions in the famous Chicago heat wave that occurred in July 1995. This heat wave affected the Midwest and eastern United States and caused in Chicago alone 525 deaths in only five days. The disastrous heat wave of 1980 in Texas and the southern plains killed more than 1,250 people and cost the nation more than $20 billion. In the forty-year period from 1936 to 1975, 20,000 humans were killed by heat waves in the United States.

In other occasions the same type of air mass can produce serious flooding. For example, in winter, warm and moist maritime air can move into coastal region of California. Because the air's content of vapor is very high the clouds that form produce precipitation. A prime example of such a situation is that of January 1, 1997. Warm moist air, originated in the Hawaiian Islands, reached northern and central California causing extensive flooding. More than 100,000 people had to be evacuated and the total property damage exceeded $1.5 billion. Flooding caused Yosemite National Park damages over $170 million and forced the park to close for two months. This warm moist flow has since been termed as the *pineapple connection*.

In general, if an air mass travels over warmer surface it develops rising motions and it is more unstable than an air mass that travels over colder surface. An important point to be made here is that in sinking motions since the temperature is increasing the relative humidity will decrease. Thus, clouds do not form in regions of sinking motions or where the surface pressure is high. Recalling the picture on page 62, it follows that in areas of permanent high surface pressure, such as around 30 N, 30 S and the poles, the sky is usually clear and there is very little precipitation. It is not surprising that at these locations we find arid regions, such as the Sahara desert and areas with very pleasant climate such as in Northern Mexico, in the Mediterranean, etc. On the other hand, in regions where rising motions are common (such as 60 N, 60 S and the equator), clouds and storms form easily.

When it comes to the United States, all air masses can affect it. The United States is 'open' in all directions. There is no barrier or barriers to hold away air masses. At the same time its geographical location is as such as to be surrounded by areas capable of originating all types of air masses. Continental polar air masses bring bitterly cold weather in winter. Maritime tropical air masses can bring hot and humid weather in the summer. Maritime polar air masses bring cool and moist weather often producing heavy precipitation along the west coast. Continental tropical air masses can bring hot dry air, which if it persists can lead to prolonged droughts. A mixed bag of all possibilities. If we look at figures 33 and 34, which show the temperature records of each State (the highest and lowest temperature ever recorded, respectively), we see that in the United States maximum temperatures can go well above 100 F and minimum temperatures can dip well below -10 or -20 F. Places like Milwaukee can easily have a spread in temperature between summer and winter of more than 150 F. Montana registers a 190 F (105 C) spread. This is more than a third of the way to the absolute zero! Even Florida's temperature can dip into single digits in winter. In summer, tropical air masses can bring heat waves to much of the Midwest.

From all the places in the globe, the United States in the only region which is directly affected by all air masses. Europe, for example, is not affected by maritime tropical air masses. Asia is not open to maritime polar air masses. In the south hemisphere no land areas are affected by continental polar air masses. This 'openness' of the United States to all possible air masses can also cause great temperature shifts in very short time intervals. On December 24, 1924 the temperature at Helena, Montana fell 88 F in just one day. On the 24th of the same month, Fairfield, Montana experienced an 84 F drop in twelve hours.

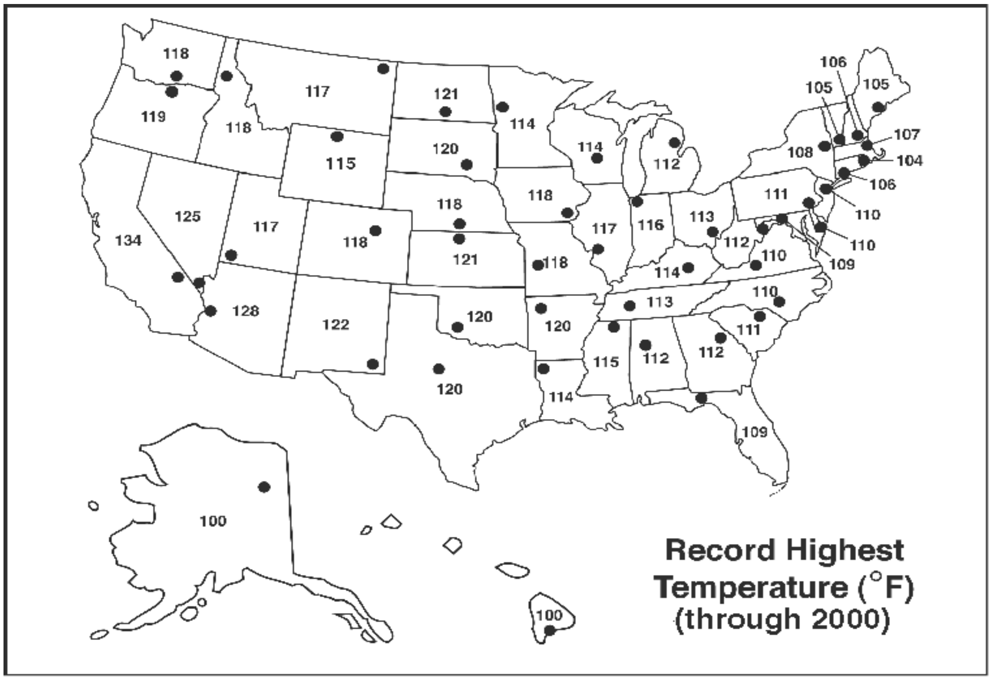


Figure 33: The highest temperature ever recorded per State. Courtesy of the National Climatic Data Center/NOAA.

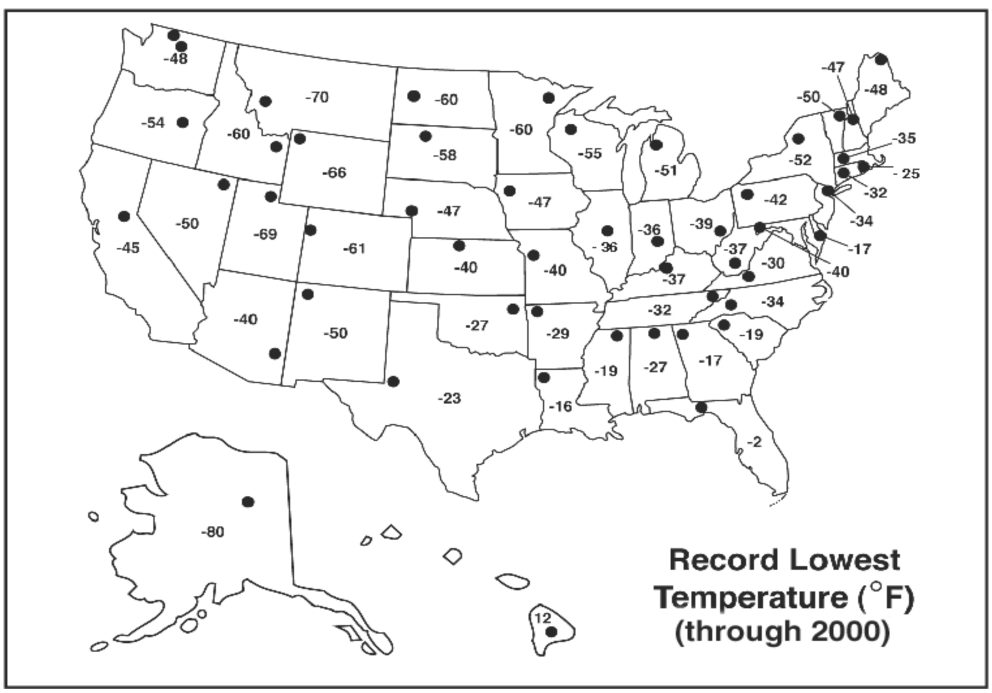


Figure 34: The lowest temperature ever recorded per State. Courtesy of the National Climatic Data Center/NOAA.

On January 22, 1943 the temperature at Rapid City, South Dakota increased by 49 degrees in two minutes while at Spearfish, South Dakota decreased by 59 degrees in 27 minutes. A recent example is the 70 F temperature drop on March 8, 2005 in the East Coast in just a few hours. The highest ever temperature variation in a day in the world is a fall of 100 F (44 F to -56 F) on January 23-24, 1916 in Browning, Montana.

If we consider longer time scales and compare the average thermal amplitude between the coldest and warmest month in regions in both hemispheres we find that in general the thermal amplitude increases as we go to higher latitudes. This makes sense because at high latitudes there is very little light in the winter and very little darkness in the summer. This results in great differences between the average winter and summer temperature. If we want to have a fair comparison of the severity of the difference in thermal amplitude, we should normalize it with respect to latitude. In this case we will find that the United States has the highest amplitude after the region in northeastern Siberia, Kazakhstan, the region of northern China, and Mongolia.

The fact that all possible air masses can ravage the United States is, however, half of the problem. The reason is that, apart for affecting its weather individually, they can also affect it in combination.

Note: In the description of cumulonimbus clouds in the previous discussion we stated that the stratosphere acts like a lid not allowing the air to rise anymore. We can now explain why. Above the tropopause the air is warmer than below the tropopause (figure 9). This as we discussed above represents a stable situation, which (see figure 32) does not allow rising motions.

PART III

Stormy weather

7. Midlatidude storms

Miniskirts were in style then, but not the best for a snowy, windy night. 16 inches of snow slows the frenetic pace of Manhattan.

Image ID: wea00957, Historic NWS Collection
Location: Manhattan, New York
Photo Date: February 10, 1969

Waterloo, 15 June 1815. Napoleon's "Army of the North" is preparing to face the Anglo-Dutch and Prussian armies in one of the most important battles of history. It is midday and clouds are gathering from the west since morning. Napoleon summons his chief meteorologist Jean Claude Attivo to discuss the weather conditions. It takes only one look at the weather map for Depuis to form his opinion "A weather system with active warm and cold fronts is approaching from the west. Rain is a certainty, heavy rain most likely. In either case the field will not be dry enough to contact the battle. Even though we are superior, we should not risk it. Postpone the battle for a few days".

It would have been that easy for Napoleon. Unfortunately for Napoleon, however, this version of the battle of Waterloo is a figment of my imagination. At that time no weather maps were available (it will take many decades before routine weather maps will be produced) and no such thing as chief meteorologist existed (let alone with a name like this). Napoleon, like many other generals in history, was at the mercy of weather.

Napoleon's plan was to attack the part of the Prussian army commanded by Prince Blücher situated near the village of Ligny, on the 16th of June 1815. Once he dealt with them, the next day he would attack the Anglo-Dutch alliance led by the Duke of Wellington and located near the village of Quatre Bras. However, the attack was delayed because one of his corps was late in arriving and taking up its position. This delay left fewer daylight hours available for the battle. In the beginning the Prussians put up a good fight. Victory was not coming easy for Napoleon. Hoping to secure the victory, at about 7:30 pm Napoleon ordered his loyal Imperial Guard to launch an attack. Soon after that, however, a strong thunderstorm presumably associated with a cold front, poured heavy rains in the battlefield, making the use of muskets impracticable. As a result the soldiers engaged in person-to-person fights using their bayonets. The Prussians were forced to retreat, but their casualties were not as great as they would have been had the French been able to use firearms. This in turn allowed the Prussian to reorganize and join the Anglo-Dutch forces later.

On June 17th, the attack on the Anglo-Dutch army was also delayed. Due to soft ground, Napoleon decided to begin the attack at midday rather than in the morning. Wellington, having heard of the Prussian retreat, decided to withdraw to a better position near the village of Mt. St. Jean, 4 km southeast of Waterloo. The retreat started at about 1:00 pm. Thus, rather than engaging in a battle, the French got involved in a pursuit. Then, at about 3:00 pm a severe thunderstorm broke out in the area, which turned the ground into quagmire. As a result, the pursuit slowed down as all three French arms (artillery, cavalry, and infantry) had to congest on the only paved road, the narrow Brussels road. This is how British officer, Captain C. Mercer, of the Royal Horse Artillery describes the weather[3]:

> *The sky had become overcast since the morning…large isolated masses of thundercloud, of the deepest, almost inky black, their lower edges hard and strongly defined, lagging down, as if momentarily about to burst, hung suspended over us, involving our position and everything on it in deep and gloomy obscurity…The first gun that was fired seemed to burst the clouds*

[3] Mercer, C., 1969 (reissue of 1927): *Journal of the Waterloo Campaign.* Kept throughout the Campaign of 1815 by the late General Cavalie Mercer. With an introduction by M. Glover and P. Davies.

> *overhead, for its report was instantly followed by an awful clap of thunder, and lightning that almost blinded us, whilst the rain came down as if a water-spout had broken over us.*

The rains continued through the night and stopped between 7:00 and 8:00 am on the 18th. Napoleon set out with general Drouot to examine the condition of the fields. It was decided that 9:00 am (the intended time for attacking) was too soon. The ground will not be dry enough for battle. Thus, for the third time in three days the attack was delayed. This time, however, the delay will prove disastrous for the French. Because of the delay the Prussian army was able to join the Anglo-Dutch army. The combined allied forces outnumbered the French and led them to a decisive victory. Napoleon lost his throne and in Vienna the allies redrew the political map of Europe thus changing the path of history for ever.

This is not the first time a weather phenomenon influenced history. There are many examples from all over the world that can testify to this[4]. The weather during the battle of Waterloo, however, introduces us to a different weather system from what we have discussed up to now. In the previous chapter the first way by which a storm can form was introduced. For that kind of a storm the only ingredient we need is a strong rising motion. This condition is satisfied usually in the summer in areas where the contrast between the heating over land and the heating over nearby water is great. Such storm development is daily news in Florida in summer. During the day the strong sun heats up the land much more than the ocean. The flow at the surface, which is normally coming from the east, is maritime in origin and thus colder than the surface is traveling over. The colder moist air in contact with the much warmer underlying surface gets warm and rises. The ensuing rising motions over land are strong enough to built cumulonimbus clouds, which result in afternoon showers or thunderstorms. This mechanism of storm formation will also occur in places where we have permanent rising motion, for example at the equator and in any other area where the surface is heated enough for rising motion to commence.

The above mechanism for storm development does not require interaction between different air masses. In our discussion up to this point we simply assume that some air mass occupies or travels over an area and inside it some air may begin to rise and possibly produce clouds and precipitation. However, individual air masses move around and it is common for different air masses to collide over an area. It thus possible, a continental polar (cold and dry) and a maritime tropical (warm and moist) air mass to meet at some point in time and space. If you recall our discussion in chapter III, cold dry air is much heavier than warm most air. Thus, when a continental and a maritime air mass collide they don't mix to produce a happy medium. Rather, they begin to push each other like two (American) football players trying to immobilize each other. But as will happen

---

[4] An interesting collection of papers on this topic has been published by the Bulletin of the American Meteorological Society. One example is the paper by J. Neumann, 1993: Great historical events that were significantly affected by the weather. Part 11: Meteorological aspects of the battle of Waterloo, Vol. 74, pages 413-420.

with the football players, the heavier air mass will win. The heavier air will go under the lighter air and will lift it. This is what happens when you open the bathroom door after you have taken a warm shower. You feet get cold as colder (and heavier) air from the room next to the bathroom, enters the bathroom and lifts the warmer air to the ceiling. This action creates a three-dimensional wave in the atmosphere. In order to picture how this wave looks and what it will do, imagine the following experiment.

Fill up your bathtub with water. Then place your hand at the bottom on one end and vertically raise your palm rapidly. This action will cause water to splash upwards exactly where the lifting of your hand is taking place. Now, what do you think you will observe on the other end of the bathtub? The motion of your hand creates a wave in the bathtub. Since this wave cannot move the bathtub, water at the other end slides over the bathtub and spills on the floor. Thus, in this example, we see that the generated wave is characterized by a lifting of water on one end and sliding over the bathtub on the other end. Now think of water as the warm air and your hand as the cold air. The cold air being heavier goes under the warm air and lifts it up. This creates a wave in which the warm air tries to push the cold air aside. This is not possible because warm air is lighter and as a result, having nowhere to go, the warm air slides over the colder air to the north. This action continues as the cold air keeps on going under the warm air (this is like repeating the lifting of you hand many times as if you wanted to remove all the water from the bathtub). This action in the real atmosphere will continue until all the warm air is lifted from the ground.

The following figures show steps in the development of a midlatitude cyclone as viewed in the horizontal (for example, in a satellite image). First the cold air mass from the north and the warm air mass are approaching each other. As we mentioned in the previous chapter air masses are associated with high pressure systems thus the sky is initially clear. The pressure is highest at their centers and decreases as we approach their boundary. By definition then they form at their boundary a *low pressure front* or *stationary front* (figure 35).

Soon after that the cold air goes under the warm air and lifts it. This as we discussed above this creates a wave. This wave is characterized by a *warm* front (the front behind which we find the warm air; red semi-circles), a *cold* front (the front behind which we find the cold air, blue triangles), and a *warm sector* where the warm air is being squeezed (figure 36). This system is embedded in the general circulation of the atmosphere and is carried by the upper air flow[5]. The whole action of the wave causes the air in the horizontal to rotate counterclockwise or cyclonically. The cold front advances faster than

---

[5] The fact that storms are coherent systems that move with the upper air flow and not with the surface winds was not realized until the year 1743. On November 2, 1743, Benjamin Franklin was set to observe a lunar eclipse in Philadelphia. The surface winds at that day were northeast. The eclipse, however, was obscured because of clouds associated with a hurricane off the Atlantic Coast. Afterwards, Franklin learned that in Boston the eclipse was not obscured and that the storm arrived there later. Franklin realized that the storm was moving northwards, which was opposite to the surface winds. He then concluded that weather systems move irrespective of the surface winds. This was an important new concept in the study of weather.

the warm front because it is pushed by heavy cold air (whereas the warm front is pushed by lighter warm air). Therefore the cold front is catching up with the warm front and begins to overtake it. The part of the warm front overtaken by the cold front is called the *occluded* front (figure 37). Finally the cold front overtakes the warm front completely, which amount to removing all the warm air from the ground. Thus, at the end of this action the cold air rules the surface and the warm air the upper levels. This is interesting because what we now have is warm air on the top of cold air, which is a situation that will not develop rising motions. Warm air in contact with cold air cools and does not rise. Consequently, at the end of this action the atmosphere is stable and the storm is over. However, what is more interesting is what ensued in between.

Now we know another mechanism for the air to rise. Bring together warm and cold air and naturally the warmer air will be forced to rise. The difference in temperature between the warm and cold air defines how strongly the warm air is lifted. The colder the air the

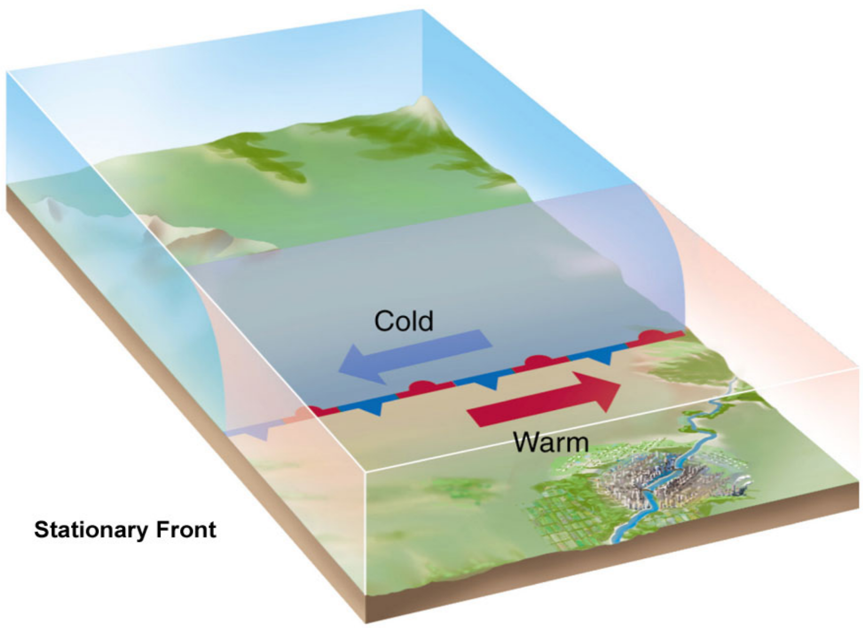


Figure 35

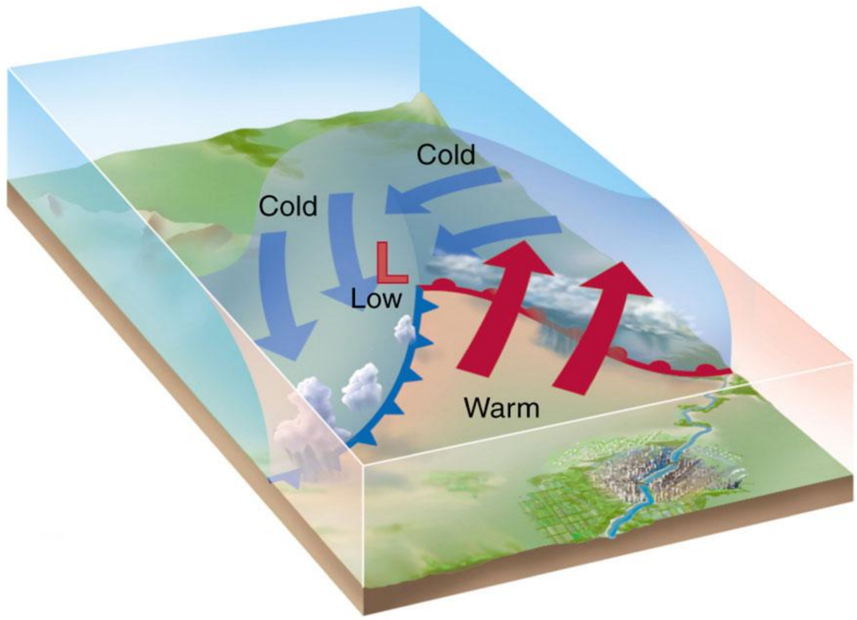


Figure 36

heavier it is and the warmer the air lighter it is. Thus, the greatest the contrast, the stronger the lifting will be. And the stronger the lifting, the thicker the cloud will grow. This contrast is greatest sometime during April and May when the north is still very cold and the south has warmed sufficiently. It is not surprising that this is the time when the Midwest (the favored meeting place between the polar and the tropical air) experiences some of its most severe storms. By definition the part of the wave where this lifting is taking place is called the cold front. The cold front separates the advancing cold air from the receding warm air. It is characterized by cumulonimbus clouds and stormy weather when the contrast between the cold and warm air is great, and cumulus clouds when the contrast is weak (figure 37).

At the other end of the wave, the warm air is forced to slide over the cold air. This is not a lifting process, however. Sliding-over is a mostly horizontal movement. Therefore, on this end we will have warm air sliding over cold air, which if the contrast between cold and warm is large enough will form clouds in the horizontal. By definition again the part of the wave where the sliding begins defines the warm front (figure 37). The further away from this front the higher the clouds will form. The highest clouds are cirrus clouds and they are the first to appear when such a system is approaching. Progressing lower level clouds such as cirrostratus, altostratus, nimbostratus, and finally stratus follow them. Such whether systems require two different air masses in order to form. For this reason they most commonly occur in midlatitudes. They are called midlatitude frontal systems or midlatitude cyclones. Most of the weather associated with these systems happens along the cold front. The clouds associated with the warm front do not produce precipitation unless the sliding-over motion has a significant vertical component to

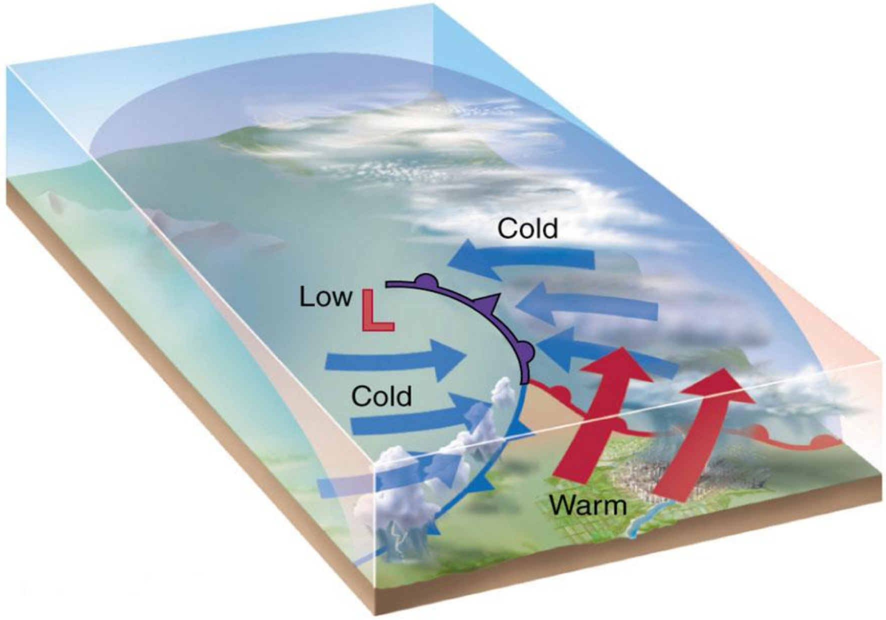


Figure 37

develop nimbostratus clouds. Still the weather with a warm front will not be severe. The weather associated with warm front is rather nice. Recall that what is in the warm sector is a warm air mass. In other wards a high pressure system associated with clear skies and warm temperatures. We should not expect to find any clouds in the warm sector except maybe some high cirrus clouds blown from the top of the cold front cumulonimbus clouds.

As we discussed previously, cold air from the north and warm air from the south have no restriction moving all over the United States. As a result, frontal systems develop all the time in all regions of the United States. Once they form, they are carried by the flow of the atmosphere until they dissipate. Thus the sequence of weather with a midlatitude system can be summarized as follows: As the system is approaching high level clouds appear, which are followed by progressing lower clouds. As the warm front approaches pressure drops (recall that both fronts were born from the initial low pressure front; thus as either one approaches pressure will fall). Some precipitation may develop but it is usually light. After the warm front passes, pressure begins to increase, the skies clear, and it nice and warm. This lasts a day or two and then the cold front approaches. The pressure begins to drop again and the sky to the west appears dark and threatening. Soon the front arrives and thunderstorms roll over the area. Once the cold front passes pressure begins to increase again, the skis clear, but it turns cold. We are now behind the cold front and at the mercy of the cold air advancing from the north. This whole sequence of events is most dramatic in winter and early spring when the contrast between an mP and a cT air mass is the greatest.

Such systems develop in the United States all the time and due to its geography these systems often become very severe. For example, midlatitude cyclones can also form east of the Rockies as warm dry air descending from the mountains encounters warm and humid air flowing northward from the Gulf of Mexico and cold dry air traveling from the north. The warm and dry air is a modified maritime polar air mass, which has invaded the country from the west coast. As the cool moist air is forced to rise over the mountains, it develops precipitation that falls on the west side of the Olympic, Cascade and Rocky Mountains. By the time this air begins its descent on the other side, it has lost its entire vapor to precipitation and it is thus very dry. As it descents (in effect sinks) it gets warmer. By the time it reaches the Great Plains it has been modified to warm and dry air (this warm dry mountain flow is known as *Chinook* wind; Chinook in American-Indian means 'snow-eater'). These type of storms formed in the northern part of the Rockies are called *Alberta Clippers.* They form in an environment where the surface air east of the Rockies is colder than the one in the southern Rocky Mountains. They move rather fast and produce snowfall of the order of 6-8 inches. Sometimes, they can produce rather hazardous conditions. For example, on April 11, 2001, such a storm developed along the New Mexico-Colorado border and tracked northeastwards. By the time it had reached the province of Ontario, it had produced 37 tornadoes, large hail and strong winds in several states in its path.

When the cold air from the north is extremely cold and the winds exceed 35 miles per hour, the storm is called a *blizzard*. Blizzards combine the effects of frigid cold temperature, strong winds and snowfall. They paralyze the northern Great Plains as well as the eastern part of the country as they easily bring wind chills in the vicinity of -40 F, and poor visibilities due to blowing snow. On January 10, 1975 extreme blizzard conditions brought wind chills in Minnesota to -80 F. If not properly dressed, blizzard conditions can be extremely hazardous. Your body temperature could decrease to the point where the body shuts down to preserve heat. Organs such as brain and heart are affected and death ensues. Even if people do not die, their flesh may freeze and suffer frostbites. The term "blizzard" was introduced on March 14, 1870 during a winter storm in Iowa and Minnesota. Blizzards develop every year in the United States and sometimes more often than anybody would wish. In the winter of 1996-1997 nine blizzards occurred in the Great Plains. The State of North Dakota was declared twice a disaster area, with Fargo receiving 117 inches of snow. Never before was North Dakota declared a winter disaster area twice in a year. Only in January these blizzards caused over $30 million in damages to farmers. Ten percent of the State's cattle herd died and 200,000 pounds of milk was wasted because it could not be delivered on time. When melting begun in late spring, the excessive snow on the ground translated into record flood levels adding to the already long suffering of the people in that area.

Midlatitude cyclones formed along the East and Gulf Coasts can be even more severe. Unlike their Rocky Mountain counterparts, they form close to water. This has several effects. First, the closeness to water makes their vapor content higher. This allows for more condensation. The heat release from the condensation heats up the air and contributes to rising motions and the development of clouds. Secondly, water in winter is warmer than adjacent land areas. As a result, the air in developing cyclones over water is heated more than the air in cyclones developing over land. Furthermore, this contrast in temperature maintains a *thermal boundary* along the coast and acts as an additional energy source for the developing cyclone. This contrast is enhanced when the continental polar air mass colliding with the warm moist air is very cold. Moreover, when a Gulf storm reaches the East Coast, additional water vapor can be supplied by flow of moist air from the Atlantic Ocean.

Storms that form along the Gulf coast can track either along the Mississippi-Ohio River valley or along the Gulf Coast and up the East Coast. Their formation can be very rapid and the development very strong. These storms, which can also be classified as blizzards (when the temperature of the polar mass is very cold and the winds are very strong), cause big time problems. In New England, they call the East Coast storms *Nor'easters* because of the northeast winds blowing when a storm is approaching. Some of these storms have become legendary. The blizzard of 1888 is credited as the most devastating one to hit the northeast. It was formed on 11 March 1888, as a developing cyclone over Georgia moved eastward toward the East Coast. The temperature of the cold air mass was in the teens. As it approached the coast it was fueled by warm oceanic flow of 70 F. This great contrast caused the storm to develop and keep on developing as the storm and the warm moist air inflow were driven up the coast toward New England. For some reason (not well know since there was hardly any data then) the storm stalled over the New York/New England region pounding the region for two days with very strong winds (in the vicinity of 80 miles per hour) and plenty of snow. Albany and Saratoga, New York, received 47 and 58 inches of snow, respectively. The blizzard, which was also referred to as the Great White Hurricane, claimed the lives of about four hundred people.
More recently, on February 6, 1978, the Northeast Blizzard of 1978 pounded the northeast with winds gusting to ninety-two miles per hour and fifteen feet surf. More than fifty inches of snow fell in several places in the path of the storm, which claimed ninety nine lives and stranded 39,000 people.

Another such famous storm is the superstorm of 12-14 March 1993. This storm, which has been called the "storm of the century" was developed off the coast of Texas and tracked eastward and then northward along the East Coast. This storm developed so greatly that reached wind speeds up to 110 miles per hour. These winds produced a rise in the sea level comparable to that of strong hurricanes. It is estimated that the amount of snow that fell in the states on its path is equivalent to the volume discharged by the Mississippi River at New Orleans in twenty days. Birmingham, Alabama, Chattanooga, Tennessee and Mt. Mitchell, North Carolina received records snowfall (17, 20 and 50 inches, respectively). Every airport on the East Coast was closed. Two hundred forty three deaths were blamed on the storm and the total damage is estimated at about $4 billion.

As we discussed in the previous chapter, when the vertical temperature structure of the air is right, snow may melt to produce other forms of precipitation, such as ice pellets, freezing rain or a mixture. Ice producing storms can be extremely dangerous as they make driving and walking conditions very hazardous. A notorious such storm (considered the worst ice storm by damage) is the 1998 ice storm. This storm occurred in the period 4-9 January 1998. It moved from Lake Ontario eastward and affected the provinces of Quebec, New Brunswick and Nova Scotia and the states of New York, Vermont, New Hampshire and Maine. This freezing rain producing storm deposited up to three inches of ice on everything on its path. Half a million homes in the United States and almost two million homes in Canada were without power for days. The total damage edged $1.5 billion the United States and $3 billion in Canada. In all likelihood, the United States may hold the world record of the largest geographical area to be covered by such a storm. In 1951, from 28th of January to 4th of February such a storm covered an enormous region from Texas to the New England states and deposited a layer of ice that in some places was four inches thick[6].

In the mountains of western United States, storms can develop when Pacific weather systems or simply cool moist air pass over the mountain ranges. The mountains provide a natural lifting mechanism that forces the air to rise, thus re-enforcing the precipitation producing engine. These storms are the main snow-producing storm in the western mountain ranges.

While other regions on Earth can experience blizzards and other severe midlatitude cyclones, no other region is so open to combinations of all possible air masses. In Europe for example, air masses arriving from the Arctic are warmer because they travel over water. Continental polar air masses may develop in Siberia, but because of the general upper airflow they tend to move eastward. The location of an extensive mountain range (the Alps) in an east-west direction across southern Europe acts as a barrier not allowing cold air from the north to collide with warm air from the south. Similarly the warm and moist air masses in southern Asia cannot penetrate the mountain ranges to come in contact with continental polar air masses formed in Siberia, which move over the Pacific Ocean. In other regions such as Australia, Africa, and South America polar continental air masses do not occur. In this case as well, the United States appears to be the most vulnerable of the inhabited regions on Earth. This is supported by the following maps (figure 38), which show the percent of time an area in the world is under storm conditions. If we exclude the oceans the United States appears to be the most active place. These maps are produced by NASA and are available from the Atlas of Extratropical Storm Tracks. They represent the picture only from September1996 to February 1997. However, a similar picture is present in any other year. The general tendency is for storms to track northeastward from the central-northern Pacific, stir southeastward over the United States, then to turn northeastward toward northern Europe and over Siberia, then southeastward through Manchuria, Korea, Japan back to the Pacific Ocean.

[6] Source: World map of Natural Hazards, Munich Reinsurance Company.

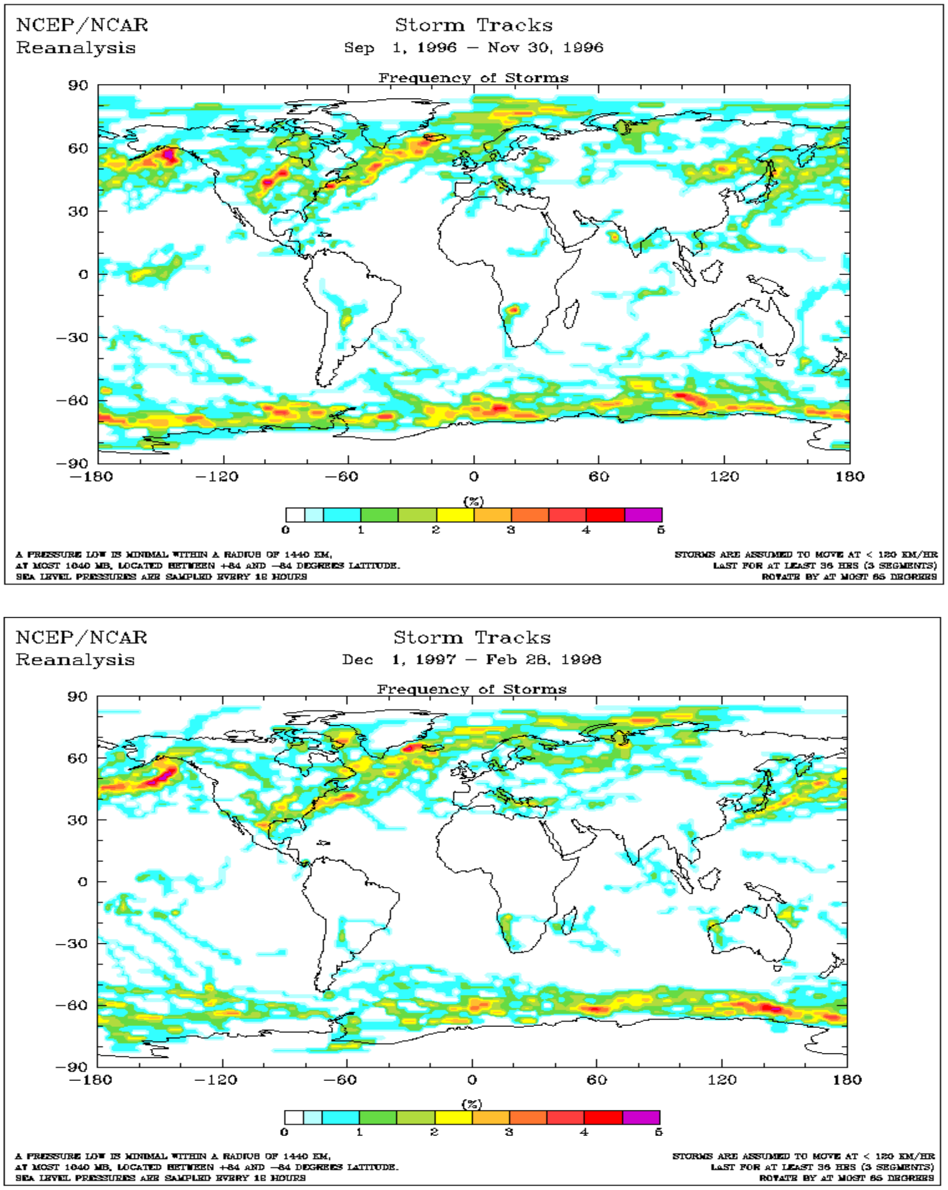


Figure 38: Storm tracks in the period 1 September - 30 November 1996 and 1 December 1997– 28 February 1998, respectively.

Worst storms in USA timeline (to 2006)

February and March 1717

A series of four storms struck New England in "The Great Snow of 1717." Four feet of snow blanketed the ground and drifts stretched 25 feet high.

January 1772

A heavy snowstorm dropped three feet of snow across Maryland and Virginia, stranding both George Washington and Thomas Jefferson in their homes. It became known as "The Washington and Jefferson Snowstorm."

November 1798

"The Long Storm" was said to be the snowiest on record for November. A foot-and-a-half of snow fell from Maryland to Maine, and New York City received 18 inches. The three-day drop was followed by a long, severe winter.

December 1811

Ships and harbors were damaged in New York City, Long Island and southern New England when gale-force winds and dangerous tides ravaged the shores.

January 1857

The eastern seaboard experienced "The Coldest Storm" with temperatures dipping to 9-degrees below zero Fahrenheit. Snowfall was between one and two feet deep.

March 1888

"The Blizzard of '88" battered New York City with below-zero temperatures, strong wind gusts and deep snow drifts. Several other cities were left without communication and transportation, but New York City suffered the most damage.

November 1898

"The Portland Storm" is named after the S.S. Portland, the ship that sank off the coast of Cape Cod, Massachusetts, in the snowstorm. The blizzard brought moderately heavy snows to the region.

January 1922

Almost 100 people were killed when the "Knickerbocker" storm dumped more than 2 feet of snow on Washington, D.C., causing the roof of the Knickerbocker Theatre to collapse.

December 1947

A post-Christmas storm covered New York with two feet of snow in 24 hours.

November 1950

"The Great Appalachian Storm" resulted in the deaths of 160 people after rain and snow pummeled the region for two days with record wind gusts in late November 1950. Pittsburgh received almost 30 inches of snow, Cleveland was covered in two feet and West Virginia, western Pennsylvania and eastern Ohio suffered in equal proportions.

January 1967

It took Chicago more than two weeks to clear highways after a series of winter storms battered the west coast of Lake Michigan. Heavy looting took place in unattended stores.

February 1969

A foot-and-a-half of snow blanketed New York City and buried snowplows in their storage lots. The city hired 10,000 snow shovelers and workers to clear the streets.

February 1977

Twenty-eight people were killed when a storm hit Ontario, Canada, and western New York state. Thousands of vehicles were stranded on the highways. The city of Buffalo was shut down for more than a week.

February 1978

Record snowfall, blizzard-like conditions, floods and hurricane winds paralyzed New England from Long Island, New York, to Boston for a week in 1978. The "New England Blizzard" stranded thousands in their cars and homes.

March 1993

The "Blizzard of the Century" raked the mid-Atlantic states from Alabama to Massachusetts. Several other states were hit with tornadoes, thunderstorms and floods. Snow fell at a rate of one-to-two inches an hour in some areas.

January 1996

The blizzard of 1996 caused more than 100 deaths in the eastern United States. To make matters worse, two more storms pummeled the region within the following week-and-a-half.

January 1998

A severe ice storm over the eastern United States and Canada in early January killed dozens, crippled utilities and caused damages estimated in the billions. Sixteen deaths in the United States and 28 in Canada were attributed to the storm. Hundreds of thousands lost electrical power and damages were estimated to be at least $1.4 billion for the United States and near $3 billion for Canada.

January 1999

A blizzard over the Midwestern United States in early January dumped 22 inches of snow in Chicago, Illinois. The storm also produced heavy snow over parts of Wisconsin, Indiana, Michigan and Ohio. Seventy-three deaths were attributed to the storm. Damage estimates ranged from $300 million to $400 million. President Clinton declared 45 Illinois counties and some parts of Indiana as disaster areas.

December 25, 2004

A major winter storm brought snow to south Texas and a rare white Christmas. It was only the second white Christmas in the history of Corpus Christi, which received 4.4 inches of snow.

January 22, 2005

A fierce blizzard slammed the Northeast region for two days, virtually shutting down parts of the country. Massachusetts, the hardest-hit state, recorded 38 inches in some areas. The blizzard was the fifth worst to hit Boston since 1892.

December 2005

An ice storm that raged through Georgia, Virginia and North and South Carolina left more than half a million people without power in the days that followed. The storm was blamed for hundreds of accidents. As it moved up the East Coast, at least four deaths were reported because of the storm.

February 2006

The storm swept up from the Midwest into the Northeast Friday, causing temperatures in some parts of western New York to plunge from 60 degrees Fahrenheit to below freezing within a few hours. Schools either did not open or closed early, and at least 328,000 people were without power in the afternoon.

9. Thunderstorms

Lightning storm over Boston

Image ID: wea00606, Historic NWS Collection
Photo Date: 1967?
Photographer: Boston globe

On the warm and humid day of 17 May 1991, St. Albans High School's lacrosse team was preparing to challenge their rivals, Landon High School, in the final game of the season. More than 1,000 parents and students were there to witness the battle. As the second quarter started, a storm began moving in. The rain forced the officials to delay the game; a controversial decision because if the game were cancelled a disaster would have been avoided. The spectators took shelter in the pavilion, but the students and players preferred to stay outside and away from their parents. Suddenly, a large explosion was heard. A lightning hit a tree and then radiated out along the ground. Before anybody could react, a living nightmare ensued. Bodies were lying unconscious on the ground. By the time the injured students were taken to the hospital several of them were dead. Lightning, one of nature's most magnificent and unforgiving displays had stricken again.

Stormy weather is associated with heavy precipitation and strong winds. In general, clouds capable to deliver such conditions are cumulonimbus. When these clouds are accompanied by lightning and thunder they are called thunderstorms. A thunderstorm is not just a cumulonimbus. It is a huge cumulonimbus, which grows to be 40,000 feet tall. A thunderstorm reaches the top of the troposphere and often has enough momentum to penetrate the lower levels of the stratosphere. A thunderstorm develops when the rising motion is very strong, in other words either when the heating at the surface is very strong or when a warm and humid air mass collides with a much colder air mass. In the former case the thunderstorm occurs within an air mass during the warm humid summers in the southern and eastern United States. In the latter case it forms along the cold front where the warn air is lifted by the colder air.

In either case, there are three distinct stages in the lifetime of a thunderstorm. The first stage is called the cumulus stage. In this stage cumulus clouds grow and merge slowly building a cumulonimbus cloud. Rising motions dominate the developing cloud. Once precipitation develops it begins to fall. The effect of falling precipitation is to create downdrafts, which oppose the rising motions inside the cloud. We are now in the second stage; the mature stage. With precipitation continuing to develop, downdrafts begin to dominate the cloud. Eventually they cut off all rising motions and the cloud enters its third stage called the final or dissipation stage. Since only sinking motions are inside the cloud, the sinking air warms, its relative humidity drops and because of that the cloud begins to evaporate.

Thunderstorms associated with a cold front may organize themselves into a long continuous line called a squall line, which can be hundred of miles long. Thunderstorms formed within a single air mass may organize themselves into thunderstorm complexes that have areas as large as the combined area of Missouri, Iowa and Illinois. Both, squall lines and thunderstorm complexes bring with them a sustained thunderstorm activity that may last more than a day.

A thunderstorm is considered as severe when one or more of the following criteria are satisfied: hail with a diameter of three quarters of an inch or greater, wind gusts of 58 miles or stronger, and/or a tornado. The most severe of thunderstorms are the so-called supercell thunderstorms. They are huge single cell thunderstorms, which produce hail that can grow to the size of a grapefruit, 100 miles per hour wind and most of the observed tornadoes. They are different than the other thunderstorms because they rotate. Inside these storms the rising motion is rotating. The rotation is achieved because the wind in the horizontal (the atmospheric flow in which the rising motions are embedded) changes in strength and direction with height in a more dramatic fashion than in typical thunderstorms. This change of the wind speed with height is called vertical wind shear. In environments of strong vertical wind shear, the rising motion breaks from its vertical path and begins to spin. As we will see in detail later this is the first ingredient in tornado formation.

A typical thunderstorm can deliver about four million tons of water! But, this is not the only problem with thunderstorms. Even when they do not spawn tornadoes, they produce wind damage, hail, and, as their name suggests, they generate lightning and thunder. Lightning has been marveled and feared alike since the beginning of time. Naturally, its grandeur and destructiveness was often identified with some deity. For the ancient Greeks it was Zeus, the King of Gods, who used it to punish those who disobey or displease him. In the Viking mythology it was the product of Thor's hammer striking an anvil as he traveled through the clouds. Native American Indians thought that lightning was the result of a mystical bird's flashing feathers. As it moved through the clouds the clapping of its wings produced thunder. Even in the East, Buddha was depicted as carrying thunderbolts. Deification of natural phenomena in the early times of humanity was very common for a simple reason. Something that cannot be explained must be the result of a divine entity. When it comes to lightning, we today understand that it is definitely not Zeus who throws it on to the poor ignorant people.

Observations, have documented that inside the cloud the higher levels become positively charged and the lower part becomes negatively charged (figure 39). Exactly how this happens is not entirely clear. One possible mechanism for this charge separation is that in the cloud the lighter ice crystals, which have positive charge, are carried by the updrafts to the higher levels, whereas the heavier falling hailstones, which have a negative charge, are accumulated in the lower part of the cloud. As the charged cloud moves over ground, friction causes a positive charge to accumulate at the ground. This positive charge follows the outline of the terrain under the cloud. Thus, if a tree or a building is present, the positive charge will from around them.

Nature does not like to be charged either positively or negatively. It much prefers the neutral state. Because of that, given the above set up, a discharge will take place between the bottom of the cloud and the underlying surface. Electrons surge from the cloud base toward the ground in a series of steps called the *step leader*. The step leader is rather faint and forked in structure. The complex geometry of the step leader is due to the fact that during the discharge the charges take a path of *least resistance*. Since the atmosphere is not homogeneous in any respect this path is often complicated. It is like trying to build a road between points A and B in a topographically complex, ragged region. The path of

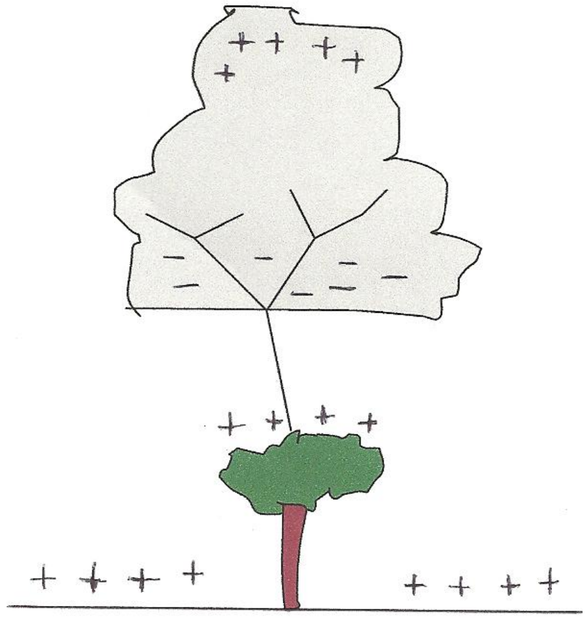


Figure 39: charge distribution with a thunderstorm.

least resistance may not be the straight line connecting A and B. You may think of this process as a process, which opens the channels through which the positive charge on the ground and the surging negative charge will communicate. Once the step leader has lowered close enough to the ground, the positive charges rush upward to meet the step leader and neutralize each other via a powerful stroke. This is the flash we actually see as lightning. Discharges between clouds and the ground are called cloud-to-ground lightning. Cloud-to-cloud discharges between negatively and positively charged regions of two clouds are also possible. Often the leader-stroke process is repeated in the same channel. The subsequent leader is called the dart leader, which proceeds downward easier now that the channel has been opened. The return stroke from the ground is weaker because most of the positive charge has been neutralized. A lightning flash may have four or more dart leaders separated by intervals of about four hundredths of a second. Because our eyes cannot react in such short times it appears that the flash flickers. The electrical energy from a single bolt is about 10 million joules. To put this into perspective, if we were able to harness this energy we could provide electricity for a house for about six hours. Given that approximately 20 billion cloud-to-ground flashes occur in the United States annually, lightning could provide each house in the United States with about two months of free electricity.

Because of the principle of least resistance, chances are that the closest positive charge to the approaching step leader will jump into the opening channel first. As a result lightning tends to strike the tallest objects in the area. This is something that unfortunately the general public does not realize. People, who find themselves outdoors in parks or other open areas in the middle of a thunderstorm, often take cover under trees. This is the wrong thing to do because lightning will strike the tallest objects and in such cases trees are the tallest objects. To maximize your safety you should move away from the trees and try to lay low but not flat on the ground. Once lightning strikes the ground, electricity flows in all directions. If you lay flat you maximize the contact area with the ground, thereby increasing the chance to intercept the diffusing current. The best advice is to crouch and touch the ground with only your feet (preferably only the toes or heels). Definitely, do not argue with the thunderstorm: On May 25, 1987, a man in his boat on a lake in Louisiana stood up and challenged the sky to strike him with lightning. He was immediately hit and died! Unlike with tornadoes, taking cover inside a car is advisable. Metal is a good conductor and electricity flows around the car's frame. Water on the other hand is a lousy conductor. You should not take a shower or come in contact with water indoors or outdoors during a thunderstorm. Also avoid talking on the phone. A sign of an impending lightning is hair standing on end and the so-called *St. Elmo's fire*. St' Elmo's fire refers to the small sparks forming when positive charge accumulates on the tips of objects extending above the ground, such as antennas. If the discharge persists, a blue-green halo may appear. Sailors often observe this phenomenon on the tips of their masts. They have named this phenomenon St. Elmo's fire after their patron saint.

Approximately, 100 people die annually from lightning strokes in the United States; more than from tornadoes or hurricanes. Lightning is also a major factor in forest fires. About 14,000 fires annually and 50 million dollars in timber losses are blamed on lightning. The effects of lightning, however, can be very pleasant. For example, in April 1932 the people of Elgin, Manitoba, had cooked dinner fallen from the sky when lightning killed 52 geese. The losses from the other product of severe thunderstorms (hail) are even more impressive. Every State in the United States is affected by hail. One to two percent of the annual crop of the United States (a value of about $1.3 billion) is lost to hail every year. While hail does not claim many lives it can seriously hurt you. On May 13, 1930, a farmer thirty miles northwest of Lubbock, Texas was exposed to an unexpected hailstorm and was beaten to death by hail. Did you know that almost 85% of all people struck by lightning are male? This may indicate that men spend more time in outdoor sports (such as baseball and golf), or it may be the price men pay for being taller than women (this is a joke!).

Six thousand bolts hit Earth every minute. Compared to the rest of the world he United States is a protagonist in both lightning frequency and in thunderstorm activity. Figure 40 shows the distribution of lightning in the globe and figure 41 shows the days per year when conditions favor the development of severe thunderstorms. In both figures the United States is one of the most active places on Earth, clearly competing with tropical regions where deep cloud development is expected every day. Other regions with severe weather potential include South America, and Northern India and neighbors.

According to the newspaper USA today (6 February 2006), in terms of monetary damage, the worst thunderstorm in the history of US was the one that ravaged Fort Worth, Texas, in May 1995. The total damage was $2 billion, $1.1 of which was attributed to hail. Lightning and flooding from the storm killed 13 and injured over 100 people.

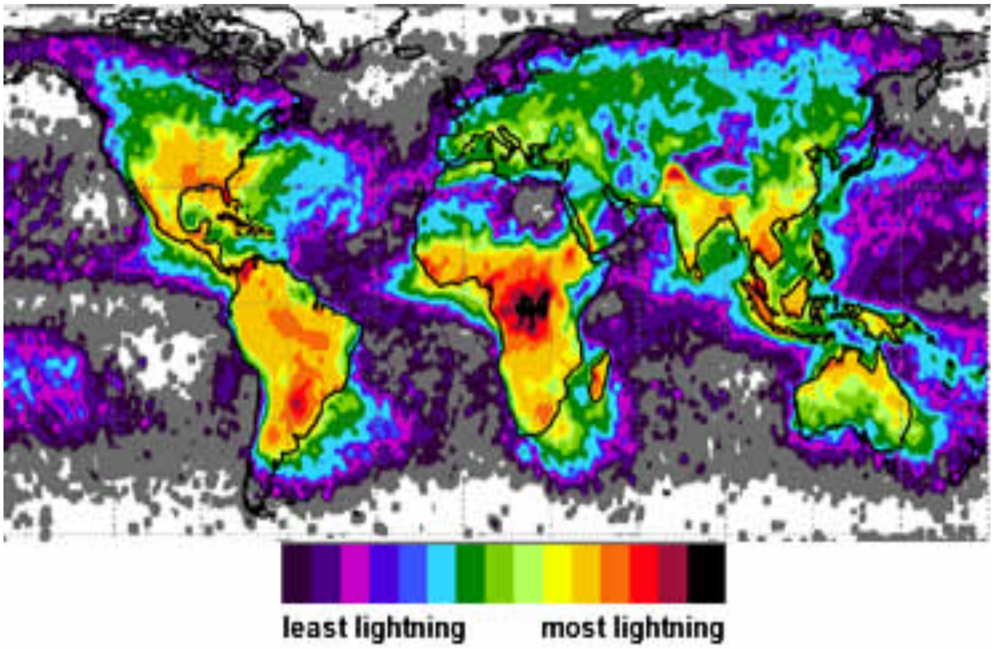


Figure 40. Occurrence of lightning on Earth. Courtesy of the US National Space Science & Technology Center. Dr. Jim Arnold jim.Arnold@msfc.nasa.gov.

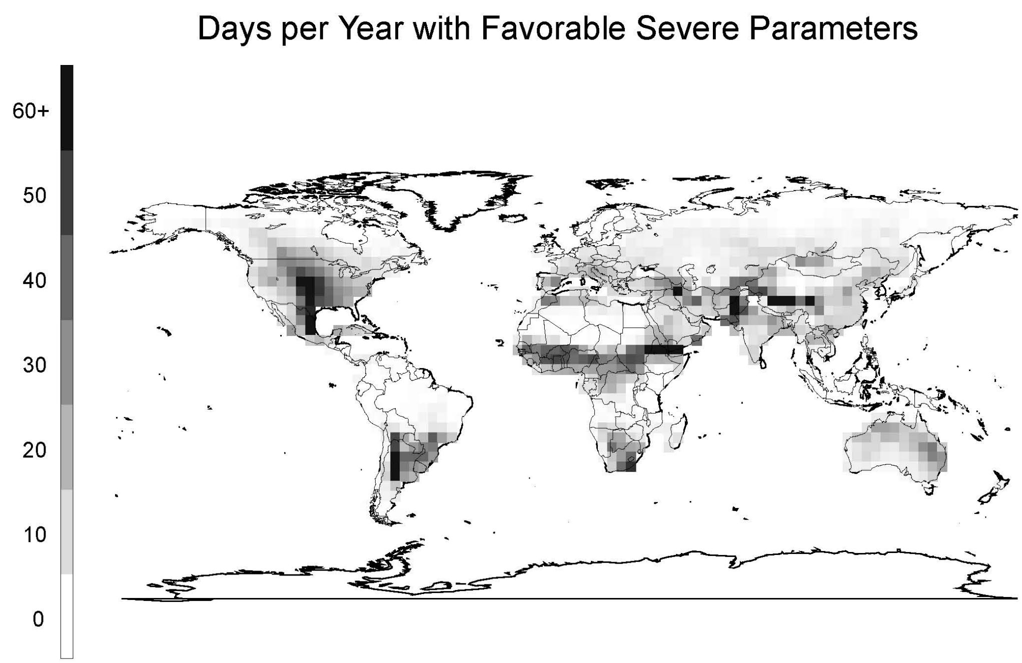


Figure 41: regions with high likelihood of producing thunderstorms. Courtesy of Dr. Harold Brooks.

Learning from a movie

In the movie *Poltergeist* the 7-year old Carol Anne, youngest child of the Freelings, is able to sense and talk to restless spirits, which eventually whisk her into another dimension through her TV set. This story by Steven Spielberg has to do a lot more with ghosts than weather, but in the early stages of the movie, and as the stage is set for the upcoming nightmare, we learn a useful lesson in atmospheric sciences. One night Carol Anne (played by Heather O'Rourke) and her brother Robbie (played by Oliver Robins) have a hard time sleeping because there is lightning and thunder. Their father (played by Craig T. Nelson) in his effort to calm them down explains that an easy way to see if the storm is approaching or is moving away from your house is to start counting the moment a lightning flash appears and stop counting when you hear the thunder. If the number to which you count increases, then the storm is moving away. If it decreases the storm is approaching. This is an accurate way and is based on the following facts. Light travels at the speed of light, which is 300,000 kilometers per second (187,500 miles per second). This is the highest possible speed in the Universe. It is reasonable then to assume that the time it takes for the light of a stroke to arrive to your eyes is zero. Lightning occurs and is sensed simultaneously. The electrical current associated with lightning is extremely hot. Its temperature is of the order of 54,000 F, which is five times hotter than the temperature at the surface of the sun! However, even though the air inside the channel is heated up dramatically, because the channel is infinitesimally narrow this heating does not affect the temperature of the atmosphere. Such high temperatures heat the air in the channel where the charges move so much that it expands explosively creating a shock wave that becomes a sound wave (much like the crackling noise you hear when you throw an ice cube in very hot water; the air inside the cube warms rapidly and expands creating shock waves). This sound wave is the thunder that accompanies lightning. These sound waves travel in the atmosphere at a speed of 0.2 miles per second. This is a much smaller speed compared to that of light. As a result the thunder is not heard the moment the flash occurs but it takes a while depending on how far the storm is. If, for example, the storm is one mile away the thunder will be heard five seconds after the lightning flash is seen. If the storm is moving away then when it is, say, 1.2 miles away it will take six seconds between the flash and the thunder. If the storm is coming toward you then when it is, say, 0.8 miles away the time interval between the flash and the thunder will be four seconds.

10. Tornadoes

Oldest known tornado photo

Image ID: wea00206, Historic NWS Collection (albert.e.theberge.jr@noaa.gov)
Location: 22 miles southwest of Howard, South Dakota
Photo Date: 1884 August 28

Tornadoes are nature's most violent storms. Wind speeds associated with a tornado can exceed 300 miles per hour; a force strong enough to destroy steel-reinforced structures, derail trains and throw automobiles over 200 feet. How do these storms get to be that violent?

As we all know, a special feature of a tornado is the rotating funnel cloud. Rotation is a key ingredient in the formation of a tornado. Somehow the air inside the thunderstorm must begin to rotate. In order for this to happen the rising motion must interact with the winds in such a way as to form a rotating rising motion. A situation that could result in a rotating updraft is the following. Imagine a Ferris wheel that can respond to the existing winds. If the wind speed and direction is uniform with height, then the top, the center and the bottom of the wheel are exposed to the same force. In this case we should not expect the wheel to rotate. If, however, the wind speed is greater on the top than on the bottom the wheel will begin to rotate clockwise with the axis of rotation parallel to the ground. In the atmosphere similar rotation of the air at low levels may be initiated if we have what we call a *strong vertical wind shear*. Vertical wind shear means that the wind is stronger at higher levels than at lower levels. If this difference is great, rotation within air close to the surface creates narrow tubes of spiraling (in the north-south direction) air. As the air at the surface begins to rise (either because of the action of a cold front or because of strong heating at the surface), the rotating tube of air is lifted and drawn into the developing cloud. This process, which is called *tilting*, is responsible for the rotation of the updraft.

This rotating rising motion is called the *mesocyclone* (figure 42 top left). This mesocyclone will then get stretched in the vertical. Exactly how this stretching happens is not clear. Evidence suggests that the lower part of the rising motion inside the cloud is slowed down by other movement in the supercell thunderstorm. As a result the upper part is now rising faster and the entire column stretches in the vertical and shrinks in the horizontal. Another possibility is that the motion accelerates due to extra heating from the latent heat of condensation. From this point on, a law of physics called the conservation of the angular momentum is going to take over and make a tornado. The angular momentum refers to an object that rotates. It is equal to the mass of the object times its rate of rotation times the radius of the object.

Angular momentum=mass x radius x rate of rotation

According to this law, this product remains always the same. For this to happen, if one variable goes up the other two have to change so that the product remains unchanged. For example, if the mass of the object remains constant, an increase in the rate of rotation must cause a decrease in the radius and vice-versa. Similarly, a decrease in the rate of rotation must be accompanied by an increase in the radius and vice-versa. It follows that, if the mesocyclone's radius decreases because of the stretching in the vertical, the rate of rotation should increase. This law is put into practice by skaters. When skaters want to spin faster, they begin spinning with hands and legs extended. Because the hands and legs are extended the radius of the skaters is large. Drawing in their hands toward the axis of rotation decreases the radius and they spin faster. When this happens in the cloud, we have a very fast rotating *low pressure vortex* (figure 42 top right). This low pressure vortex acts like a powerful vacuum, which begins to suck in the air from below the cloud base. As this air rushes in that vortex, it cools rapidly and condenses into a visible cloud (figure 42 bottom left). This is the *funnel cloud*, which appears to descent as the rushing air keeps on condensing. Once the funnel cloud reaches the surface it is called a *tornado* (figure 42 bottom right). When a tornado touches on the ground it picks up dirt or whatever is on its path. However, contact with the ground cuts off the ingredient necessary for its formation and sustainability (the rising air) and the tornado will soon after that die out.

How a tornado looks inside is still an open question. Simply, the extreme winds do not allow direct observations to be made. However, if we believe the testimony of a framer from Greensburg, Kansas who on June 16, 1928 reported looking up into a funnel cloud of a dissipating tornado, then inside the funnel cloud the clouds are rotating and constant lightning zigzagging from side to side creates a brightly lighted interior.

A supercell may produce several tornadoes. Observations, suggest that often a new updraft forms just as the previous tornado dissipated. In addition, some times more than one tornado may be forming at the same time. Thus, a family of tornadoes may be spawn from a supercell. The strength of the winds with a tornado depends on how much the mesocyclone will be stretched. Consider a mesocyclone with a radius of 2 miles rotating at 5 miles per hour. The angular momentum per unit mass will then be 2x5=10 (in some appropriate units). For a typical tornado with a radius of $1/15^{th}$ of a mile, the rate of rotation should be 10x15=150 miles per hour. Thus, thin funnel clouds (often called "rope" tornadoes) can be very devastating even though they are not massive. The size and shape of a tornado does not correlate with its strength.

While there is a good chance that a supercell and a mesocyclone will produce tornadoes, not all of them do. Simply, all the conditions have to be right for a storm to produce a tornado. Also, it is possible to get a tornado without a mesocyclone. In this case we don't have the tubes of spiraling air that form because of vertical wind shear. Rather, differences in wind direction and speed at some level in the horizontal may break the horizontal flow into more or less planar vortices, which may then develop when they interact with updrafts. In this case the tornadoes are weaker. These tornadoes are called landspouts because of their similarity to waterspouts, another tornado vortex which is sometimes observed over water bodies. Other tornado-like vortices include the *dust devils*. Dust devils are associated with dry convection (rising dry air). They form over hot surfaces typically in desert regions, and they are rather weak. Most of tornadoes in the northern hemisphere rotate counter-clockwise (cyclonically). Warm air moving to the north, cold moving to the south, and strong atmospheric flow come in from the west, create a situation in which the storms rotate counterclockwise. Tornadoes usually rotate that same way. Sometimes opposite direction swirls develop under a thunderstorm. About 1 in 100 tornadoes rotate clockwise.

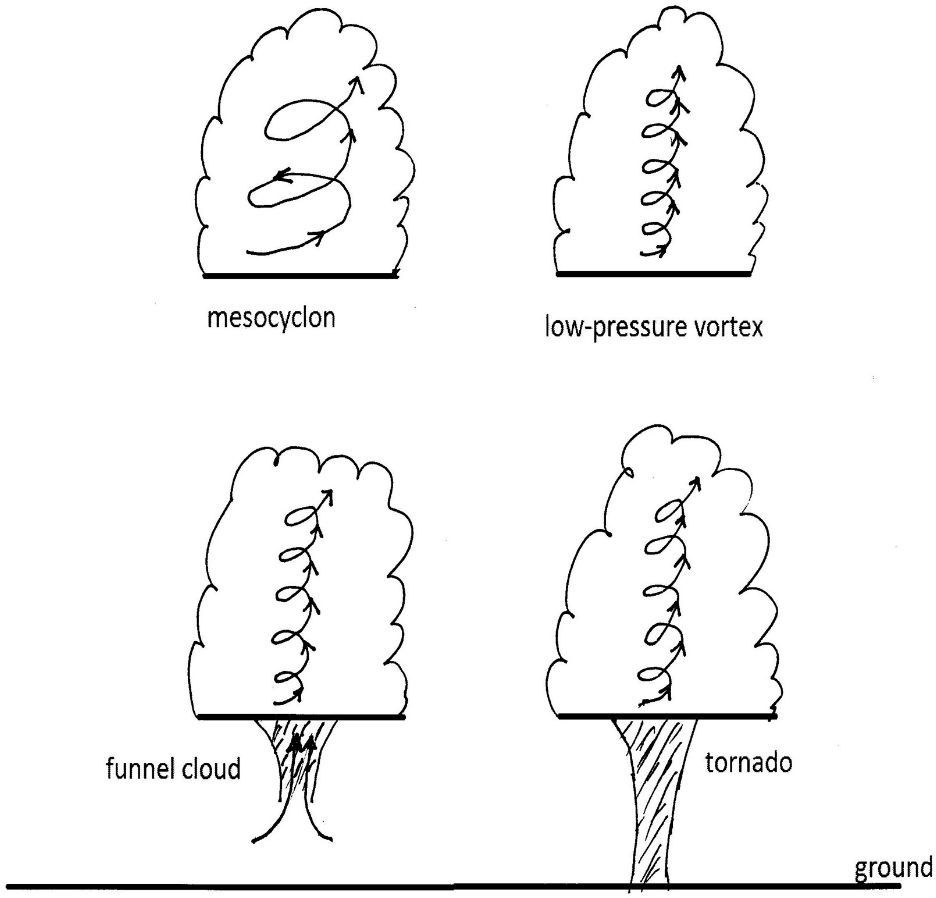


Figure 42: Stages in the formation of a tornado.

Tornados are classified according to their intensity into six categories. The scale used in this classification is called the Fujita scale, after the Theodore Fujita of the University of Chicago.

Category F0 tornadoes are weak. Their winds range from 40-72 miles per hour. Their spoils are limited to broken tree branches and damaged sign boards.

Category F1 tornadoes are also classified as weak. Winds with an F1 tornado range from 73-112 miles per hour. The damages are moderate as they snap trees and break windows.

Category F2 tornadoes are classified as strong tornadoes. F2 tornadoes reach wind speeds up to 157 miles per hour and they can claim large trees and weak structures.

Category F3 tornadoes are also classified as strong. They can pack winds up to 206 miles per hour and can bring severe damages. They can overrun cars and they can remove walls from buildings.

Category F4 tornadoes are really violent. An F4 tornado generates winds up to 260 miles per hour and can devastate house.

Category F5 tornadoes are also classified as violent. The damage is incredible. Winds up to 318 miles per hour can damage steel-reinforced structures and can move automobiles 300 feet.

Seventy percent of the tornadoes in the United States form from March to July, with May being the month with most tornadoes (an average of five per day). The most severe tornadoes tend to develop in late April in the so-called *tornado alley* of the Great Plains, which stretches from Texas to Nebraska. This is the place and the time when strong vertical wind shear is present together with cold air form the north colliding with warm moist air from the south. While tornadoes can occur any time of the day, they prefer the afternoon hours when the air is the warmest and thus the most unstable. However, destructive tornadoes can and are developed away from the tornado alley. For example, in March 1984, 36 tornadoes swept South and North Carolina leaving 59 people dead and causing hundreds of millions of dollars in damage. One of those 36 tornadoes was a category F4 tornado with a diameter of 2.5 miles. Even places like Los Angeles have experienced a tornado. On March1, 1983 a tornado hit the downtown area of Los Angeles damaging 100 houses and injuring over thirty people.

The United States reports on the average 1,000 tornadoes annually. In 1998, 1,424 tornadoes were reported. The year 2004 was a record-setter with over 1,700 tornadoes. The State with the highest incidents of tornadoes per area is Oklahoma followed by Kansas. Every State has experienced a tornado; even Alaska. The least hit State in the contiguous United States is Nevada with 0.05 tornadoes per 10,000 square miles area.

The United States is the tornado capital of the world. Seventy five percent of the world's tornadoes occur in the United States. The following map (figure 43) shows the world distribution of tornadoes. It also shows the major agricultural areas. Interestingly, the majority of tornadoes occur in agricultural areas. This is not because tornadoes are attracted by crops. Rather, crops need moisture to grow and the temperature variation associated with changing seasons; condition found in the same areas.

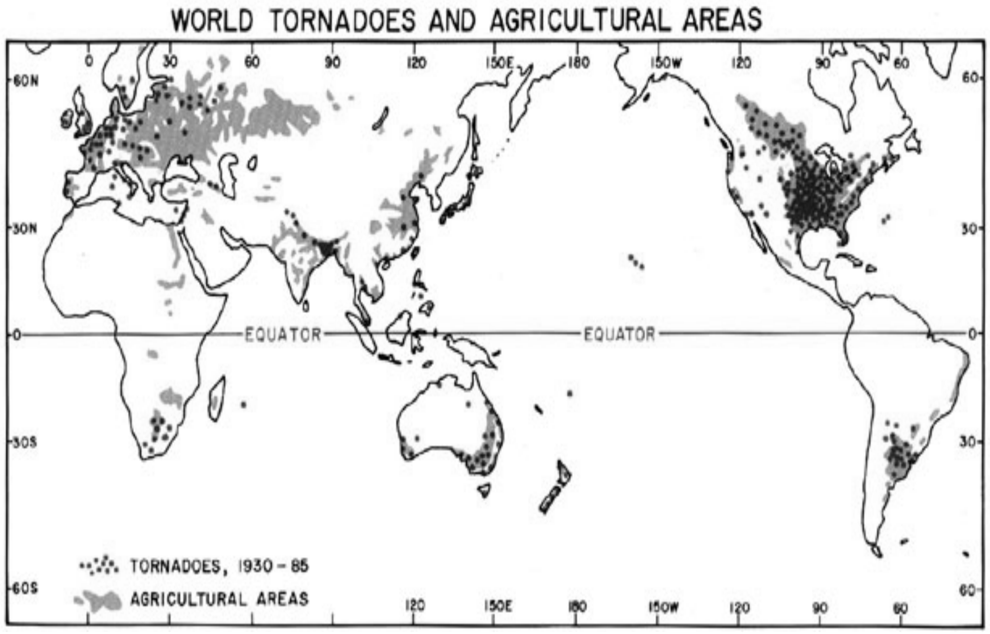


Figure 43: Global distribution of tornadoes. ***(****Courtesy of Dr. T. T. Fujita, University of Chicago)* http://www.windows.ucar.edu/

When the atmospheric conditions favor the formation of a tornado, the weather office issues a *tornado watch*. If a tornado is spotted and reported, then a *tornado warning* is issues. Always when severe weather threatens listen to the radio or television for tornado warnings in your area. When it comes to tornado safety several misconceptions exist. First, unlike in the case of lightning, you are not safe inside a car. As we just discussed cars can be overturned or thrown around by a tornado. Second, highway overpasses do not provide a safe place to hide. This misconception has been propagated by a video on tornadoes showing several people surviving a tornado. This is not correct. The channel below the overpass creates very strong winds, which can lead to serious injuries.
If you are outdoors, you should try to lay low, preferably in a ditch. Do not try to outrun a tornado. First, you may not know what you are getting in to. Other tornadoes may form in the area. Second, a tornado can change direction unpredictably. If you are indoors and a tornado is approaching, go to a place with no windows; a basement if available. If a basement is not available, choose a room with not too many windows and stay in the middle. If you can, get under a table or some other sturdy furniture to protect yourself from flying material. A bathroom may not be a bad idea since plumbing provides extra support for the walls. In all cases protect your head either with pillows or matrices or your hands. If you leave in a mobile home get out and find shelter in a safer place. The myth that mobile homes attract tornadoes is just a myth. Mobile homes stand a greater chance to be destroyed simply because they are very fragile.

Regarding tornado safety, several other myths have been propagated. One of them is that opening windows minimizes destruction because it equalizes the pressure between the inside and the outside of the house. This not only is incorrect, but it makes the situation more dangerous because by doing so we effectively open the door to high-speed winds and with them flying debris. Another myth is that if you seek protection in a basement the best place will be the southwest corner of the basement. Because many tornadoes travel come from the southwest (and thus travel toward northeast) this myth assumes that debris will be blown in a northeasterly direction, avoiding the southwest corner of the basement. However, tornadoes once on the ground do not really prefer a direction. If the house is hit by a tornado it may collapse into the basement. Thus, the safest place in the basement is under a sturdy protection (such as under stairs).

Tornadoes are known to do some strange things. In the movie *The Wizard of Oz*, Dorothy, her dog Toto, and her Kansas farmhouse are taken away by a swirling tornado over the rainbow and into the magical Land of Oz. If you think that this is far fetched listen to this. In 1991, a Kansas (!) tornado sucked a mother and her seven-year-old son out of their house in a bathtub. Subsequently, the bathtub hit the ground and tossed mother and son into the backyard of a neighboring house. While both survived with just a few scratches, the fate of the bathtub is still unknown.

The deadliest tornadoes are those that form in families. A tornado family is many tornadoes spawned by the same thunderstorm or supercell. Typically, the new tornado emerges as the previous tornado dies out. However, there have been cases when more than one tornado exists at the same time. When the family produces six or more tornadoes, we have a *tornado outbreak*. The worst tornado outbreak in the history of the United States is the out break of 3-4 April 1974. In those two days tornadoes were developing continuously for 16 hours. Very warm and moist air from the south, cold air from the north, and a very strong vertical wind shear all came together over the Midwest. Several supercell thunderstorms formed and moved with the advancing cold front. It was the worst outbreak in terms of number of tornadoes, total damage, area affected, and combined path length. Ten States (Alabama, Georgia, North Carolina, Tennessee, Virginia, West Virginia, Kentucky, Ohio, Indiana and Illinois) were affected by this outbreak of 148 tornadoes. More than 300 people died and more than 5,500 people were injured. Over 27,000 families were affected with a total property damage of about $600 million. Reportedly, there were 15 tornadoes raging on the ground at the same time! The combined path of all the tornadoes in this outbreak was about 2,600 miles. This is over half the average total path of all tornadoes in a year. The deadliest tornado outbreak in the United States is the “Enigma Outbreak”, which happened on February 19, 1884. During this outbreak 60 tornadoes menaced the southeast and part of the Midwest killing 800 people.

The deadliest single tornado in the history of the United States is the Tri-State tornado of 18 March 1925. The tornado formed in southeastern Missouri and tracked northwestward and over Illinois and Indiana. In its 219-mile path the destruction was devastating. Towns like Gorham, Annapolis, Parrish and Griffin were completely destroyed. Based on the damage patterns in Illinois it is estimated that the funnel cloud was one mile wide and moving at a speed of 60 miles per hour. A record death toll of 695 people is unprecedented and most likely never to be broken. Over 2,000 people were injured and the total damage in 1925 dollars was over $16 million. Because very limited data exist from that time, a question that still remains open is whether this event was just a single tornado or a family of tornadoes. If it were a single tornado, then it lasted more than three hours. Such durations are not normal; on the other hand who said nature behaves normally? The following table (NWS/NOAA) gives the ten deadliest single-event tornadoes.

Date	Location(s)	Deaths
18 March 1925	Missouri, Illinois, Indiana	695
6 May 1840	Natchez, Mississippi	317
27 May 1896	St. Louis, Missouri	255
5 April 1936	Tupelo, Mississippi	216
6 April 1936	Gainesville, Georgia	203
9 April 1947	Woodward, Oklahoma	181
24 April 1908	Amite, Louisiana and Purvis, Mississippi	143
12 June 1899	New Richmond, Wisconsin	117
8 June 1953	Flint, Michigan	115
11 May 1953	Waco, Texas	114

Before the second deadliest tornado moved to the Natchez to claim the lives of 317 people, it crossed the Mississippi river. It is said that as it crossed the river it sucked out all the water! Since the mid 1950s, while there have been plenty of severe tornadoes, none has claimed as many lives. This is due to dramatic developments in our understanding of weather and technology that provides early warnings.

For the history, the first ever tornado forecast was made by Air Force Colonel Robert Miller on March 25, 1948. Five days before, a tornado had struck the Tinker Air Force Base in Oklahoma City where Miller was on forecasting duty. The tornado caused $10 million in damage and injured several people. Miller was curious to understand the conditions that caused the tornado to form and asked for permission to research the problem. For the next three days he and his commanding officer Major J. Fawbush, investigated the atmospheric flow and conditions during the 20th of March 1948 and on other days where tornadoes had formed. On the morning of the 25th they noticed that the condition of the atmosphere was very similar to that on the 20th. Statistically, the chances for a tornado striking the same place within five days are an astronomical 1 in 20 million. Nevertheless, as the day progressed and thunderstorms began to develop, the two brave forecasters issued the first tornado warning in history at 2:50 p.m. And this was not just the first tornado warning. It was also accurate. At 6:00 p.m. a tornado hit the base for the second time in five days. Because of this warning, the airplanes had been tied down and the employees had been evacuated. As a result the damage was less and no injuries were reported.

11. Hurricanes

Eye wall of a hurricane

Image ID: fly00178, Flying with NOAA Collection

Unlike any other storms a hurricane forms only over tropical waters and grows to be a monster. When it makes landfall it brings terror and destruction with 155 miles per hour winds, huge waves and heavy rains. The name hurricane is used to describe such storms formed in the Atlantic Ocean. When these storms form in the Pacific Ocean they are called *typhoons* and when they are formed in the Indian Ocean they are called *cyclones*. The term hurricane is derived from Huracan, a god of evil recognized by the ancient Central American tribe of Tainos. The name typhoon is derived from the Cantonese tai-fung, meaning great wind. In the Philippines, they are known as baguios.

A clear characteristic of a hurricane is its rather circular structure. Unlike other weather phenomena (individual clouds, midlatitude storms, lightning), a hurricane is very orderly. Such order indicates that some organization is required for a hurricane to develop. For a hurricane to form, a cluster of thunderstorms must exist and must get organized into a hurricane. The problem, however, is, that thunderstorms will not develop on their own over ocean water. Simply, the surface of the ocean, while warm, is not warm enough to boost strong rising motions that build thunderstorms. For thunderstorms to form over ocean water some convergence of air must exist at the surface. At the convergence point air accumulates and is forced to rise (much like when you build a sand pile at the beach by converging sand with your hands). If the convergence is strong, this process might lead to thunderstorm development.

Recall that at the equator the two easterly surface winds flows north and south of the equator merge at the Inter Tropical Convergence Zone (ITCZ) and move around the planet. However, the merging boundary is not exactly at the equator. Because the planet is tilted, the solar radiation hits the area south of the equator more directly than the equatorial areas during northern hemisphere winter. Similarly, during northern hemisphere summer, it hits more directly areas north of the equator than areas at the equator (see figure 19). Since the Hadley cells are the result of the greater solar heating around the equator, their location is determined by this annual swaying. The Hadley cells and the ITCZ move northward in the period June-November and southward in the rest of the year. The ITCZ provides the place where convergence might initiate thunderstorm formation. Other possibilities for convergence include preexisting midlatitude cold fronts that may move to the tropics from the north, and disturbances moving out of Africa.

The organization of this cluster of thunderstorms into a hurricane involves the Coriolis force and friction from the surface of the ocean. If we recall our discussion on atmospheric motions we will remember that the what determines the motion of air in the atmosphere is the pressure gradient force (the difference in pressure between two point), which provides the initial impulse that starts the motion and the Coriolis force that deflects everything to the right in the northern hemisphere and to the left in the southern hemisphere. It is this action of the Coriolis force that ultimately modifies the surface flow associated with the northern and southern easterly trade winds. If the two trade winds converged at the equator where the Coriolis force is zero, then they will merge and move westward on a straight line along the equator as in figure 44 (top). However, as the southern hemisphere trade winds move into the northern hemisphere, the Coriolis force, which was deflecting them to the left in the southern hemisphere, will now bend them to the right (figure 44 bottom).

This condition can cause the converging air at the ITCZ to begin a counterclockwise rotation. If we ignore friction for the moment, the two forces acting on a rotating parcel of air is the pressure gradient force, which set the air in motion to begin with, and the Coriolis force, which deflects it from the straight path. According to Newton's laws of motion if the net force acting upon an object is zero (in other words either there is no force present or if the forces balance each other), then the object remains at rest or if it is in motion it moves at a constant speed on a straight line. If the net force is not zero, then the object accelerates, which means the objects velocity changes. However, velocity is not just a number but it is a vector; it has both a magnitude (speed) and a direction. As such, a change in velocity can be either a change in speed and /or a change in direction.

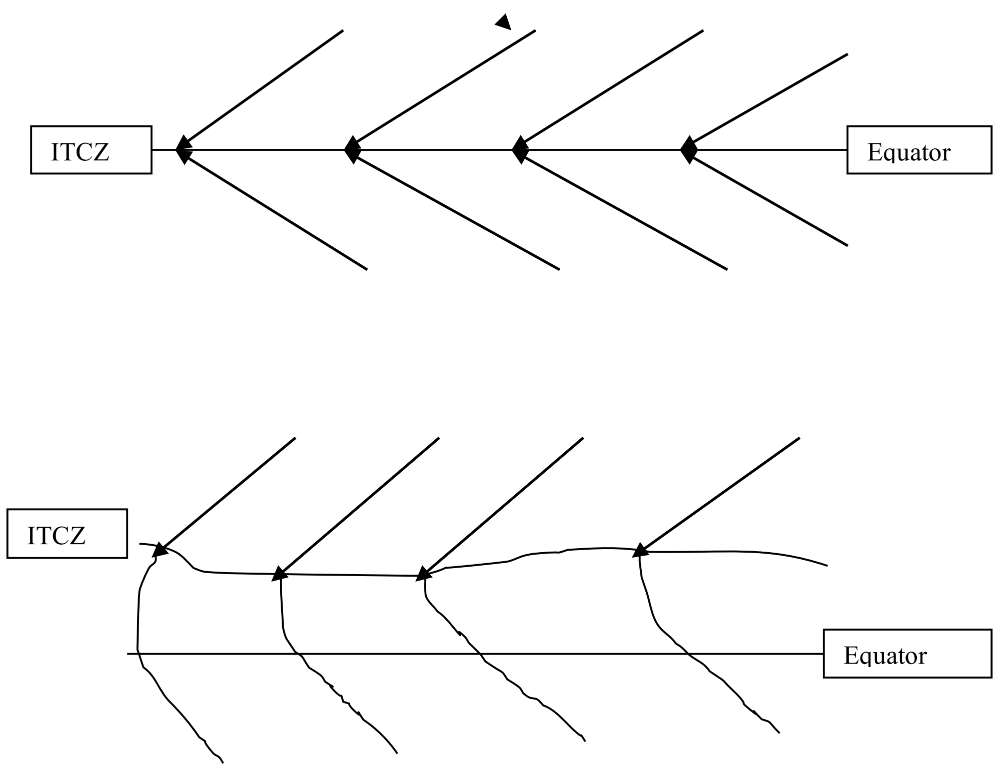


Figure 44: As the southern hemisphere trades enter the northern hemisphere the Coriolis force deflects them to the right.

When the motion of an object is curved, then it changes direction constantly. Thus, in a rotating motion there must be a net force acting on the object constantly, meaning that the forces present can not balance each other. For the rotating parcel this means that the pressure gradient force (PGF) and the Coriolis force (CF) cannot be equal to each other. Their difference defines the net force, which keeps the parcel going around and around like a rotating stone attached to a string (figure 45 left). This net force is known as the *centripetal force*, and as the name suggests it is directed toward the center of the rotation. In the example with the rotating stone this force is directed toward the center along the string. If we cut the string (thereby eliminating the net force), the stone flies out on a tangent and in a straight line.

If the force of friction (F) is also present (and when we are at the surface it is), then an extra force is involved. What will its effect be? In this case the forces adjust themselves and as a result the air does not just go around in a counterclockwise rotation but it is forced to converge toward the center (figure 45 right).

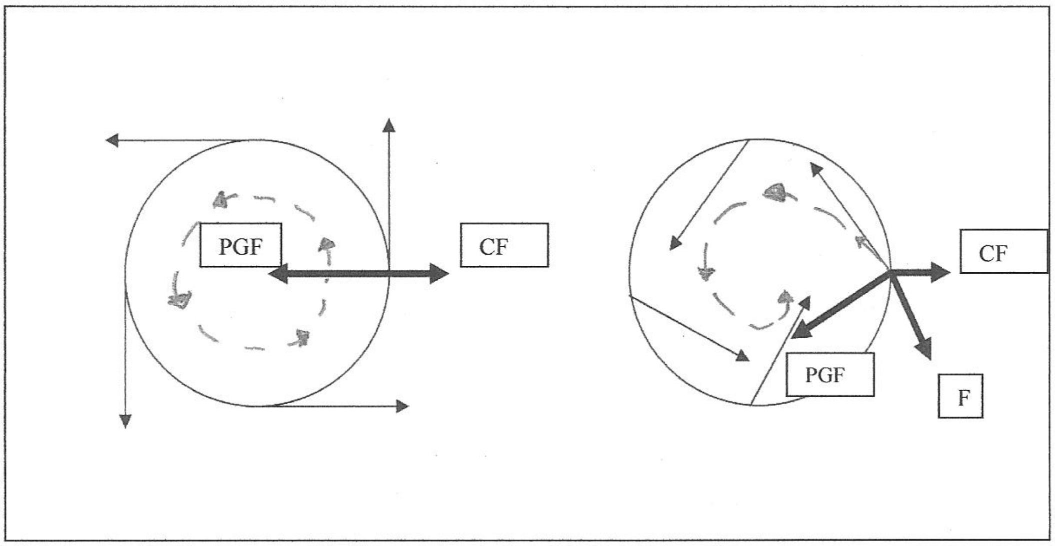


Figure 45: Forces (heavy arrows) and air movement (thin arrows) with a cyclonic rotation without friction (left) and with friction (right).

Thus, because of the Coriolis force and surface friction, the air at the surface begins to converge toward the center of the rotation. Once this is established it will be a matter of time for the thunderstorms to organize and create a hurricane. As the spiraling air is approaching the center its distance from the center decreases. In effect the radius of rotation decreases. Remember what happens if the radius of a spinning object decreases (as in the example with the skaters who bring their arms closer to the axis or center of rotation)? According to the law of the conservation of angular momentum they spin faster and faster. As such the speed of the approaching the center air is increasing. Now pay attention here. Since the angular momentum is defined as *mass of the object x radius x speed,* if the object were allowed to reach the center its radius will become zero. Since the angular momentum has to be conserved this means that as its radius tends to zero its speed has to approach infinity. Because this is not possible the air can only come within a distance from the center. At some point it cannot continue its path toward the center and it rises. In a sense it hits an invisible cylindrical wall and is forced to rise. As the warm moist air rises it condenses and clouds form. As we have explained earlier, when the air rises it creates higher pressure aloft compared to the pressure at the levels west and east of the rising motion. As a result at higher levels the rising air diverges outward. Inside the cylindrical wall, a compensating sinking motion ensues (figure 46). Because sinking motion warms the air cloud formation is inhibited there. These clear skies around the center of the storm are called the *eye* of the hurricane. The clouds formed at the perimeter of this cylindrical wall define the hurricane's *eyewall*.

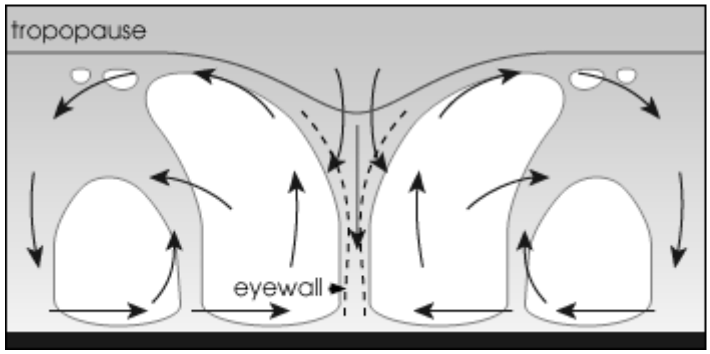


Figure 46: A vertical cross-section of a hurricane. Graphic by Robert Simmon, NASA GSFC).

Analogous to a chimney, this upper air divergence vents the tropical system, preventing the air converging at the surface from piling up around the center. If this were to occur, the surface pressure would increase and rising motions would be suppressed. The above process then becomes something like a chain reaction. The condensing air releases heat into the environment (recall that while evaporation requires heat to occur, its opposite, condensation, gives back this heat). This extra heat warms the air, which rises faster. This together with the upper air divergence allows more air to rush toward the center and repeat the process. A chain reaction now begins, which as long as the storm is over the ocean and the source of energy (warm moist air) is uninterrupted, will cause the storm to keep on developing. Once the storm makes landfall or reaches far to the north (where the surface water is colder) the moisture and the warm air are cut off and the storm begins to decay. Also, a hurricane will begin to dissipate if it enters a region where the prevailing condition is upper sinking motion, like the one that is occurring at about 30 N or 30 S. Large-scale subsidence suppresses rising motion, thereby weakening storms.

Once the cluster of thunderstorms reaches a wind speed of 23 miles per hour, it is called a tropical depression and is given a number. As winds increase to 39 miles per hour, the storm is called a tropical storm and receives a name. Beginning in 1953, female names were used exclusively. The alternation of male and female names began in the late 1970s. Finally, when wind speeds reach 74 miles per hour, the storm is classified as a hurricane.

Unlike in the case of a tornado, here a strong vertical wind shear would inhibit the formation of a hurricane. Strong horizontal winds will disperse the heat released by condensation, which fuels the hurricane, and may also tear apart the vertical structure of the hurricane, which is needed to sustain the rising of the converging air at the surface and the divergence in the upper levels. Thus, the necessary ingredients in the formation of a hurricane are 1) warm moist surface air, typically at least 81 F, 2) weak vertical wind shear, and 3) a latitude at least five degrees north or south of the equator, so that the Coriolis effect is sufficient to initiate rotation. We should note here that the original step in the formation of a hurricane was assumed to be converging air that begins to rotate counterclockwise. What if the air begun rotating clockwise? In such a case the forces involved (pressure gradient, Coriolis and friction) adjust themselves in such a way so that the air that is rotating clockwise is not anymore forced to converge at the center, but is forced to diverge outward (away from the center) (figure 47). In this case convergence cannot occur and thunderstorms cannot form. This also explains why *all* hurricanes (unlike tornadoes) rotate counterclockwise.

Because the storm spends a long time over water, the chain reaction discussed above keeps on building the hurricane. The energy associated with a hurricane is mind-boggling. Estimates indicate that an average hurricane is the equivalent of 1.4×10^{15} Watt. This is more than 1% of the net solar energy flowing towards the Earth (120×10^{15} Watt)! Few things in nature can compare to the destructive force of a hurricane. Called the greatest storm on Earth, a hurricane ravages coastal regions with sustained winds of 155 mph or higher, intense areas of rainfall and a storm surge. In fact, during its life cycle a hurricane consumes as much energy as 10,000 nuclear bombs!

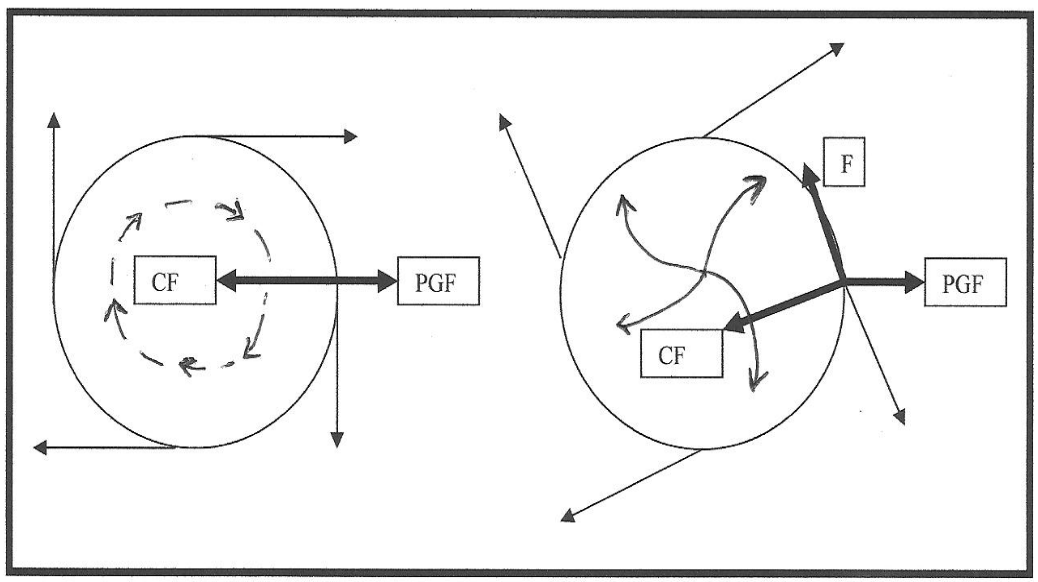


Figure 47: Forces (heavy arrows) and air movement (thin arrows) with an anti- cyclonic (clockwise) rotation in the presence of friction[7].

---

[7] The wind associated with curved flow either cyclonic (figure 45) or anti-cyclonic (figure 47) is called gradient wind. As we can see, however, in figure 22 between a low (cyclonic) and a high (anti-cyclonic) system the isobars can be more or less straight lines. In this case the flow is not curved thus it does not change direction. This flow is called a *geostrophic flow*. In this case the need for a net force to change the direction is not needed and the two forces can become equal and cancel each other. This geostrophic wind is the result of the Coriolis force balancing the pressure gradient force.

Like with the tornadoes, hurricanes are also classified in categories according to the Saffir-Simpson Scale. The Saffir-Simpson Hurricane Scale is a 1-5 rating based on the hurricane's intensity. It provides an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. The determining factor for the classification is the wind speed.

Category One Hurricane:

Winds 74-95 miles per hour. Storm surge generally 4-5 ft above normal. No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Some coastal road flooding and minor pier damage.

Category Two Hurricane:

Winds 96-110 miles per hour. Storm surge generally 6-8 feet above normal. Some roof, door, and window damage in buildings. Damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.

Category Three Hurricane:

Winds 111-130 miles per hour. Storm surge generally 9-12 ft above normal. Some structural damage to small residences and utility buildings. Damage to shrubbery and trees with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the center of the hurricane. Flooding near the coast destroys smaller structures with larger structures damaged from floating debris. Terrain continuously lower than 5 ft above mean sea level may be flooded inland 8 miles (13 km) or more. Evacuation of low-lying residences with several blocks of the shoreline may be required.

Category Four Hurricane:

Winds 131-155 miles per hour. Storm surge generally 13-18 ft above normal. Complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water 3-5 hours before arrival of the center of the hurricane. Major damage to lower floors of structures near the shore. Terrain lower than 10 ft above sea level may be flooded requiring massive evacuation of residential areas as far inland as 6 miles (10 km).

Category Five Hurricane:

> Winds greater than 155 miles per hour. Storm surge generally greater than 18 ft above normal. Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the center of the hurricane. Major damage to lower floors of all structures located less than 15 ft above sea level and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5-10 miles (8-16 km) of the shoreline may be required.

The intensity of a hurricane is measured by its central pressure. The lower the central pressure the more intense the hurricane is. The most intense hurricane in the history of the United States was an unnamed hurricane that occurred on Labor Day in 1935 in Florida. It was a category five hurricane with a central pressure of 892 millibars (normally at sea level pressure averages 1013 millibars) and winds in excess of 200 miles per hour. According to South Florida Sun-Sentinel people caught in the open were blasted by sand with such force that it stripped away their clothing and ripped at their skin. This unnamed hurricane was also the 5th most deadly hurricane killing 408 people. The only other category 5 hurricane to strike the U.S. coast was Camille, which hit Mississippi in August 1969, then continued north to cause flooding that killed 154 people in Virginia's mountains. Camille's winds reached 184 miles per hour and its central pressure deepen to 909 millibars. The storm surge was 23 feet above normal high-tide level.

The third most intense hurricane is still fresh in our memory and its effects will be felt for a long time. Tropical depression 12 formed on August 24, 2005 over the Bahamas. By next day it was category 1 hurricane Katrina, which made its first landfall near North Miami, Florida. There it caused flooding, eleven deaths and left over a million people without power. While over land it weakened to a tropical storm, but once over the open and warm water of the Gulf of Mexico it begun to intensify again. Within a couple of days it became a category 5 hurricane reaching a central pressure of 902 millibars with maximum sustained winds of 175 miles per hour (280 Kilometers per hour) and wind gusts of the order of 200 miles per hour. An upper air system, which happened to be moving southeastward from the Midwest, caused Katrina to change direction and to move northward making landfall on August 29, 2005 at Buras-Triumph, Louisiana. At that time Katrina was a category 3 hurricane with a central pressure of 915 millibars and with sustained winds of 140 miles per hour. The rest is history hopefully never to be repeated again. The city of New Orleans (which lies below sea level) was hit almost head on and was left at the mercy of over 20 feet of water surge, which finally damaged the levies and inundated the city. Millions of people were and are still affected and probably thousands died (the death toll is not yet determined, but as of September 2005 is over 1000 people). If it were not for early warnings and the evacuation of the city, hundreds of thousands will be dead.

The following table lists the ten most intense hurricanes to hit the contiguous United States.

Most Intense[1] Hurricanes in the United States[2]

Rank	Hurricane	Year	Category[3]
1.	Unnamed, Florida Keys	1935	5
2.	Camille (MS/LA/VA)	1969	5
3	Katrina, (LA/MS)	2005	3
4.	Andrew (FL/LA)	1992	5
5.	Unnamed (Indianola, TX)	1886	4
6.	Unnamed (Florida Keys/TX)	1919	4
7.	Unnamed (Lake Okeechobee, FL)	1928	4
8.	Donna (FL/Eastern U.S.)	1960	4
9.	Unnamed (New Orleans, LA)	1915	4
10.	Carla, TX	1961	4

1. Intensity is for time of landfall. May have been stronger at other times.
2. 1851–2005.
3. Saffir-Simpson Hurricane scale: Cat. 1 = weak; Cat. 5 = devastating.

Source: National Oceanic and Atmospheric Administration (NOAA).

The most intense storm on record was typhoon Tip in the northwest Pacific Ocean in October 1979, with a central pressure of 870 millibars. Hurricane Gilbert, which struck Mexico in mid-September 1988, is the most intense for the Atlantic basin, with an estimated 888-millibar lowest pressure. This hurricane did not make landfall in the United States but in Mexico where it caused the death of 200 people.

The deadliest hurricane to hit the States is an unnamed category 4 hurricane, which slammed into Galveston, Texas on Saturday September 8, 1900. Because at that time monitoring systems such as weather radars and satellites were not available, it was not possible to warn the population of the impending storm. Ships at sea were not well equipped to broadcast the weather conditions they observed. As a result, while several agencies, such as the Weather Bureau, were aware that a storm is brewing in the Gulf of Mexico, they had no way to predict its path and warn the population. More than eight thousand people lost their lives. Most of the deaths occurred in the low-lying coastal regions as water for the storm surge flooded them. The deadliest storm in the world was a cyclone, which hit Bangladesh in 1970. The human loss was simply enormous. More than 300,000 people died as the storm surge ravaged the coast of Bangladesh. These incredible numbers are unfortunately not unusual in that part of the world. In April 1991, a similar cyclone with wind in excess of 160 miles per hour killed 140,000 people. Overpopulation and non-existing infrastructure to deal with natural hazards in Bangladesh are the primary reasons for such disasters. The deadliest hurricane in the Atlantic basin was the Great Hurricane in 10-16 October, 1780 in the Lesser Antilles, which claimed the lives of more than 22,000 people. The second deadliest is the recent hurricane Mitch. Mitch formed in late October 1998 over very warm water and in an environment of no vertical wind shear. Both these conditioned allowed Mitch to develop into a category 5 hurricane with winds in the vicinity of 180 miles per hour and a storm surge of 44 feet. Incredible amounts of rain (75 inches) in Honduras and Nicaragua, caused flooding and mudslides that destroyed entire villages and killed more than 11,000 people. More than 3 million people were left homeless and the total damages reached $5 billion. In Honduras over 50% of the crops were lost. The Great Hurricane and Mitch did not reach the States. The table below lists the ten deadliest hurricanes to hit the United States. Note that all of them occurred earlier in the 20th century. Even though in the later half many stronger hurricanes have hit the United States the death toll is much less. This is due to the modern monitoring and warning systems available in the States. A hurricane now can be followed closely and its path can be predicted with a reasonable accuracy. Early warnings provide people with plenty of time to prepare for the storm or to evacuate.

Deadliest Hurricanes in the United States (U.S. Mainland)[1]

Rank	Hurricane	Year	Category[2]	Deaths
1.	Galveston, Tex.	1900	4	8,000[3]
2.	Lake Okeechobee, Fla.	1928	4	2,500
3.	Katrina (La./Miss.)	2005	3	1,800[4]
4.	Florida Keys/S. Tex.	1919	4	600[5]
5.	New England	1938	3	600
6.	Florida Keys	1935	5	408
7.	Audrey (SW La./N. Tex.)	1957	4	390
8.	NE U.S.	1944	3	390[6]
9.	Grand Isle, La.	1909	4	350
10.	New Orleans, La.	1915	4	275
10.	Galveston, Tex.	1915	4	275

1. 1900–2007.
2. At landfall. Saffir-Simpson Hurricane scale: Cat. 1 = weak; Cat. 5 = devastating.
3. May actually have been as high as 10,000 to 12,000.
4. Approximated.
5. Over 500 of these lost on ships at sea; 600–900 estimated deaths.
6. Some 344 of these lost on ships at sea.
Source: National Oceanic and Atmospheric Administration (NOAA).

The costliest hurricane in the history of the United States is definitely Katrina. Even though it is still early for a final figure, early estimates put the cost of Katrina's destruction close to 100 billion dollars. Before Katrina the 'honor' for the costlier hurricane belonged to Andrew. In the beginning tropical storm Andrew looked like it will never become a hurricane. However, as it moved over an area of warm water and weak vertical wind shear, it started intensifying rapidly. In two days its winds increased form 50 miles per hour to 135 miles per hour. Finally, it became a category 5 hurricane and made landfall in Miami on the morning of August 24, 1992. Initially, Andrew was classified as a category 4 hurricane. Later, however, and after examining the severe damage was upgraded into category 5. With sustained surface winds of 150 miles an hour and estimated peak winds of the order of 200 miles per hour, Andrew destroyed 50,000 homes in Homestead, Florida as it roared across Florida and into the Gulf of Mexico. It took Andrew four hours to cross Florida and while over land it decayed to category 1 hurricane. Once over water, however, it regained some of its strength and slammed into Louisiana with 130 miles per hour winds. Due to the warning systems, the death toll was kept to a minimum, as hundreds of thousand of people were evacuated. The total deaths attributed directly to Andrew were 26. Additional indirect loss of life increased this number to 105 as of January 1993. Andrew destroyed more than 25,000 homes and damaged an additional 100,000 homes. The total damage from Andrew is estimated at about $35 billion. If Andrew made landfall only 12 miles to the north it would have struck downtown Miami. If that were the case the total damages could have exceeded $200 billion.

Hurricanes will continue to pose a threat to the United States. As the population and wealth increase, a category 4 or 5 hurricane may lead to enormous economic loss. For example, if the unnamed category 4 hurricane that struck SE Florida/Alabama in 1926 were to strike the same area today the estimated damages would reach $90 billion. In the summer 2004, category 4 hurricane Ivan made landfall near Gulf Shores, Alabama. At that time scientists were warning that if this or any other category 4 or 5 hurricane were to hit directly New Orleans, the whole city could be submerged. Unfortunately, within a year this fear became reality. Below is a list of the ten costliest hurricanes to strike the United States.

The longest lasting hurricane on record is Ginger. She formed on September 9, 1971 east of the Bahamas and and meandered through the open Atlantic Ocean for 27 days. She finally made landfall in North Carolina where she caused very little damage as a category 1 hurricane. After that she turned back to sea and dissipated.

Costliest Hurricanes in the United States (U.S. Mainland)[1]

Rank	Hurricane	Location	Year	Category[2]	Damage (in billions)
1.	Katrina	La./Miss.	2005	3	$96.0[3]
2.	Andrew	Fla./La.	1992	5	26.5
3.	Charley	Fla.	2004	4	15.0
4.	Wilma	Fla.	2005	3	14.4[3]
5.	Ivan	Ala./Fla.	2004	3	14.2

6.	Rita	Tex./La.	2005	3	$9.4[3]
7.	Frances	Fla.	2004	2	8.9
8.	Hugo	S.C.	1989	4	7.0
9.	Jeanne	Fla.	2004	3	6.9
10.	Allison	Tex.	2001	TS[4]	5.0

NOTE: Damages are listed in U.S. dollars and are not adjusted for inflation.
1. 1900–2005.
2. At landfall. Saffir-Simpson Hurricane scale: Cat. 1 = weak; Cat. 5 = devastating.
3. Estimated.
4. Tropical storm intensity.
Source: National Oceanic and Atmospheric Administration (NOAA).

As figure 48 shows, there are basically six basins in the world that are affected by hurricanes (or typhoons or cyclones). This figure shows locations of tropical cyclones observed by NASA's Microwave Imager instrument during the period from January 1, 1998 to December 31, 2000. Each dot represents one observation. The solid lines indicate the boundaries of the six ocean basins analyzed in the study. The six basins are: Atlantic (ATL), east-central Pacific (ECPAC), northwest Pacific (NWPAC), north Indian Ocean (NIND), south Indian Ocean (SIND), and South Pacific (SPAC). The United States is in the second most frequently affected basin in the world. The first is the east coast of Asia.

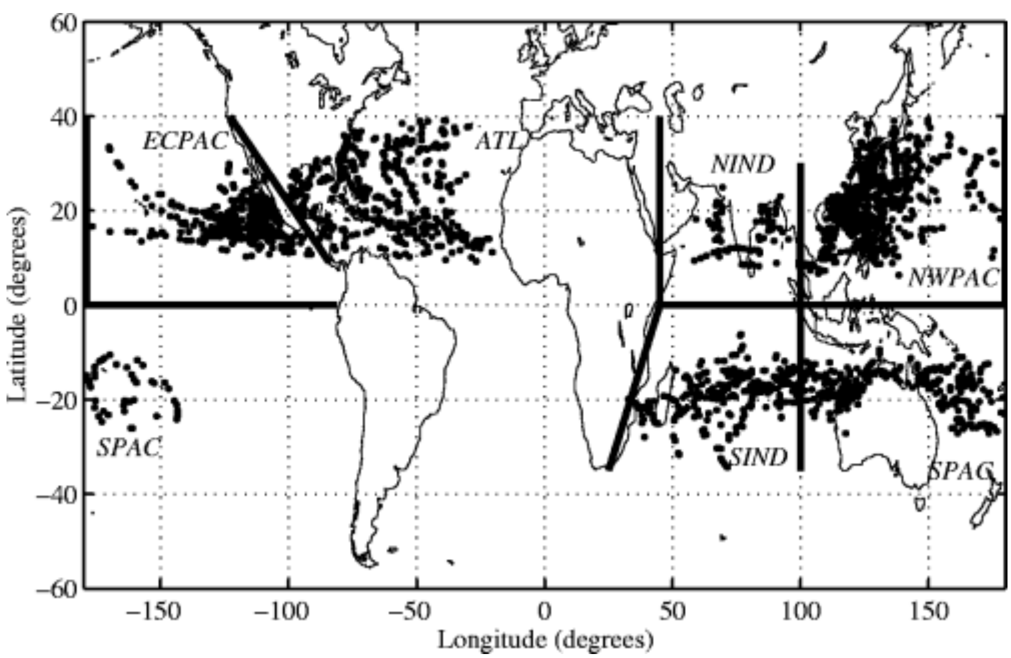


Figure 48: Basins where hurricanes form. Credit: Lonfat et al., University of Miami (1998-2000

12. Floods

Speed limit sign for cars now being used for boats

Image ID: wea00702, Historic NWS Collection

During the 20th century, floods were the number-one natural disaster in the United States in terms of property damage. They can occur at any time of the year and can strike at any time of the day or night. Most property damage results from the flow of sediment-laden water. Flood currents also possess destructive power, which can be either instantaneous when lateral forces destroy structures or slow when erosion undermines bridges and foundations of other structures. Lives are also lost as people are swept away by the raging waters.

There are several types of flood. The first type is the *flash flood*. A flash flood is localized and occurs when smaller rivers do not have time to react on a slow moving thunderstorm. High rainfall amounts over relative short times result in situations where the river's discharge cannot catch up with the volume of water supplied by the storm. They happen rapidly and, like the thunderstorms causing them, do not last very long. Nevertheless, they can be very dangerous as they occur with little or no warning at all. And because the culprit moves very slowly or becomes stationary it dumps all its water in a small area. A terrifying flash flood occurred in the Big Thompson Canyon in Colorado on July 31, 1976. An almost stationary thunderstorm deluged the canyon with over ten inches of rain in a few hours and caused the drowning of 145 campers as well as $136 million in damage. It is reported that the river swelled into a raging torrent of water 19 feet high. People in campers and cars were trapped. The flash flood destroyed 152 businesses and 418 homes and damaged another 138 homes. At the peak of the flood, water raged at 31,200 cubic feet/second, four times the previous flood record.

The second type is *widespread floods*. These are the result of prolonged and large amounts of rainfall. In these cases, water rises slowly and eventually overflows to cover large areas. While they cause more damage than flash floods, they do not result in great loss of life because usually there is plenty of time for issuing warnings. The severity of this type of flood can be accentuated in times when in addition to rain there is rapid melting of ice. Because the ground may be still frozen infiltration is limited and runoff is augmented. The situation can get even more severe by ice jams in the rivers.

The third type is *coastal floods*. They are the result of the storm surge that accompanies hurricanes and strong midlatitude storms. Because of that, this type is more frequent along the East Coast and the Gulf Coast where most of such storms occur.

The map on the next page (figure 49) gives the location of the most significant floods of the 20th century in the United States. Numbers 1 to 20 refer, in sequence from the earliest to the latest, to the 20 most significant widespread floods. Number 1 occurred during March-April 1913 in Ohio. This statewide flood inundated Dayton, claimed the lives of 427 people and caused $143 million (uninflated) in damages. If we exclude deaths from hurricane-induced storm surges, this was the deadliest flood. Number 13 occurred during May-September 1993 in the Mississippi River basin of the Central United States. This flood, which we will discuss in more detail soon, was the worst flood in the 20th century. Numbers 21 to 24 refer to flash floods. Number 21 occurred on June 14, 1903 in Oregon. The city of Heppner was destroyed and 225 people lost their lives. Number 25 is an ice-jam flood that occurred in May 1992 with the Yukon River in Alaska. Numbers 26, 27, and 28 are coastal floods associate with hurricanes (number 26 corresponds to the deadliest hurricane that made landfall in Galveston, Texas in September 1900). Numbers 29, 30, and 31 are floods caused by dam failures. Number 32 is a mud-flow flood sparked by the eruption of Mount St. Helens. Clearly, floods do not have a preference when it comes to location. They occur everywhere in the United States.

An important flood in the history of the United States is number 2, which occurred in April-May 1927 with the Mississippi river from Missouri to Louisiana. In the early 20th century the United States was undergoing development. A natural infrastructure aiding this development and expansion was the waterways of the Mississippi River, which provided the means for low-cost and efficient transport of many materials. At the same time it provided a convenient source of water for industries, which were naturally established along the river. The flood of 1927, however, showed how vulnerable the industries and the country were to flooding. The Great Flood of 1927 was one of the worst natural disasters of the 1900s. After months of unusually heavy rain during late 1926 and early 1927, the Mississippi River flooded.

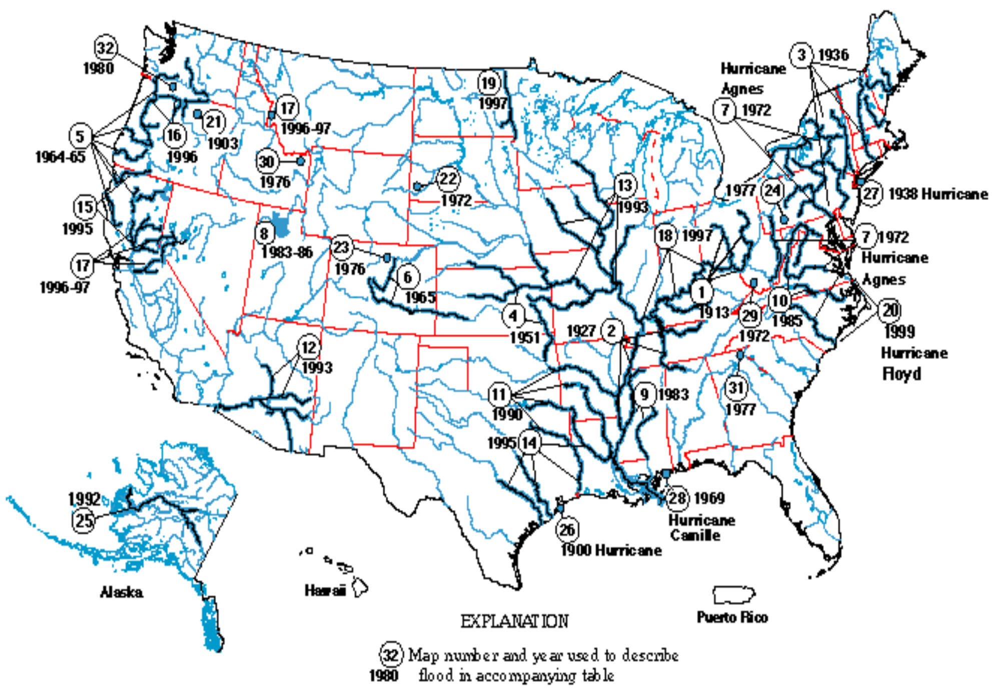


Figure 49: Location of the most significant floods of the 20th century. Courtesy of C harles A. Perry, USGS Fact Sheet 024-00. Used with permission.

As Stephen Ambrose reports in his Expedition Journal of May 1, 2001 National Geographic, on Good Friday, April 15, 1927, the Memphis Commercial Appeal warned:

"The roaring Mississippi River, bank and levee full from St. Louis to New Orleans, is believed to be on its mightiest rampage...All along the Mississippi considerable fear is felt over the prospects for the greatest flood in history." Indeed, as the rain continued setting new records, the river swelled and flowed with such force that the residents in Berry Woods are quoted as having said that the flooding waters were "like facing an angry, dark ocean". Also in Ambrose's report, a man recalled, decades later, "I saw a whole tree just disappear, sucked under by the current, then saw it shoot up, it must have been a hundred yards [downstream]. It looked like a missile fired by a submarine."

After the failure of a levee at Mounds Landing, Mississippi, the flooding river rushed with a force equivalent to that of Niagara Falls. Ten feet of water covered towns up to 60 miles away from the river. Even after 5 weeks, the area around Mounds Landing was covered with 10 feet of water. During the peak of the flood the river was about 80 miles wide and the flooding waters covered 26,000 square miles in seven states. More than half a million people had to be evacuated and the damage exceeded 230 million of 1927 dollars. Today this corresponds to more than five billion dollars. According to a report by Jim Taylor of the Arkansas Department of Parks and Tourism the flood of 1927 was the state's worst natural disaster. The flood claimed 98 lives and caused $38 million (1927 value) in property damages and $12.5 million in crop losses. Lost to the waters were 2,200 homes, 1,185 barns, nine cotton gins, 8,940 head of cattle, 5,833 mules and horses, more than 32,000 hogs, and 215,617 chickens. Another 4,241 homes, 5,582 barns, 78 cotton gins, 645 stores, and numerous bridges and miles of railroad track were damaged.

The flood of 1927 had far reaching effects. As very forcefully argued in the book by John M. Barry "Rising Tide: The Great Mississippi Flood of 1927 and how it Changed America" the flood influenced to a large degree the future of politics in the United States. At the time of the flooding, President Coolidge refused to visit flood sites. Hoover, who was then Secretary of Commerce, was called in. He traveled around organizing relief efforts, visited levee camps, gained popularity, and was hailed as a national hero. This led him to be a presidential contender in the next election. In his campaign, Hoover promised to help the African Americans of the South if they voted for him during the presidential race. They did, but Hoover never delivered on his promise. Discontent African Americans left the party of Lincoln. They also began to leave Mississippi and moving to a more promising place: Chicago. The population and politics of the region and of the United States were changed for ever.

In addition, the flood changed flood-control policy. The magnitude of that calamity prompted the action of the Congress, which in 1928 passed the Flood Control Act. This Act aimed at developing a series of levees and dams along the Mississippi River to control its watershed's waterways. This was the famous "Tame the mighty Mississippi" charge of now president Hoover. By 1936, the Army Corps of Engineers built 29 locks and dams, hundreds of runoff channels, and 1000 miles of levees. And indeed the Mississippi River was tamed since for 65 years no major flooding disaster occurred. Until, the summer of 1993…

In the period of 1991-1993 the water temperature off the West Coast was warmer than usual. Warmer temperatures mean a greater supply of water vapor in the atmosphere that can be transported over the United States. At the same time increased thunderstorm activity in the eastern Pacific due to El Nino (more on El Nino later), transported moisture in the upper levels, which was then, with the help of the modified atmospheric circulation, directed over the United States. These enhanced amounts of moisture resulted in record rainfall in the Midwest in the summer of 1992. These records continue to break as in the spring of 1993 the upper Midwest experienced the wettest months. As if this were not enough an abnormal surface wind flow provided yet another source of moisture in the Midwest from the Gulf of Mexico. The combined result of continuous influx of moisture for more than a year resulted in great precipitation amounts. Some areas received over 30 inches of rain during the summer of 1993, 200% more than usual. With high soil moisture levels from record rainfall in the preceding year, most of the rain drained directly into the Mississippi River, resulting in a tremendous flood that pushed the mighty Mississippi to its limit again. El Nino, however, is not the only factor in widespread floods. For, example during the 2004-2005 winter, California experienced an incredible amount of rainfall and flooding without El Nino being present in the tropical Pacific. In general, it is not unusual that the flow over a region, which is responsible for stirring weather systems, to deviate from the normal flow and 'lock' into a different and persistent flow that brings more moisture and more precipitation producing weather systems over the region.

The satellite images on the next page (figure 50), show the area in the junction of Mississippi, Missouri, and Illinois Rivers before (top) and during the peak of the flood. The magnitude of the disaster is clearly visible. The states of Minnesota, Iowa, Illinois, and Missouri were the hardest hit. The river height at St. Louis, Missouri was over 50 feet above flood stage for over 100 days. Water from the flood covered over 17,000 square miles of normally dry land. The flood destroyed over 80% of levees in the upper Mississippi River. It also destroyed 50,000 homes and displaced 70,000 people. 52 flood-related deaths occurred. More than seventy-five towns were inundated. Some were never built again and some (Valmeyer, Illinois, Rhineland, Missouri, New Pattonsburg, Missouri) were moved to a safer location. The final damage estimate was 15-20 billion dollars. When all was over, this flood was characterized as a 500-year flood, meaning that such floods happen on the average every 500 years.

Mark Twain once said the Mississippi River "cannot be tamed, curbed or confined...you cannot bar its path with an obstruction which it will not tear down, dance over and laugh at. The Mississippi River will always have its own way, no engineering skill can persuade it to do otherwise..." And so far, it appears that Mark Twain was correct. The Mississippi remains its own ruler.

Many floods have followed the flooding of the Mississippi River in 1993 year after year. Texas in 1994. California's Central Valley in 1995, the Pacific Northwest in 1996, California in 1997, Grand Forks, N.D., in 1997, the Ohio River in 1997.

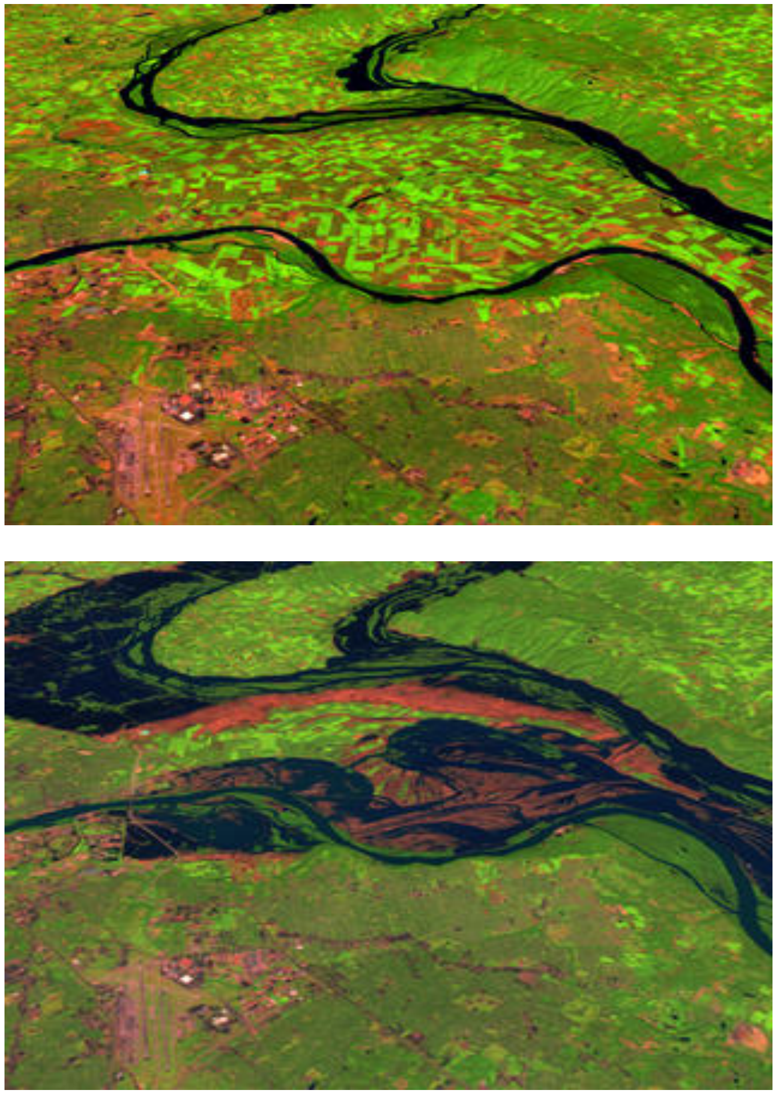


Figure 50: Parts of the Mississippi before and after the f flood. Mississippi, Missouri, and Illinois Rivers before (August 1991) and during the flood of 1993 (July 1993) (courtesy of NASA) bert.ulrich@hq.nasa.gov

When it comes to worldwide flooding many areas in the world are vulnerable. The map below (figure 51) shows the distribution of extreme flood events from 1985 to 2002. It is based on a survey of flood events using the Global Archive of extreme flood events since 1985 compiled by the Dartmouth Flood Observatory. The various shades and symbols refer to individual years. Here darker shades do not indicate hard hit regions. Areas that experience frequent flooding are those with many of these shades or symbols on the top of each other. From this map it would appear that areas where flooding is a frequent problem include the United States, Southeast Asia and China, India, Europe, Central America, and Southeast South America. However, because such global records do not extend far in the past, it is not clear which of these regions experiences a greater frequency and/or extent of floods. According to NOAA's Top Global Weather, Water and Climate Events of the 20th Century, 10 major flooding disasters occurred in 1900, 1911, 1915, 1931, 1935, 1950, 1954, 1959, 1991 and 1998 in China, mainly in the Yangtze

River Valley. This is not more than what occurred in the United States. In fact, if we consider the flood of 1998 in China, it does not appear that the extent is greater than the extent of flooding in the United States (see figure 52). A similar observation can be made for the other top 10 flood in China, the flood of 1991.

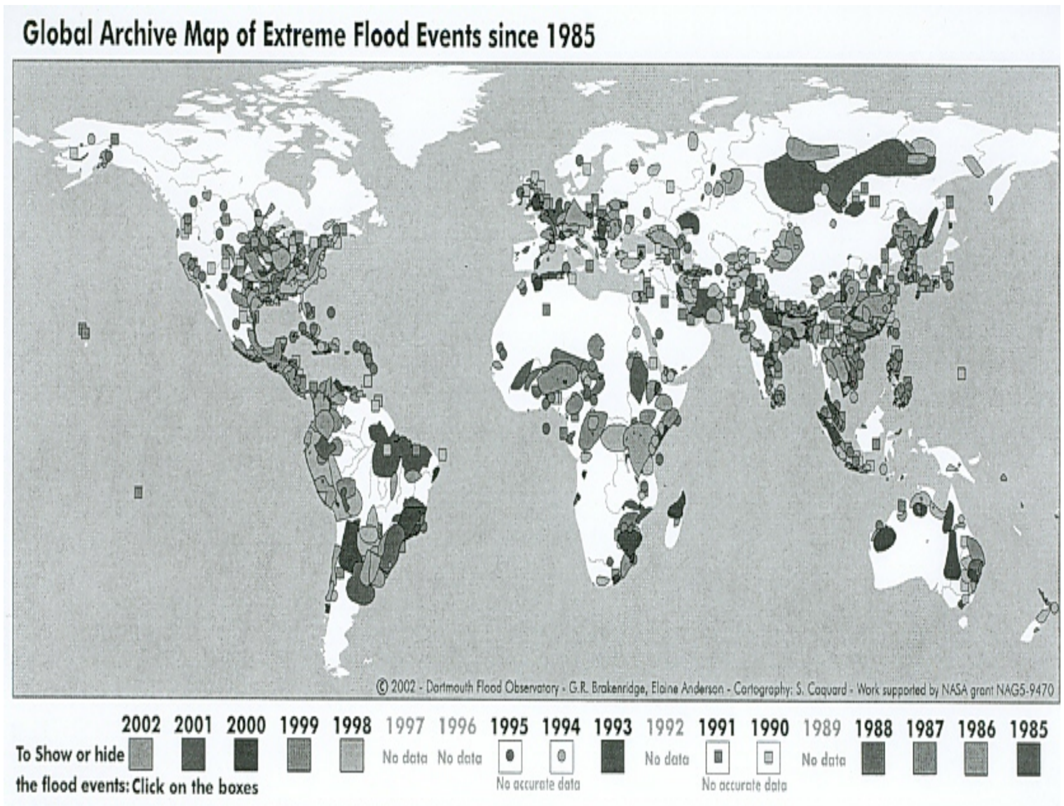


Figure 51: Distribution of extreme flood event in the period 1985-2002. See text for details.

Furthermore, the Hydrologic Research Center in San Diego, California (a Center with worldwide expertise in flooding and other hydrological applications) has reported that the United States has more flash floods than any other place on Earth. Therefore, even if the United States in not documented as the worst place when it comes to floods, it definitely is a protagonist. Note that many of the devastating floods that occur in parts of Southeast Asia are often associated with typhoons or tropical systems and because of the poor weather infrastructure of these countries usually cause thousands of deaths (which makes them more of a disaster), unlike in the United States or Europe where efficient infrastructure and early warning systems are in place.

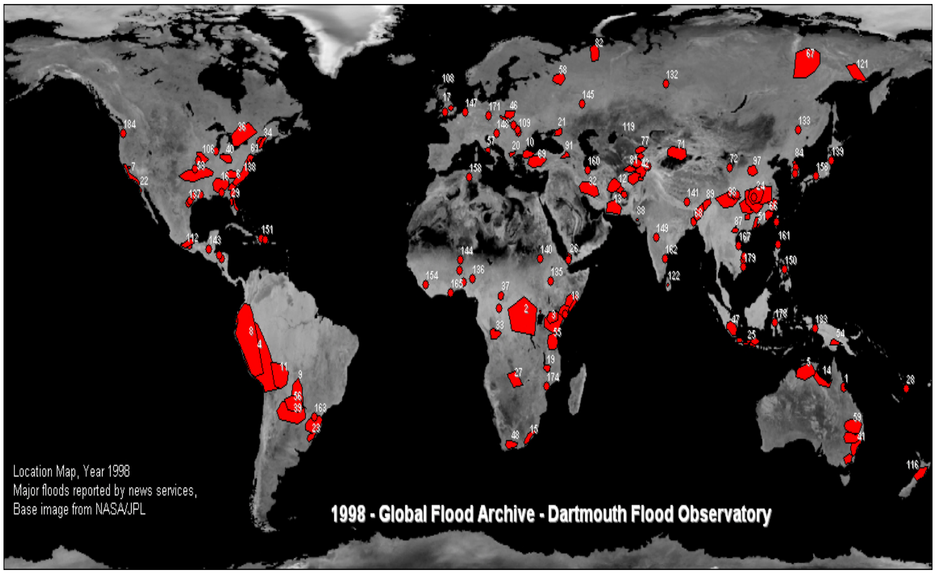


Figure 52: Global flood extent in 1998.

13. Droughts

A dust storm approaching Spearman. In: "Monthly Weather Review," Volume 63, April 1935, p. 148. Sunday April 14, 1935 was called black Sunday because the dust storm turned day into night. Many believed the world was coming to an end.

Image ID: wea01422, Historic NWS Collection
Location: Texas, Spearman
Photo Date: 1935 April 14

Drought has long been recognized as one of the most deceitful causes of human misery. Because it is long-lasting and affects large areas, it has gained the unfortunate distinction of being the natural disaster that annually claims the most victims.

In general, drought occurs when a region is dominated by high pressure. Remember that high pressure at the surface is associated with sinking motion. Sinking motion is the opposite of rising motion. When this sinking motion is strong, it suppresses all chances of rising motion thus inhibiting cloud and rain formation. In addition, a high pressure acts like a rock in a river; water cannot push it away so it has to go around it. Similarly, high pressure systems in the atmosphere are like impenetrable fortresses. They cannot be pushed away easily and all storm systems have to go around them. Thus, in a region dominated by a high pressure system there is hardly any precipitation. As we have seen earlier, there are places on earth where such sinking motion is a permanent phenomenon. These areas will, by definition, be dry; the Sahara desert, Saudi Arabia etc. Also, regions on the lee side of mountains across a westerly flow will be dry, because the air that flows over the mountain develops precipitation and loses all its moisture in the windward side and then it gets warmer during its descend on the leeward side. However, due to fluctuations and natural variability, the atmospheric flow may often organize itself into a regime far from normal. Some times this situation may result in a high pressure system establishing itself over an area where it would not have been found normally. Thus, drought conditions can be established even in areas that normally receive significant precipitation. One of the problems with drought is its ability to feed on itself. Once the conditions are placed, a feedback mechanism is established that makes these conditions long lasting. When rainfall decreases there is less water to evaporate from the ground and other sources of water. As a result, the heat that would have been consumed during evaporation is available to be absorbed by the ground, which gets warmer and then warms the air close to it. As this process continues, the additional warming causes abnormally high temperatures and heat waves during droughts. The high pressure gets stronger and basically becomes “unmovable” by weather systems carrying precipitation (midlatitude storms).

Droughts occur in all of the world's continents. In recent decades the most severe and devastating droughts have occurred in Africa, but the fact is that devastating droughts have occurred in many areas even in areas that normally receive significant annual rainfalls, such as the United States.

The most unforgettable drought to strike the United States is that of the Great Plains 1931-1937 drought or otherwise known the *Dust Bowl*.

The Dust Bowl was caused by a combination of weather and overuse and abuse of the prairie lands. Before settlement, natural deep-rooted grasses that were resistant to droughts covered the ground. When people moved west, these grasses were plowed under to raise crops and were grazed by free cattle. The long-term result was that the soil was exposed to the prairie winds, which blew away the rich topsoil. The first ‘black blizzards’, or dust storms, began in November 1933, raising billowing clouds of dust to the skies. Those clouds would last for days and block out the sun, forcing people to use indoor lights throughout the day. The drought continued for years and the affected area expanded north and eastward. Dust storms threw particles in the atmosphere which would reach as far east as New York City. It is estimated that about 350 million tons of soil was carried into the air and transported away. The Dust Bowl's first such storm started on November 13, 1933 and spread from Montana to the East Coast where black rain fell in New York and brown snow in Vermont. At least a hundred dust storms were recorded in a single year in parts of Texas and Oklahoma. Sand and silt scrubbed the paint off houses and automobiles. Crops were undergrown and livestock died of suffocation and starvation. Hundreds died from respiratory problems, and thousands abandoned their farms and moved elsewhere.

By 1934 the Dust Bowl had turned the Great Plains into a desert. "If you would like to have your heart broken, just come out here," wrote Ernie Pyle, a roving reporter in Kansas, just north of the Oklahoma border, in June of 1936. "This is the dust-storm country. It is the saddest land I have ever seen." Personal accounts abound from that time. In his memoir *Farming the dust bowl* Laurence Svobida recounts: "...At other times a cloud is seen to be approaching from a distance of many miles. Already it has the banked appearance of a cumulus cloud, but it is black instead of white, and it hangs low, seeming to hug the earth. Instead of being slow to change its form, it appears to be rolling on itself from the crest downward. As it sweeps onward, the landscape is progressively blotted out. Birds fly in terror before the storm, and only those that are strong of wing may escape. The smaller birds fly until they are exhausted, then fall to the ground, to share the fate of the thousands of jack rabbits which perish from suffocation."

The magnitude and devastation of the drought and the misery it bestowed on the people could not escape the pen of one of the greatest American writers. John Steinbeck wrote in his 1939 novel *The Grapes of Wrath*: "And then the dispossessed were drawn west- from Kansas, Oklahoma, Texas, New Mexico; from Nevada and Arkansas, families, tribes, dusted out, tractored out. Carloads, caravans, homeless and hungry; twenty thousand and fifty thousand and a hundred thousand and two hundred thousand. They streamed over the mountains, hungry and restless - restless as ants, scurrying to find work to do - to lift, to push, to pull, to pick, to cut - anything, any burden to bear, for food. The kids are hungry. We got no place to live. Like ants scurrying for work, for food, and most of all for land."

In 1936, Congress passed the Soil Conservation Act, which allocated $500 million to farmers who started planting soil-building crops. This program helped stop overproduction of crops. In addition, agricultural and conservation education programs were created along with "shelter belts," rows of trees planted as windbreaks. The drought finally ended by 1937. Good weather returned and remained good. Very good crop harvests continued through the crucial World War II years that come ahead.

Not long after the devastating drought in 1930s, another drought pummeled the country. During the 1950s the United States as a whole experienced some of the driest summers. From 1952 to 1957 the Southern Plains, the Southwest and finally the northeastern and Mid-Atlantic states were struck by a comparable drought. But the lesson from the Dust

Bowl averted a repeat socioeconomic disaster. Changes in agricultural practices and a better economy helped mitigate the tragic results of the drought of 1930s. Nevertheless, thousands of farm families had to move off from their land and damages were into the billions of dollars. Only four years later another severe drought hammered the United States; the drought of 1961-1966. A rare re-arrengement of the atmospheric circulation directed warm and moist air to the east leaving the Northeastern United States with hardly any precipitation for many years (1961-1966). The drought affected fourteen northeastern states (approximately 7% of the continental United States) and millions of people. Many communities were ordered to reduce its water usage. Crops failed, affecting dairy farms and cranberry bogs. Industries that depended on water decreased production. As a side result, record forest fires also occurred during 1963. The drought finally ended after heavy snowfalls in 1966-67. In 1988 a severe but not as prolonged drought affected the United States again. This time the area from the southern Appalachians, the Ohio Valley, the Midwest and the northern Great Plains was affected. Even though short lasting, this drought had severe consequences. Corn production fell almost by 50% and the total grain production declined by 31%. The Mississippi River reached record low levels only five years later after it reached record high levels in the flood of 1993. The total cost of this event is estimated to about $40 billion (in 1998 dollars).

Recent research using reconstructed data indicates evidence of many droughts in the past. For example, it appears that a drought in the 16th century exceeded the Dust Bowl drought of the 1930s in duration, intensity, and total area affected. Other evidence suggests 20+ year droughts or *mega-droughts* in 936, 1034, 1150 and 1300 A.D. One of these mega-droughts may have contributed to the extinction of the Anasazi people. The Anasazi were Native Indians that lived in the Long House Valley in Arizona. But sometime around 1350 A.D. they vanished. Archaeologists George Cumerman and Jeffrey Dean developed a computerized replica of Long House Valley environment from 800 A.D. to 1350 A.D. and populated it with 'digital farmers' whose survival depended on simple rules. Simulations shown in an excellent article by Jonathan Rauch in the April 2002 issue of *Atlantic Monthly* clearly demonstrate that random environmental effects related to availability of water can indeed explain many of the settlement patterns and possibly the final extinction[8].

In fact, it appears that recently (1998-2003 and later) the United States may have experienced one of the biggest droughts in its history. In several regions, groundwater was disappearing and the rivers were running dry. As a result, the number of devastating forest fires was on the rise. The drought was gradual and prolonged. In Denver, low reservoir levels prompted restrictions in water usage. In Charlotte, North Carolina the reservoirs, which are usually 80% full, fell to around 35% full. On the east coast, 15% of electricity comes from hydroelectric dams, but with the stream flow way down, less than 30% of the dams' power could be used. The drought in the west could be the worst in 500 years, with effects in the Colorado River basin even worse than during the Dust Bowl years, scientists at the U.S. Geological Survey say. The drought produced the lowest flow in the Colorado River on record, with an annual average flow of only 5.4 million acre-

[8] Rauch, J. Seeing around corners, *Atlantic Monthly*, April 2002

feet at Lees Ferry, Arizona, during the period 2001-2003. By comparison, during the Dust Bowl years, between 1930 and 1937, the annual flow averaged about 10.2 million acre-feet. Scientists used tree-ring reconstructions of Colorado River flows to estimate what conditions were like before record-keeping began in 1895. Using that method, the lowest five-year average of water flow was 8.84 million acre-feet in the years 1590-1594 (in the drought of the 16th century). From 1999 through 2003, water flow has been 7.11 million. Accordingly, the recent drought may be the worst in the last 1,000 years.

The details behind the mechanisms that set up a drought are not well understood. Each drought has its own special features. Even though a single factor has not been identified, one important variable appears to be ocean temperature. Recent research has indicated that abnormal water temperatures over the Pacific and/or Atlantic Oceans may trigger a drought in the United States. From this point of view, being in between two oceans would make the United States vulnerable to droughts and explain the frequent severe droughts that plague it. Figure 53 shows the percent area of the country in severe and extreme drought conditions as a function of time from January 1895 to March 2002. As you can see, some part of the country is under the drought conditions at all times. In at least 15 occasions as much as 30% of the country is under drought conditions; and these are not just drought conditions, they are severe or extreme conditions. During the drought of 1930s about 2/3 of the country were under such conditions. In the fifties almost half of the contiguous United States was hit by drought. The United States' longest dry spell began on October 3, 1912 at Bagdad, California. It lasted for 767 days in which not a drop of rain fell.

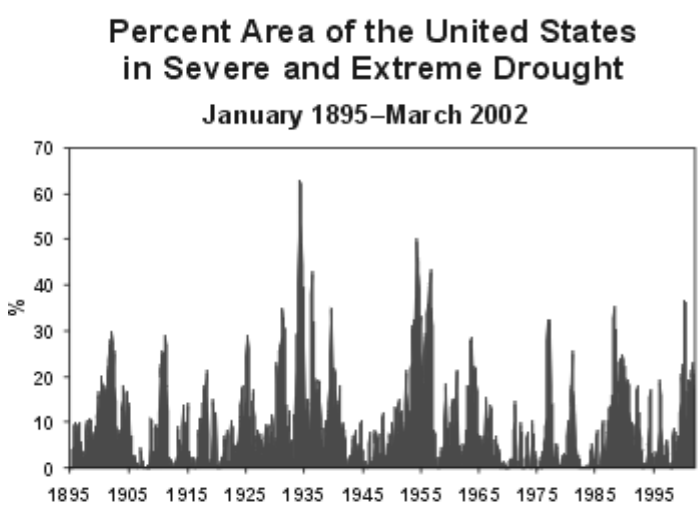


Figure 53: © 2005 National Drought Mitigation Center, University of Nebraska-Lincoln.

If we want to compare the United States to other regions in the world we will find out that again the United States is a protagonist. The following map (figure 54) was reconstructed from a map produced by the Food and Agriculture Organization (FAO) of the United Nations. It gives the probability of a drought occurring at locations on the planet. All areas that are normally dry (such as deserts, semi-deserts, highlands etc) have been excluded. According to this map, droughts occur relatively frequently even in areas that are prone to flooding with the United States being one of the principal areas. Other vulnerable regions include China, India and the Sahel region of Africa, Europe (including Ukraine and parts of Russia), Eastern Australia, and parts of South America and Africa. According to NOAA's Top Global Weather, Water and Climate Events of the 20th Century, four major droughts occurred in China in the 20th century, two in India and one in the Ukraine and Volga regions. In the Sahel regions three major droughts have occurred, one lasting almost 15 years. Unfortunately, as in the case with floods, poor infrastructure and planning in those countries resulted in great numbers of deaths in all events.

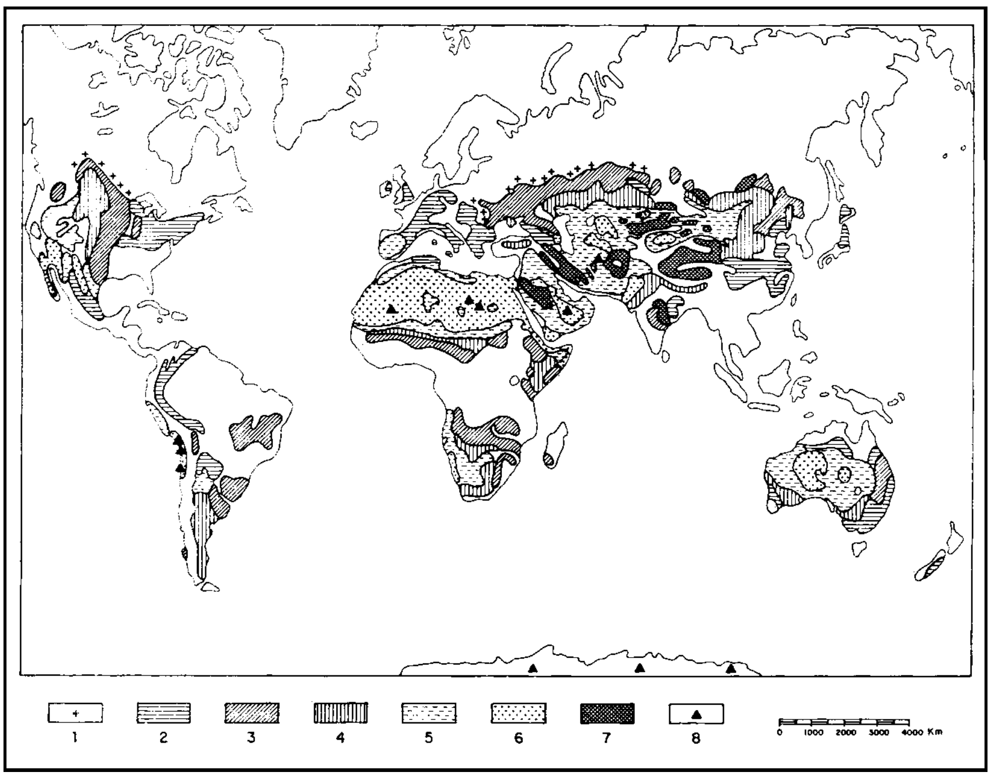


*Figure 54: Drought probability. Legend: **1**. Areas of sporadic very rare droughts; probability <10%; areas transitional to humid zones. **2.** Rare drought; probability of 10-15%. **3.** Frequent drought; probability 20-25%.*

14. El Nino

The El Nino event of 1926 was for Californians one to remember. Its destructiveness produced waves that broke second-story windows of the Capitola Hotel shown here. Photograph courtesy of Sandy Lydon.

In the middle of January, a fisherman in Peru looks desperately at the swarm of dead fish floating in the ocean. “It is this time again,” he murmurs to himself, “El Nino has arrived. Warm water..., not enough fish..., the birds will migrate... At least they can do that. We can only stay and hope that it does not last long.”

El Nino, Spanish for ‘The Child’, is a recurring phenomenon in the tropical Pacific Ocean that could be the single most influential phenomenon of our climate system. It owes its name to ‘Christ Child’ because it usually starts some time in December. Peruvian fishermen, who every several years noticed a change of the cold north-flowing stream, in which they fished, to a warm south-flowing ocean current, coined the name in the late 1800s. These fishermen knew very well that this change meant troubles for their business. What they did not know is that many areas of the world will have to, one way or another, suffer the consequences of El Nino.

To explain how this phenomenon occurs we have to again recall the general circulation of the atmosphere. If you recall, because of the spinning of the planet, the two Hadley cells emerge in the latitude belts of 0-30 N and 0-30 S. Air rises at the equator. This rising motion increases the pressure at higher levels at the equator in relation to the pressure at the same levels north and south of the equator. This makes the pressure aloft at the equator higher and as a result the flow turns and sinks at about 30 N and 30 S. The flow that converges at the surface is then deflected by the Coriolis force to the right in the belt 0-30 N and to the left in the belt 0-30 S. This, as we have discussed in chapter IV establishes at the surface the northern and southern hemisphere easterly trade winds (figure 55).

As these surface winds travel westward over the Pacific Ocean they act like a broom that sweeps the warm surface water (the surface water is warm because is exposed to solar heating) and accumulates it in the western Pacific Ocean in the area of Indonesia. In the eastern Pacific Ocean, because of the removal of warm surface water, an upwelling of colder water takes place. This colder water brings the nutrients from the deep waters, which maintain a healthy fish population in Peru, Ecuador, and Chile. The accumulation of warm surface water in the west and the upwelling of colder water in the east cause the air to rise over Indonesia and to sink off the west coast of South America, thereby establishing yet another convection pattern. This pattern, which is shown by the black arrows figure 56, is called the *Walker circulation* in honor of Sir Gilbert Walker, a Director-General of British observatories in India who, early last century, identified a number of relationships between seasonal climate variations in Asia and the Pacific region. This circulation brings rainfall to the west and clear skies to the east. The above-described conditions represent the normal conditions. The general sea topography has a ‘groove’ along the equator deepening to the east (where surface water is removed) and is highest toward the west (where surface water is accumulated). With such a configuration when a wind anomaly occurs (for example, weaker trade winds), the warm water to the west sloshes back and spreads over the whole tropical Pacific basin covering the colder surface water to the east. Everywhere in the tropical Pacific we now have warm surface water. The Walker circulation breaks down as air rises basically everywhere

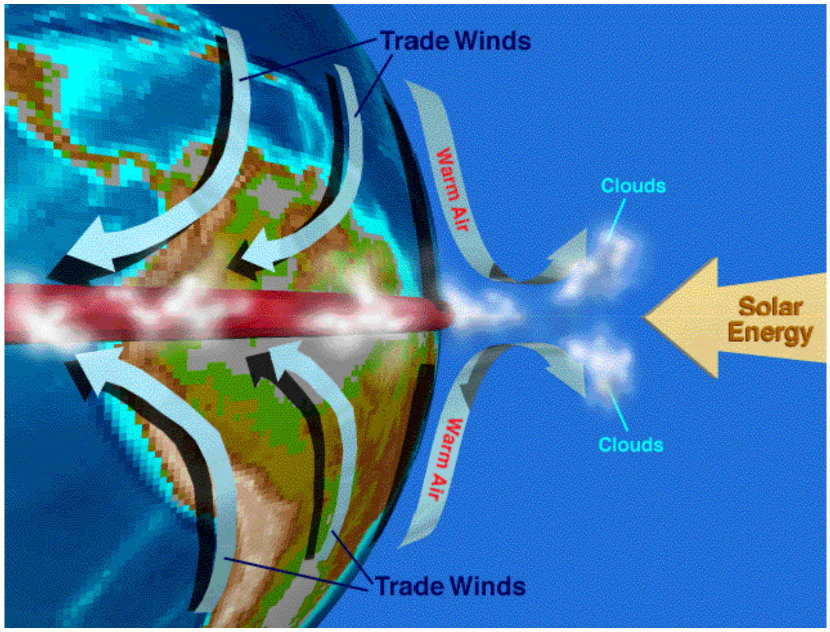


Figure 55: Surface winds north and south of the equator. Figure courtesy of Dr. M. A. Cane.

in the central Pacific. The upwelling in the eastern Pacific is cut off and needed nutrients to sustain the fish population are gone. As a result there is fewer fish and the fishery industry suffers great losses (in 1972 such an event caused the collapse of the once-large anchovy fishery industry in Peru). We now have an El Nino (figure 57).

Once an El Nino matures, the trade winds return to normal and the cycle is repeated. The normal conditions (especially when the contrast between the cool east and the warm west is great) are called a La Nina. El Nino is also referred to as a warm event and La Nina as a cold event. The cycle does not repeat regularly. The El Nino/La Nina cycle is rather aperiodic with an average period of about 4-5 years.

The problem with El Nino is unfortunately not confined to the fishery industry. Because of its large scale, El Nino affects many areas of the world. Under normal conditions, Indonesia, the southeastern edges of Asia and northeastern Australia are wet and the west coast of South America is cool and dry. This situation reverses during an El Nino. Severe droughts now strike Indonesia and its neighbors, whereas most of South America becomes wetter and warmer. Such changes in these regions are anticipated because they are under the influence of the Walker circulation. The effects of El Nino, however, are not confined in that area of the world. Even though far away, another unfortunate area will be affected. Which is this region? Make a wild guess!

The rest of the atmosphere does not just sit there and watches El Nino and La Nina succeeding each other. The changes in the Walker circulation and in the surface temperature patterns in the tropical Pacific are too dramatic and too extensive to leave the rest of the atmospheric circulation unaffected. You may think of the changes in the tropical Pacific as 'breaking news'. The 'news' are broadcasted by the 'media' thus reaching and affecting faraway places. In the atmosphere 'media' are established via several physical mechanisms, which allow the tropics to communicate with the higher

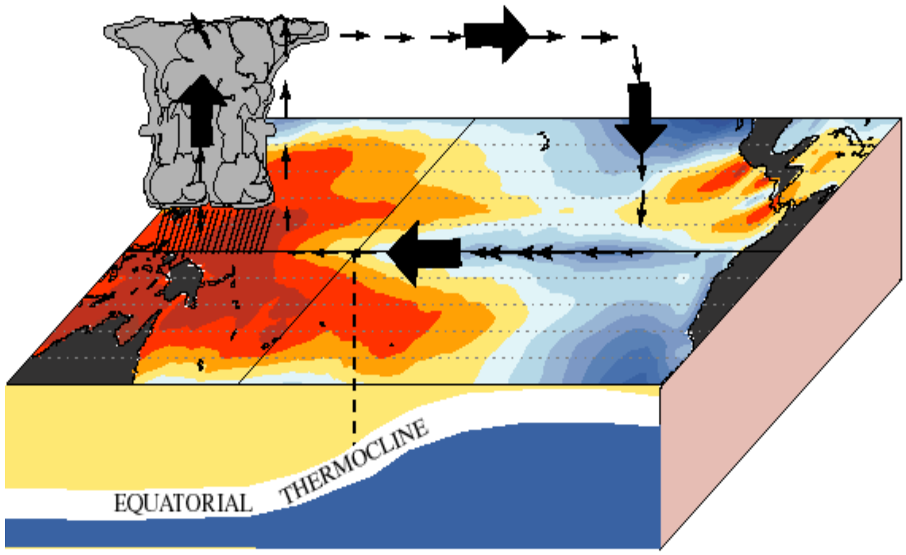


Figure 56: The Walker circulation. Courtesy of NOAA/NWS/Climate Prediction Center.

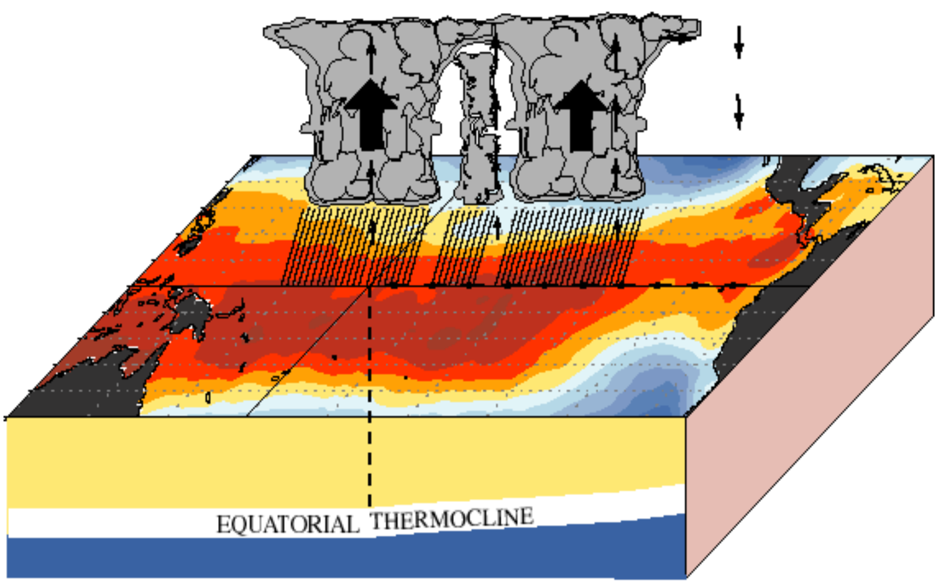


Figure 57: El Nino conditions. Courtesy of NOAA/NWS/Climate Prediction Center.

latitudes. And as in the case of breaking news the areas to be affected more directly will be the areas closer to the source. It is not surprising then to see that the atmospheric circulation over the North Pacific Ocean and North America will be the first to feel the changes happening to its neighbor to the south. During an El Nino the average flow over the contiguous United States is more or less zonal (figure 58) and it tracks into California and across the southern United States. Under La Nina conditions the flow is strongly meridional and as a result the storms from Pacific are diverted to the north. The associated conditions over N. America are now almost reversed.

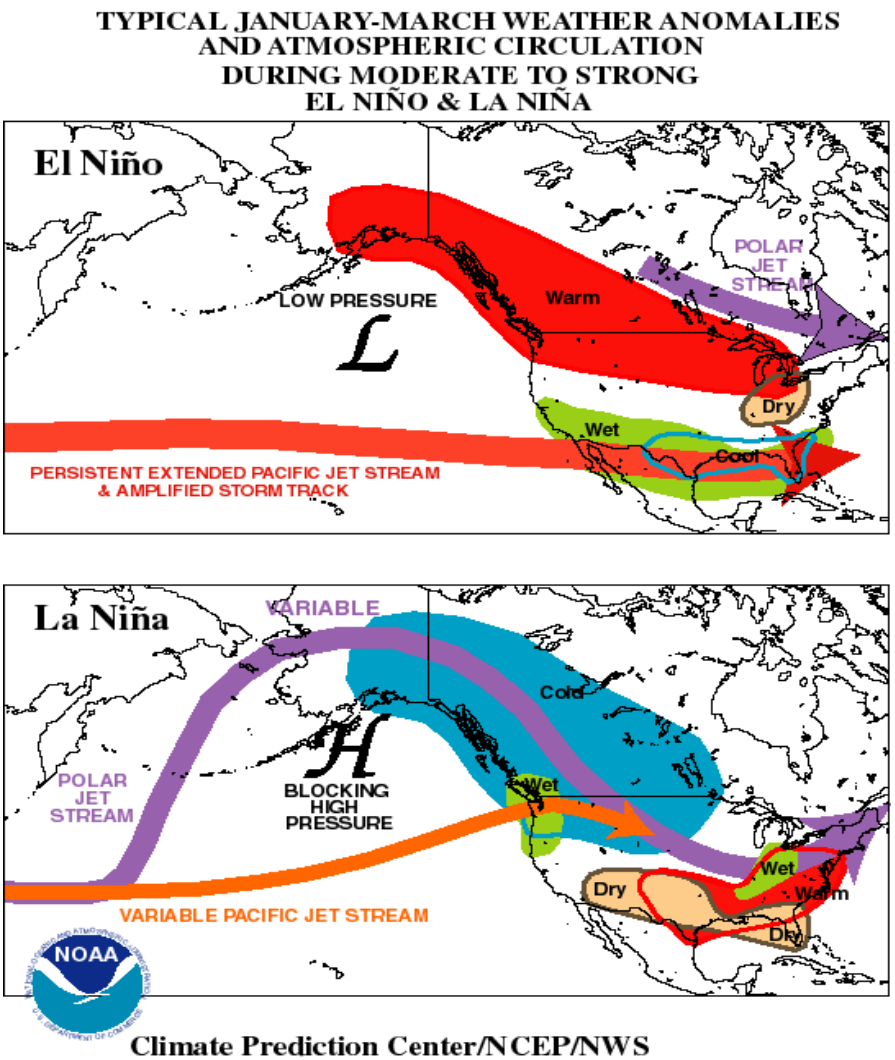


Figure 58: Conditions associated with El Nino (top) and la Nina (bottom).

These changes bring an increased number of storms along the California coast, increased rainfall in the southern States and warmer temperatures in the Pacific Northwest. The severe flooding in California in 1998 and in Mississippi in 1993 are attributed to strong El Nino events brewing in the tropical Pacific at those times. Together with changes in the atmospheric circulation, warm surface water bouncing off the west coast of South America can often reach as far as the West Coast of the United States. This raises the temperature of coastal water by several degrees. This in turn increases evaporation and the supply of extra moisture, which can then be incorporated into the storms to produce greater amounts of rainfall.

By studying the weather conditions associated with El Nino years scientists have been able to identify certain recurring patterns with an El Nino event. These relations are called *El Nino teleconnections*, and while statistical in nature they point to several relationships. From all the places in the world not in the immediate area of El Nino, the United States is the one most affected. Europe, Africa, and most of central and north Asia are also affected but to a lesser degree. The most significant of teleconnections between El Nino and the United States appear to be the following:

- A drier and warmer than normal fall and winter in the Pacific Northwest.
- A wetter and stormier than normal winter in California and the southern States
- A warmer than normal late fall and winter in the northern Great Plains and the upper Midwest
- An increase in the number of East Coast winter storms.

There is also a suggestion that during El Nino years there is fewer Atlantic hurricanes. Studies indicate that less probable for hurricanes to occur during El Nino years than in non-El Nino years. The physical explanation is that during El Nino years the zonal flow interrupts with the development of a hurricane by blowing off its top. The worst El Nino of the 20th century is the 1982-83 event. Significant meteorological changes resulted in many weather related disasters all over the world. In the United States flooding and mudslides occurred in the Colorado River basin and downpouring in the Gulf States claimed many lives and serious property damage. Unusually mild weather and a lack of snow were evident across much of the central and northeastern portion of the U.S. The economic impacts of this El Nino event were tremendous. The overall loss to the world economy in 1982-83 as a result of the changes to climate due to the El Niño amounted to over $8 billion. The cost to the United States alone was more than one billion dollars.

The cold phase (La Nina) also has its effect on the United States. The most important effects are the following:

- Drier than normal Southeast, Great Plains, and Southwest. A tendency for wetter than normal Mississippi and Ohio Valleys. The Pacific Northwest tends to be wetter during La Nina than El Nino.
- Colder-than-normal conditions become more likely across the northern U.S. and milder than normal conditions across the South and East.

Some research also suggests that outbreaks of violent tornadoes east of the Mississippi River may be more likely during springs that follow La Nina than during those that follow El Nino.

There is evidence that one of the culprits behind the onset of the 1988 drought might have been La Nina. During La Nina, the surface of tropical Pacific is colder than it is during El Nino. It appears that the adjustment of the atmospheric flow to these colder temperatures involved the establishment of a high pressure system over the central United States; a key ingredient in setting up drought conditions.

Located between two great oceans does not expose the United States to the effects of El Nino only. Other related to oceans features of our climate have been identified that affect the weather in the United States. The first is the North Atlantic Oscillation (NAO). This phenomenon is caused by a net displacement of air from the Arctic and Icelandic regions to the subtropical belt near the Azores and the Iberian Peninsula. On the average (recall our general circulation), in the former region the surface pressure is low and in the later regions is high. This ‘sea saw’ (as has come to be known) of atmospheric mass makes the low pressure area over the Icelandic regions even lower, which makes the low pressure system a stronger low pressure system. The transports of this mass in the Azores region make the high pressure system even higher, which means that the high pressure system becomes stronger. This increase in pressure difference (which defines the positive phase of NAO; figure 59 top) results in stronger westerly winds and stronger winter storms. At the same time it modifies the pathways of the storms, which now become more northerly. The effect of these changes is that northern Europe experiences wetter winters and southern Europe drier winters. The effects, however, do not extend over Europe only. North America is also affected. The stronger westerly flow makes the penetration of cold air masses from Canada difficult. As a result, Canada experiences cold and dry winters and the eastern United States experiences mild and wet conditions. When the air displacement relaxes, the pressure difference decreases and we go into the negative phase (figure 59 bottom). During this phase the westerlies are not so strong and more or less the opposite effects are observed. The eastern United States experiences more frequent cold outbreaks and snowy winters.

This phenomenon is known for more than two centuries. The Danish missionary Hans Egede Saabye, while in Greenland during 1779-1778, wrote in his diary "In Greenland, all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely." Fishermen were also aware of this phenomenon because it has major impacts on oceanic ecosystems and North Atlantic fish stocks.

Despite the effort and research on this subject, very little is known about the mechanisms involved in this oscillation. Early suspicions that it relates to El Nino cannot be proven with great certainty. Many suspect that NAO is a result of many complex factors combining to produce an almost “random” event. Nevertheless, it does affect the United States and its complexity makes it quite unpredictable, which means that its effects can be fully surprising.

The second oscillation is the Pacific Decadal Oscillation (PDO). Only recently discovered, this oscillation has also a positive (warm) and negative (cold) phase (figure 60). During the warm phase the sea temperatures at the surface tend to be anomalously cool in the central North Pacific Ocean and unusually warm along the west coast of the Americas. The sea level pressure also varies, with low pressures over the North Pacific and high pressures over western North America and the subtropical Pacific. During the cold phase the opposite is observed. The change in location of the cold and warm water masses alters the flow of the atmosphere above the ocean. During the warm phase the flow delivers storms across the United States. During the cold phase this is reversed and the United States is usually drier. Major changes in northeast Pacific marine ecosystems have also been correlated with phase changes in the PDO. During warm phases coastal ocean biological productivity is enhanced in Alaska and is reduced off the West Coast of the contiguous United States. The opposite is observed during cold PDO phases. The PDO and the El Nino/La Nina cycle interact with each other. This is unavoidable since they both occur in the same ocean. However, the typical time scales associated with PDO and El Nino are much different. While an El Nino or a La Nina event usually last less than two years, a PDO phase appears to last 20-30 years. Even though the data are not long enough to confidently define this time scale, the PDO is undeniably a much slower phenomenon. However, an El Nino might enhance the effects of the warm PDO phase in the United States, as it accentuates the warmth of the surface water along the west coast. Similarly, a La Nina in the tropical Pacific might enhance the effects of a cold PDO phase. In the late nineties, it appears that the PDO has switched from warm to cold phase.

In the coming years more information and research will undoubtedly provide insights about El Nino and especially about the North Atlantic Oscillation and the Pacific Decadal Oscillation. However, while our understanding and prediction of these phenomena will improve, their effects will remain the same. What also will remain a fact is that the United States is the only place on earth that is exposed to the effects of all three: to El Nino/La Nina cycle, to NAO and to PDO.

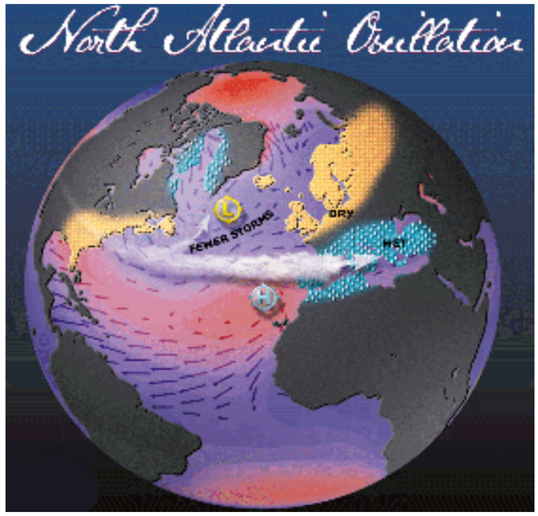


Figure 59: The positive (top) and negative phase of NAO. Source: Martin Visbeck.

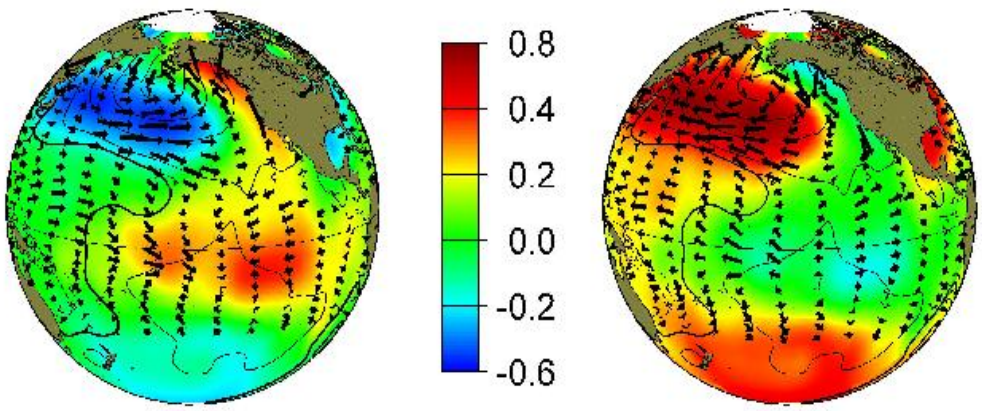


Figure 60: The warm (left) and cold (right) phases of PDO. Courtesy of University of Washington/JISAO.

15. Some records and local climate classification

The Guinness book lists 30 world records for weather extremes. Nine of them (most than any other place of the same area on Earth) belong to the contiguous United States (Hawaii is also credited with one record, which is not listed here). They are the following:

1. **The biggest temperature variation in one day**: A fall from 44 F to -56 F (100 F variation) at Browning, Montana, January 23-24, 1916.
2. **Greatest drop in pressure measured in a tornado**: 100 mb near Manchester, South Dakota on June 24, 2004. This is 1/10th of the pressure the whole atmosphere exerts on the Earth's surface.
3. **Greatest snowfall from a snowstorm**: 189 inches at Mount Shasta Ski Bowl, California, February 13-19, 1959.
4. **Greatest snowfall in a 12-month period**: 1,224 inches (102 feet) at Paradise, Mt. Rainier, Washington between February 19, 1971 and February 18, 1972.
5. **Largest measured tornado**: 5,250 feet in diameter. Occurred near Mulhall, Oklahoma on May 2, 1999.
6. **Longest discontinuous tornado:** Occurred on May 26, 1917. It traveled 293 miles across Illinois and Indiana.
7. **Most tornadoes in 24 hours:** 148 tornadoes swept through the southern and mid-western States on 3-4 April, 1974
8. **Windiest place in the world:** Mount Washington, New Hampshire where a wind speed of 231 miles per hour was recorded on 12 April, 1934.
9. **Largest snowflake:** January 28, 1887 at Fort Keogh, Montana. The snowflake, which was described in the journal Monthly Weather Review, was 15 inches in diameter and 8 inches thick.

Some other records found in NOAA's archives include 1) the greatest 42-minute rainfall total (12 inches at Holt, Missouri on June 22, 1947), 2) Greatest snowfall in one month (390 inches at Tamarack, California, January 1911), and 3) Greatest snowfall in 24 hours (76 inches at Silverlake, Colorado on April 14, 1921).

What is amazing about these records is that they are not records that one should expect by virtue of the country being in a specific location. For example, the record for the coldest temperature belongs to Vostok, Antarctica. The record for the highest temperature is claimed by El Azizia, Libya with 136 F (Death Valley, California is a very close second with 134 F). Both these records, however, are expected. One is at the coldest region of the planet and other is in the Sahara desert. What makes the United States records stand out is that most of them do not represent the expected. They represent great departures from the expected. In my opinion this is what makes the weather of a place hard to deal with. Such large fluctuations are very common in the United States in both time (from day to day or month to month, etc.) and space (from State to State). Consider, for example the following list of major weather events that occurred in December 2004 around the globe according to National Climatic Data Center, NOAA:

December 1: Record heat in Australia.
December 2: Very strong winter typhoon in Taiwan.
December 3: Very strong winter typhoon in Philippines.
December 3: Record heat in Canada.
December 5: Record rain in California.
December 12: Worst floods in 40 years in Malaysia.
December 15: 50 foot waves in Hawaii.
December 16: Record cold in Florida.
December 17: Hurricane force winds in California.
December 17: Hurricane force winds in France.
December 19: Record heat in Montana.
December 19: Coldest December 19th in 50 years in Israel.
December 19: Hurricane force winds in England and Germany.
December 21: Hurricane Force Winds in Canada and United States (Montana).
December 23: Severe storms in South Africa.
December 23: Hurricane force winds in Finland.
December 23: Worst storm in Ohio's history.
December 23: Huge Storm in the Sea of Japan.
December 24: Severe storms in Finland and Scotland.
December 25: First snow in 86 years in Texas Town.
December 26: Unexpected snow in England.
December 28: Alaska rainfall 212% above normal.
December 28: Heavy rains and floods claim 20 lives in Iran.
December 29: Abnormally high temperatures in the Midwest.
December 30: First snowfall ever in United Arab Emirates.

Eight out of the 25 listed events occurred in the contiguous United States (one more occurred in Hawaii and one more in Alaska). No other region on the planet had as many. And this is not an exception. When it comes to significant weather events, the United States is, time after time, one the hardest if not the hardest hit areas of the world.

Additional evidence in favor of this and previously made arguments is supplied by a comparison of regional climates in the United States and in the rest of the world.
The word climate derives from the Greek word κλίμα, which indicates the angle of the incident solar radiation at a place. This angle depends on latitude and as we all know the characteristics of regional climate vary with latitude. In 1918, the Russian born scientist Wladimir Koppen published a subjective climate classification system based on temperature and precipitation. As meteorological observations increased through the years, the system was modified and refined from its original version and today, known as the *Koppen classification system*, it represents the accepted boundaries between regional climates. The system divides climate into six major climate types (figure 61).

The first type is climate type **A** and refers to tropical moist climates. For a region to be qualified for this type it must have in all months an average temperature above 64 F and precipitation must exceed evaporation. This type is further subdivided to **Af** (if all months receive more than 2.4 inches of rain), **Am** (if there is a short dry season with at least one month receiving less than 2.4 inches of rain) and **Aw** (if the summer is wet and winter is dry). The regions assigned this climate type comprise 36% of the Earth's land surface.

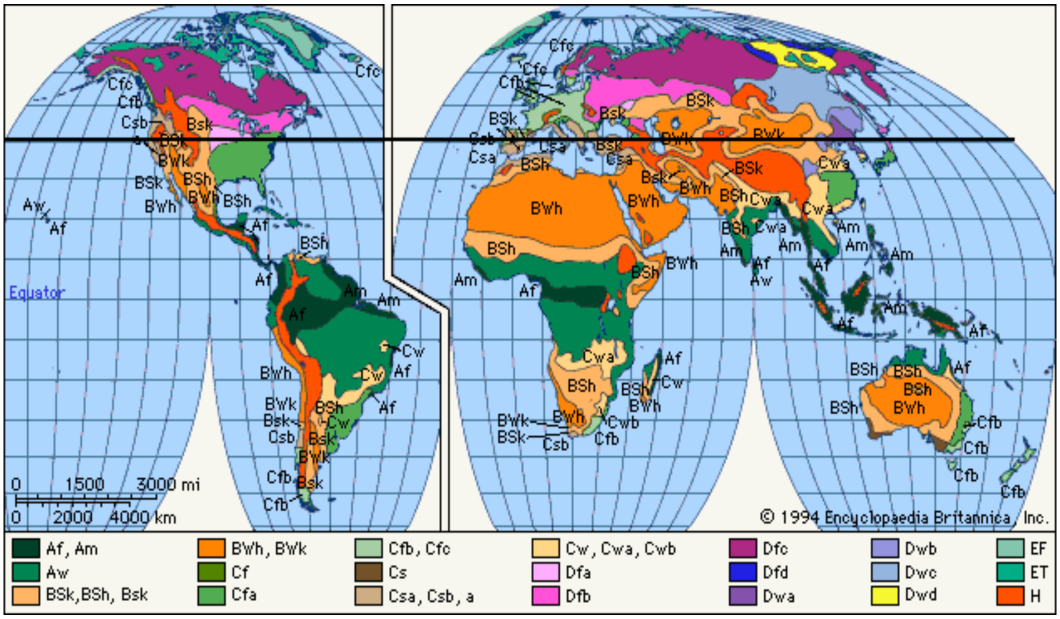


Figure 61: The Koppen classification system. Source: Encyclopedia Britannica.

The second type is climate type **B** and refers to dry climates. Here, yearly precipitation is lower than evaporation. This climate type is subdivided into **BW** (for desert areas where precipitation is less than half of evaporation; for example, Phoenix, Arizona) and **BS** (for semi-arid, steppe regions where precipitation is greater than half of evaporation; for example, the US Great Plains). The total area of dry climate regions is 35% of the planet's land area.

The third type is type **C** and it represents humid climates with mild winters. 27% of Earth's surface and 55% of world's population fall into this type. The criteria for type **C** climate are that the warmest month should be at least 50 F, on the average, and the coldest month should be at least 32 F but less than 64.4 F. As with the other types, this type is also divided into subtypes based on precipitation. Subtype **Cf** refers to moist areas with no dry period (the letter **f** stands for the German word *feucht* or moist). Florida and Texas are good example of a **Cf** climate type. Subtype **Cw** has only winter as dry period (examples include areas in Brazil and China). Subtype **Cs** has dry summers. The Mediterranean regions and California have this type. Mid-latitude storms are the main systems delivering precipitation to areas with this type of climate.

The fourth climate type is type **D**, which represents moist climates with severe winters. To qualify for this type a place must have its warmest months above 50 F and its coldest month below 32 F. This type is subdivide to moist all the time, **Df**, (areas like Boston) and moist with dry winter, **Dw,** (areas like Manchuria). Winters with type **D** are bitter cold with strong winds and in the case of **Df** with blizzards and snowstorms. The areas under this type sum up to 21% of the total land area.

Climate type **E** represents Polar climates. In this case the warmest month is not warmer than 50 F. For this type we have two subdivisions, **ET** for tundra (northeastern part of the Canadian Northwest territories) and **EF** for polar ice cap (for example, most of Greenland).

The final type is climate type **H** and it is reserved for highland areas. Because the temperature decreases with altitude it is possible for mountainous areas to be in low latitudes but have permanent ice cap. In this case, and to avoid complications, we simply assign these places to the undifferentiated highland type.

Each subtype is also subdivided to differentiate warm from mild and cold regions. For instance, Florida and Texas located along the Gulf of Mexico are designated as **Cfa** with **a** indicating that the average temperature of the warmest month is above 72°F. Thus, **Cfa** represents a mild mid-latitude climate with no dry season and a hot summer. Subtypes **Cfb** and **Cfc** represent moist climates at higher (colder) and lower (warmer) latitudes, respectively. England, for example is **Cfb** whereas the coastal region of northern Norway is **Cfc**). Similarly, Des Moines, Iowa, is classified as **Dfa**, whereas Winnipeg, Manitoba, is classified as **Dfb** and Northern Quebec is classified as **Dfc**.

Figure 61 shows the distribution of the climate types in the globe. There is a lot of detail and variability in this map but we can make two important observations.

- Nowhere else in the world except in the USA there is such a close proximity between **Cfa** (humid hot summers) and **Dfa** or **Dfb**(severe winters), which represent two extremes.
- If we were to travel from New York, to Chicago, to Denver, and over the Mountains to San Francisco (more or less across the 40 N latitude outlined by the thick solid line), we will move from a moist type **C**, to a type **D**, to a type **B**, to a type **H**, and finally to a dry type **C**. The only types we will not encounter will be the tropical and the polar types (thank God!). Such transitions do not occur over the same distance in other parts of the world at this or any other latitude.

The above two points testify about the complexity, diversity and extremity of weather in the United States. Together with our previous evidence they underscore the fact that the United States will always have to deal with the reality that it is located in an area of our planet that is open to everything. It is open to both the Pacific and Atlantic Oceans and thus to their 'mood' swings. It is open to the north and south and thus to all possible air masses and their combinations. It is affected by both easterly and westerly flow and as such it is vulnerable to midlatitude and tropical storms. It is not surprising that every possible weather calamity occurs in the United States and not just every once in a while but normally. In the grant climate scheme the United States is, simply, in the middle of everything. As if this were not enough the fate of our already multifarious climate is at the mercy of *global climate change*.

16. Climate change

Glacier in East Coast Mountains of Baffin Island, Nunavut, Canada.
John T. Andrews, INSTAAR and Department of Geological Sciences, University of Colorado, Boulder.

In Icelandic sagas it is assumed that ancient giants used to leave in Scandinavia. These giants were all children of a huge Ice Giant who ruled the north. When the Ice Giant was killed, his blood raised the sea levels and drowned all his children. These ancient giants refer to mammoths and other large mammals that existed thousands of years ago. This story may be the first recorded myth about the existence of an ice age. Its coming to an end melted the extensive ice sheets and raised the sea levels that killed all these creatures.

We now know that mammoths and other giant mammals were thriving thousand of years ago. Whether a change in the climate was responsible for their extinction, or over-hunting by humans, or a combination, nobody knows for sure. But, what we know for sure is that climate does change. Climate fluctuates between two states. One state is the one we are in now and have been for the last 10,000-12,000 thousand years. The other state is a much colder state, where the average temperature of the planet is 10 F lower. This might not sound like much, but when it comes to the average of the planet it represents a serious change. As temperatures fall, most of precipitation in the north falls in the form of snow, which then turns into an ice layer. Because summers also cool, their warmth cannot melt all the ice that formed during the winter months and as a result the ice, grows. Every year a new layer of ice is added on the top of the previous layer and as the temperatures keep on falling the ice spreads southward. This moving mass of ice is called a *glacier.* Keep these processes going for many thousands of years and the glacier can reach as far south as Indiana. Figure 62 shows the extent of ice sheets today (top) and 18,000 years ago when the planet was experiencing its last ice age. During that time ice covered all of Canada and the northern United States. The vertical extend of the ice was an incredible two miles at some places. The only other region in the world affected was Scandinavia and northern Russia and Siberia. If a new ice age were to happen today, places like New York, Boston, and Chicago will be obliterated by the crushing ice. The rest of the United States will also see dramatic changes.

As the Earth cools the climate becomes drier because the global 'weather machine' that evaporates water from the oceans and drops it on the land is less effective when the temperatures are colder and when the polar sea ice is extensive. As a result colder and drier than present conditions predominate across most of the USA. The eastern deciduous and conifer forests are gradually replaced by more open conifer woodlands with cooler-climate species of pines and a large component of spruce. The open spruce woodland slowly spreads further west, into what is now the prairie zone. The increased aridity and lowered sea levels make Florida a land of drifting sand dunes.

The young Swiss naturalist Louis Agassiz first proposed the idea that an ice age had occurred in the early 1800s. Agassiz noted that the slow action of mountain glaciers in Switzerland had affected the surrounding landscape. His evidence included *glacial till*, *rock striations*, and *loess*. Glacial till is a mixture of sediment particles whose size may range from fine grains to house-sized rocks. They are lifted from the ground and transported to other places as the glacier advances. Large glacial till rocks that have been moved hundreds, or even thousands, of miles from their source are called *erratics*. Rock

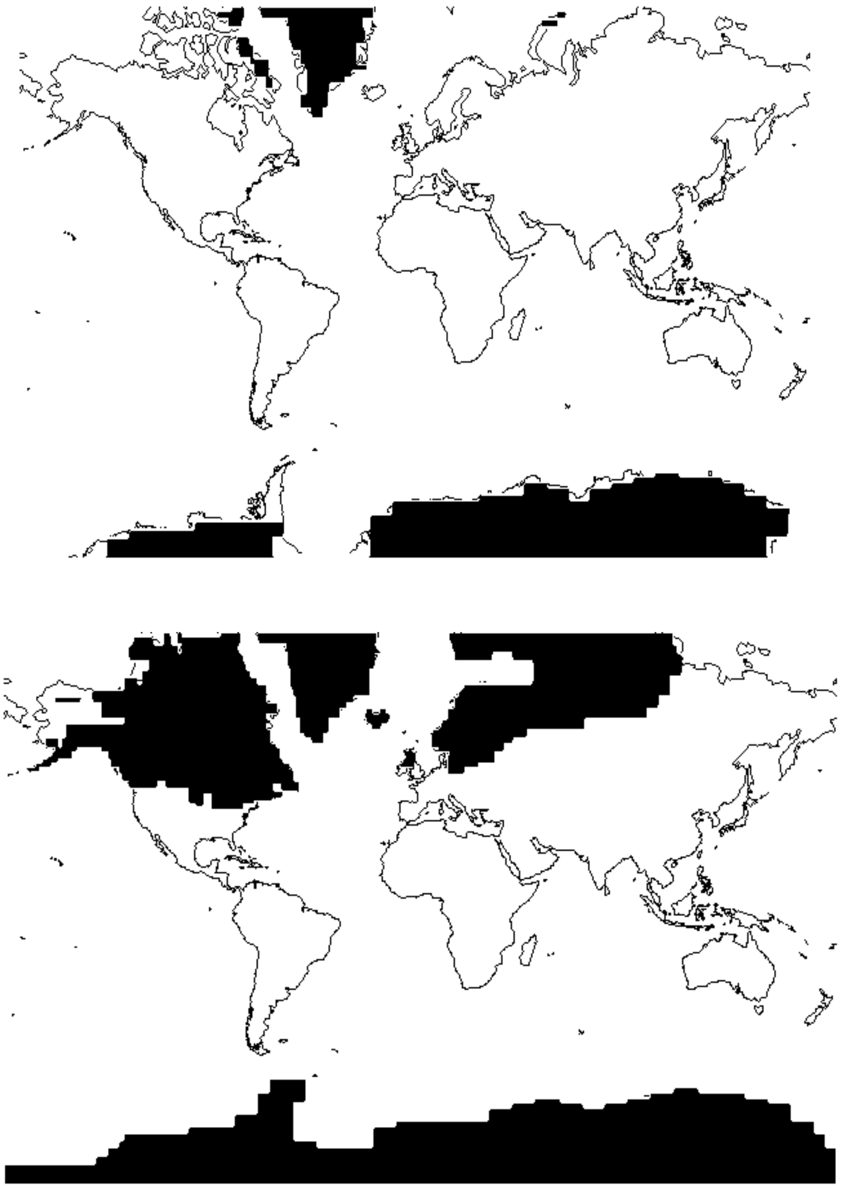


Figure 62: Ice extent now (top) and during ice ages (bottom). Source:http://www.ncdc.noaa.gov/cgi-bin/paleo/peltice.pl

striations are large grooves and channels that form on the surface of rocks as a glacier grinds against them. Loess is created when glaciers grind up stones into fine particles known as *glacial flour*. This flour is then transported away from its source by wind and by streams of melt water and is deposited on flood plains as silt. When this silt dries, it is picked up by wind and is spread across the landscape, often over very large distances. In

Colorado, loess from ancient mountain glaciers covers most of the eastern part of the State.

Agassiz was the first one to note that these features occurred in areas far from the mountains, where no glaciers existed. Based on these observations, Agassiz deduced that extensive glaciers had existed in the past.

Today we know that many ice ages have occurred in the past and that an ice age is followed by today's climate, which is followed by a new ice age and so on. Because such climate shifts are too dramatic in certain places of the planet, they leave a trail of evidence behind them. To start with there is geological evidence. The advancing or retreat of the glaciers and the pressure exerted by it on the underlying surface modify the surface. The last ice age, refered to as the Wisconsinan glaciation, had a considerable effect on the landscape of the North America. The Great Lakes were formed by ice deepening old valleys. The old Teays River drainage system was largely reshaped into the Ohio River drainage system. The flow of other rivers was disrupted and diverted to new channels, such as the Niagara, which formed a waterfall when the waterflow encountered a steep slope. Long Island was formed from glacial till and the numerous lakes on the Canadian Shield in northern Canada were created by the action of the ice. Perhaps the biggest events an ice age have caused in the United States (and elswhere) are the *megafloods*. One such megaflood, possibly the biggest flood in the world for which there is geological evidence, took place about 15,000 years ago when the last ice age was waning down. When the ice sheets advance they may form a natural ice dam plugging the valleys below lakes. Such an ice dam formed near a lake known as Glacial Lake Missoula (then half the size of today's Lake Michigan). Over time, the lake weakened the structure of the ice dam, eventually breaking through it. In a time interval of just 48 hours, geologists believe, the collapse sent 500 cubic *miles* of water cascading across the Pacific Northwest. This tremendous deluge created, practically overnight, the very unusual landscapes of eastern Washington known as the scablands. Another megaflood of about the same severity occurred at about the same time in the Altay Mountains of Siberia. Simply, ice ages can modify the terrain completely.

The main tool to decipher the mysteries of ice ages is the *ice cores*. As we mentioned above as the planet cools layers of ice form one of the top of another. Inside each layer secrets of the conditions of the atmosphere at the time of the ice formation are hidden. In the beginning of this book we saw that oxygen is one of the main gases in the atmosphere. We also know that water is made of 2 atoms of hydrogen and 1 atom of oxygen. However, both hydrogen and oxygen have isotopes. Isotope means 'same place' referring to the fact that isotopes of a given element have the same atomic number and hence occupy the same place in the Periodic Table. Isotopes have different atomic mass, which means that one is heavier than the other. For example, hydrogen has three isotopes: normal hydrogen (H), deuterium (D), and tritium (T). Normal hydrogen consists of 1 proton and 1 electron and has an atomic mass of 1. Deuterium has 1 neutron in addition to 1 proton and 1 electron, which makes its atomic mass equal to 2. Tritium has yet another neutron, and an atomic mass of 3. Oxygen has two isotopes: oxygen-16 (^{16}O) and the heavier oxygen-18 (^{18}O). While water in the form $H^{16}O\,H$ (our cherished H_2O) is the most common, heavier water as HOD or $H^{18}OH$ also forms. The different atomic mass of the isotopes causes the different types of water to have different properties. For example, water evaporates easier and condenses more readily when it is in the form of HOD or $H^{18}OH$ than when it is normal (and lighter) water, $H^{16}OH$. Since evaporation depends on temperature, in times of higher temperatures there will be more HOD or $H^{18}OH$ in the air than in times of lower temperatures. Thus when this air develops precipitation in the Polar regions there will be more D or ^{18}O in the ice layer during warmer conditions. Ice cores drilled in Greenland and Antarctica (some of the more than a mile long) have clearly shown that the concentration of isotopes fluctuates in the various layers. This variation has been translated into temperature fluctuations over thousands of years in the past (figure 63).

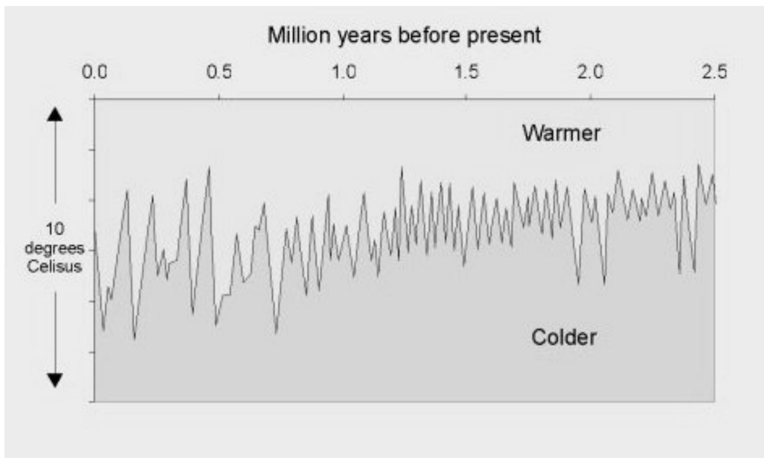


Figure 63: Temperature fluctuations from ice cores.

A similar picture emerges from other climate reconstruction, such as records of deep-sea records of foraminifers. More (less) oxygen-18 in the air during warm (cold) conditions means that the ocean remains with less (more) oxygen-18 when the climate is warmer (colder). Foraminifera are unicellular organisms that build their skeleton from calcium carbonate, incorporating oxygen from the seawater. As they die they sink and are deposited on the ocean floor. By measuring the ratio of oxygen-16 to oxygen-18 in the skeletons of foraminifera from different levels of sediment from the ocean floor, scientists can construct graphs that again relate to temperature fluctuations.

Other tools, such as the studies of pollen in soil deposits and annual growth of tree rings can also produce proxy temperature records. The overall conclusion is beyond argument. The swinging of our climate form ice ages to today’s climate is proven beyond a doubt.

What might be causing this oscillation? The answer to this question can be found to the source of energy for our climate: solar radiation. We know by now how weather depends on solar radiation. We have seen how solar radiation sets things up in the atmosphere and how the amount of radiation received determines how warm or how cold a place will get. It is reasonable then to assume that if somehow the amount of radiation received by Earth changes so will its average temperature. This assumption is behind the *Milankovitch* *theory of climatic change*. Milutin Milankovitch was a Serbian mathematician born in 1879. He was the first to promote the theory that long-term climate changes occur because of the motion of the planet.

It is well known that the orbit of Earth around the Sun is elliptical. It is also known that the shape of this ellipse fluctuates from more elliptic to less elliptic. How elongated the ellipse is defines Earth’s *eccentricity* (figure 64). As we discussed in an earlier chapter, because the orbit is an ellipse the planet receives more radiation at the perihelion (closest point) than in the aphelion (farthest point). Nowadays, the difference in distance between the aphelion and perihelion is about 3%. This 3% difference in distance means that Earth experiences a 6% increase in received solar energy in January than in July. When the Earth's orbit becomes more elliptical the amount of solar energy received at the perihelion could be 20 to 30% more than at the aphelion. Undoubtedly, such changes would result in significant climate changes. At present the orbital eccentricity is nearly at the minimum of its cycle, which repeats every 100,000 years.

It is also known that the earth spins on its axis and that axis is tilted. As a result at the perihelion the northern hemisphere is facing away from the Sun whereas the southern hemisphere is facing more directly the source of heat. Because of that at the perihelion the northern hemisphere has winter and the southern hemisphere summer. At the aphelion the opposite takes place and the seasons reverse. Now, if the tilt increases, it means that at the perihelion the northern hemisphere is facing even more away from the Sun, meaning that it is intercepting less radiation. At the same time the southern hemisphere is facing more directly, thus it is intercepting more radiation than before. This means that the winters in the northern hemisphere will become colder and the summers in the southern hemisphere will become warmer. Similarly, the summers in the northern hemisphere will become warmer and the winters in the southern hemisphere will become colder. Thus, if the tilt increases the extremes between the seasons increase. This, however, is not the only problem. Because of colder temperatures during winter, more snow will accumulate. One may argue that this extra snow will melt because of the temperatures during summer will be higher. But unfortunately, our climate system is not that linear. The truth is that because of the uneven distribution of land and water in the two hemispheres, the increase in temperature in the summer is not enough to offset the extra snow. As a result snow cover increases and as this continues over many years glaciers begin to form and occupy land areas. Because ice is very reflecting, more ice means that more sunlight is reflected, which in turn means that the temperature will drop further. Eventually both summers and winter will become cooler, which will reduce melting in the summer even more. This is a positive feedback mechanism, which accelerates the cooling and the spreading of glaciers. At present, the tilt is in about the middle of its range of 21.5-24.5 degrees. This oscillation, which is called the *obliquity* of the Earth’s axis, has a periodicity of 41,000 years.

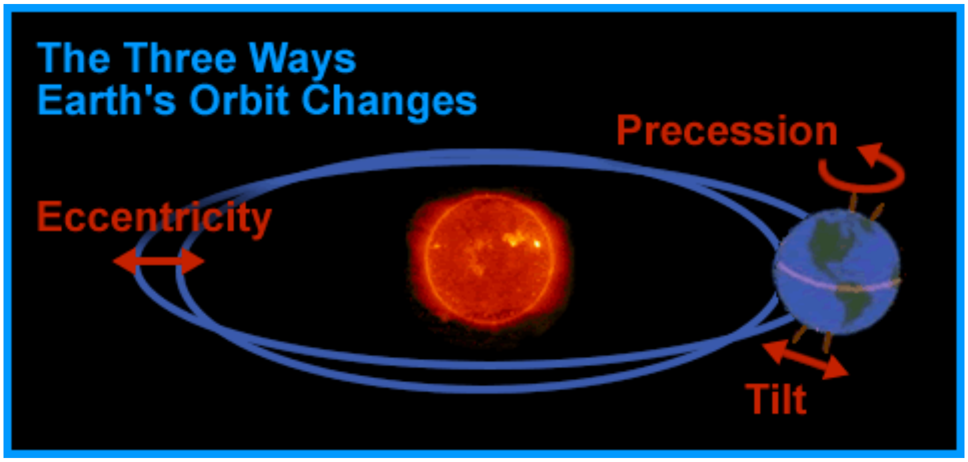


Figure 64: Eccentricity, Precession, and Tilt affect the amount of solar radiation received. Courtesy of UCAR

Finally, it is also known that as the planet spins it wobbles back and forth on its axis. This motion is similar to a spinning toy top running down and beginning to wobble back and forth on its axis. This wobble, which is called the Earth's *precession* has a period of 23,000 years and can also affect the amount of radiation received on the planet. All three changes can be viewed as external forcing to climate, dictating the amount of solar radiation received by the planet. From the three forcings the obliquity is the stronger, followed by the precession. The weakest forcing is the eccentricity.

These three motions are the basic components of Milankovitch's theory. And indeed, mathematical analysis of records like the one shown in figure 63 has identified these periodicities. In fact, in the last 800,000 years, ice sheets have peaked every 100,000 years, which coincides with the eccentricity. Superimposed on this cycle the 41,000 and 23,000 years cycles of the obliquity and precession have also been identified. Interestingly, before that (between 800,000 and 2 million years ago), the 100,000 year periodicity is absent. During this time the dominant forcing is the obliquity with its 41,000 year periodicity. While it is expected that the obliquity will be the dominant forcing, the fact that in the last 800,000 years the dominant forcing is the weakest of the three, has stirred some controversy. The point to be made here is that climate is very complex and nonlinear and that these three forcings are not they only ones acting on climate. Many other factors contribute to how climate evolves. In fact, we now know that superimposed to the above climate shifts are many shorter time scale shifts. It appears that climate can shift from cold to warm slowly over long time scales and abruptly over short time scales.

Nevertheless, it is now accepted that when the new ice age (whether severe or not, slow or abrupt) comes, the United States will be one of the few areas that will be affected severely. Of course, unlike in the movie *The Day After Tomorrow* where Earth plunges into an ice age in just three weeks, such a change may take many years.

Let us now turn into the other climate change scenario; that of a warming climate. As we have discussed in Part II chapter 2, in the last 120 years or so an overall positive temperature trend known as global warming is observed. What can global warming do to weather? How does it affect it and which areas of the world are more vulnerable?

Recall that greenhouse gases such as CO_2 do not absorb visible light (which is the main radiation warming the planet during the day) but absorb some of the infrared radiation that is emitted by the Earth's surface (which cools the surface at night). This absorption keeps the air close to the surface warmer than it would have been if these gases were not present in the atmosphere. Simple logic then, tells us that if the concentration of these gases in the atmosphere increases, the absorption will be stronger and more of the escaping heat will be retained close to the surface. As a result, the temperature near the surface will increase. Think of these gases as a blanket keeping the planet warm at night. Increasing their concentration will have an effect similar to adding another blanket: get warmer. This is the basic physical principle behind what is now called the *greenhouse warming theory*. Many believe that the observed global warming is related to the increase of carbon dioxide and other greenhouse gases.

While this makes perfect sense, there is a lot of controversy and unanswered questions. The reason is that the climate system is very complicated and has many components. Because of that, many argue that the problem is not as simple "more carbon dioxide in, higher temperatures out". For example, the oceans have the ability to absorb carbon dioxide. Exactly how much is not clear but they do. And some believe that they have the ability to absorb all the extra carbon dioxide thrown in the atmosphere. This fraction of scientists content that the recent warming is just the result of climate's natural variability. In fact, in the past the planet was as warm as today and in sync with carbon dioxide without humans polluting the air. Simply, warmer temperatures make the planet greener, which naturally increases, through photosynthesis, the amount of carbon dioxide in the atmosphere.

Whatever the complete picture is, two points are in my opinion clear. First, the issue of polluting the planet should not be taken lightly or ignored, because by changing the natural concentration of greenhouse gases in effect we are altering the atmosphere. And exactly because the climate system is complicated we never know what the effect of that modification may be. Some argue that an accelerated warming may actually lead to an unexpected ice age. Be this as it may, the climate system should have some tolerance to fluctuations. Like a bench that is built to withstand a certain weight. But what are the limits of this tolerance in the climate system, is unknown. Clearly, we must strive to establish an optimum balance between economic growth and a healthy environment. Second, a warming planet will have consequences. Higher temperatures mean more evaporation. More evaporation means more precipitation. Thus, the hydrological cycle is expected to intensify. Higher temperatures also mean that some of the ice in the Arctic and Antarctica will melt. This will raise the sea levels. Simply, the climate will adjust to warmer temperatures. But will it adjust to make life easier or to make it more difficult? Will this adjustment be uniform or some areas of the world will be hit harder than others?

These questions are being addressed currently by both data analyses and by modeling. Unfortunately, the quality and limitation of data in some regions of the planet does not allow for a complete evaluation of the effects of global warming. At the same time modeling has limitations too. A climate model is a set of equations that describe the physics of the atmosphere, the oceans and the land, their interactions, and the time changes of weather variables such as temperature, pressure, precipitation etc. Once you have a model you can change some of its parameters (for example the amount of carbon dioxide in the atmosphere) and see the reaction of the model. Such modeling helps us understand many aspects of the very complicated climate system. However, no model (and there are several used) is perfect or complete

Regardless of limitations, some of the effects of the recent global warming have been identified. Already by the mid 1990s several studies established that the extremes in precipitation are increasing. This means that the frequency of more intense and less intense events has increased. In other words, rather than observing mostly moderate events and every once in a while an extreme event, we observe more heavy rain events and more drought conditions[9]. This tendency was first identified for the United States, but subsequently was confirmed for other regions in the world in the midlatitudes (Europe, China, and Australia). Results from model simulations confirm these observed changes. For the United States models project that if the warming trend continues extreme precipitation events will occur twice as frequently as currently. At the same time more frequent and longer lasting heat waves will most likely afflict the United States. In addition, models predict that there will be stronger tropical storms than presently. This prediction has become a major issue these days especially with hurricane Katrina ravaging New Orleans. Studies with observed data, however, are not conclusive. While some studies indicate that hurricane destructiveness is on the rise, other studies caution against connecting this increase to global warming.[10]. Other observed changes include higher maximum and minimum daily temperatures and fewer frost days in most land areas[11]. Another effect of increasing temperatures is an increase in the frequency of El Nino events. Data analyses and some models strongly indicate that in a warming planet, El Nino events (and their effects) will occur more frequently than La Nina events[12].

[9] Karl, T.R. et al. Trends in high-frequency climate variability in the twentieth century. *Nature*, **377**, 217-220, 1995; Tsonis, A.A. Widespread increases in low-frequency variability of precipitation over the past century. *Nature*, **382**, 700-702, 1996.

[10] Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688, 2005; Elsner, J.B. and Tsonis, A.A. Annual variability of hurricane destructiveness and its relationship to global warming; Pielke, R.A. Jr. et al. Hurricanes and global warming. *Bull. Amer. Meteor. Soc*. 2005.

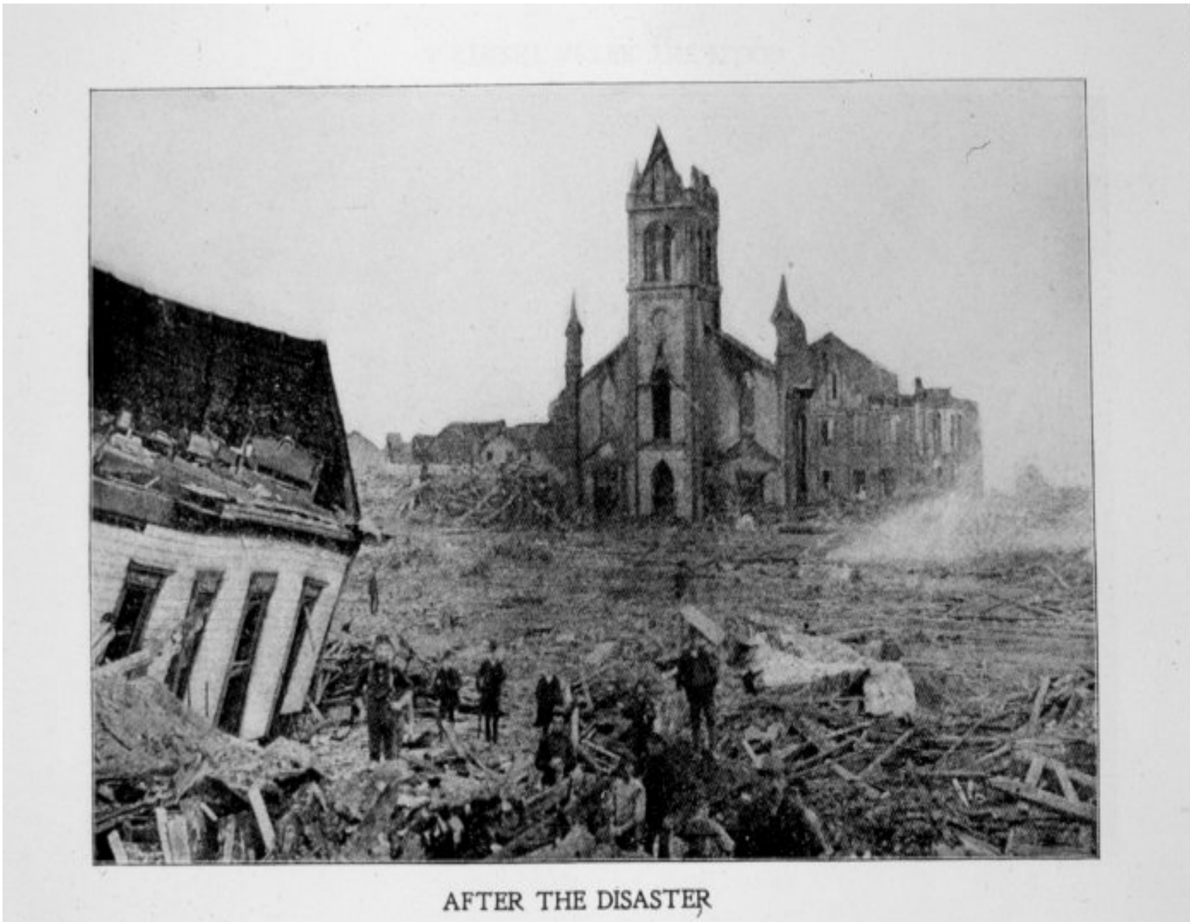
[11] Climate Change 2001: The scientific basis, 3rd assessment IPCC report, Cambridge university press, Cambridge, 2001.

[12] Tsonis, A.A. et al., Unfolding the relationship between global temperature and ENSO. *Geophys. Res. Lett.* **32**, 2005

Thus, many changes in regional climate are expected with global warming. Whether this warming is occurring naturally or it is induced by human activity, it appears that many places in the world will be affected. In the United States we have already began seeing some of these effects.

You may wonder, when I mention “models predict” that how is it possible for a model to predict the effects of a warming planet decades ahead of time when we cannot forecast if it will rain in New York three days in advance? This is a legitimate doubt, which needs to be addressed. As we discuss in the appendix, predictability of weather is yet one more ‘calamity’ of weather and in some places the weather may be more predictable than others. However, the weather prediction problem involves many “time scales”. If you want to predict the every day weather changes, you need to consider different details and set up than when you want to predict average changes over a long time interval. In other words, for long time scales we are more interested in the average picture than in the details. For example, for short term predictions we do not need to include in the models the changes in solar radiation due to the eccentricity or precession of the axis. On the other hand, if we wish to study long term changes we need to include these factors. In fact, it may very well be that predicting the long term average behavior of climate is more reliable than predicting the weather a month or less in advance. Nevertheless, accurate predictions are limited. And they are limited for several different reasons, which surprisingly are natural in origin (see Appendix 4).

17. The Cost of Weather



AFTER THE DISASTER

The Galveston Hurricane - Damage caused by the hurricane and storm surge. This was the greatest natural disaster in terms of loss of life in U.S. history. At least 8,000 individuals died in this hurricane

Image ID: wea00586, Historic NWS Collection
Location: Galveston, Texas
Photo Date: 1900, September 1-10

In the previous chapters we presented economic damages occurred with major weather disasters. These damages, however, are only the tip of the iceberg. The total yearly cost of weather in the United States is much higher. Exact estimates of weather related damage is very difficult to assess. Nevertheless, several sources have tried to document the economic impacts of various weather extremes. For example, the table below gives an idea of the average yearly combined tornado, hurricane, and flood damage. The source of this data is the Extreme Weather Sourcebook 2001 created at the National Center for Atmospheric Research (NCAR) in the Environmental and Societal Impacts Group. Average damages close to 12 billion per year are attributed to these causes (5, 1, and 6 billion for hurricanes, tornadoes, and floods, respectively). The State with the highest cost is Florida and the State with the lowest cost is Delaware.

Combined Tornado, Hurricane, and Flood Damage

State	**Rank**	**Av/Yr (millions 1999 US$)**
Average Annual U.S. Combined Damage (excluding Hawaii and Puerto Rico)		$11,370
Alabama	18	$185.0
Alaska	39	$37.18
Arizona	38	$50.76
Arkansas	25	$138.1
California	6	$524.9
Colorado	16	$202.9
Connecticut	9	$368.0
Delaware	49	$.7718
Florida	1	$1,669
Georgia	32	$74.18
Idaho	40	$35.79
Illinois	13	$268.5
Indiana	20	$169.9
Iowa	10	$366.2
Kansas	26	$136.6
Kentucky	24	$145.9
Louisiana	2	$966.9

Maine	46	$9.693
Maryland/D.C.	35	$58.18
Massachusetts	27	$124.6
Michigan	36	$58.16
Minnesota	14	$224.4
Mississippi	7	$463.5
Missouri	11	$336.4
Montana	42	$29.53
Nebraska	30	$93.83
Nevada	43	$28.41
New Hampshire	47	$8.305
New Jersey	22	$150.1
New Mexico	45	$10.66
New York	8	$426.5
North Carolina	4	$715.0
North Dakota	19	$172.3
Ohio	23	$147.9
Oklahoma	17	$192.0
Oregon	15	$204.0
Pennsylvania	5	$701.5
Rhode Island	41	$30.03
South Carolina	12	$289.2
South Dakota	28	$97.25
Tennessee	34	$60.20
Texas	3	$909.4
Utah	33	$66.97
Vermont	44	$17.24
Virginia	21	$153.0
Washington	37	$56.62
West Virginia	29	$94.69
Wisconsin	31	$91.15
Wyoming	48	$5.749

Hawaii	n/a	$93.64
Puerto Rico/USVI	n/a	$203.0

The National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA) also records damages from weather disasters. In the period 1980-2004 NOAA lists 62 events that have resulted in at least one billion dollars damage each. Of those, 20 are tropical storms/hurricanes with an average damage of 7.2 billion each and a combined death toll of over 700 people. Twelve out of the 62 disasters are floods not associated with tropical storms or hurricanes. Each one of those has caused on the average 4.6 billions in damage. All twelve of them have claimed the lives of 350 people. The third most frequent calamity is heat waves/droughts, which is the costliest and deadliest weather disaster. Ten severe droughts have occurred in the last 25 years. Each one costs the nation an average of 14.4 billion dollars. More staggering is the death toll. More than 18,000 people have died as a result of heat waves and droughts (this includes heat-stress related deaths). Seven tornado outbreaks, six fires (a byproduct of droughts), two freezes, two blizzards, two ice storms, and one Noreaster complete this VID (Very Important Disasters) list. On the average the United States can expect 2.5 extreme events per year and an average damage of 16 billion dollars per year. The hardest hit area is the southeast US and the least is the Wisconsin-Michigan region.

Disaster type with damages greater than 1 billion dollars	**Number of events**	**Damages in billions of dollars**	**Deaths**
Tropical storms/Hurricanes	20	144	715
Non-tropical floods	12	55	350
Heat waves/droughts	10	144	>18,000
Tornados/severe thunderstorms	7	13	320
Fires	6	13	70
Freezes	2	6	-
Blizzards	2	9	450
Ice storms	2	5	25
Noreaster	1	2	20
TOTAL	**62**	**391**	

If we exclude from this table the damages due to hurricanes, floods, and tornadoes, we remain with the effect of all the rest of the types, which sums up to 179 billion or 7.2 billion dollars per year (and this will not include events that cost less than a billion dollars). From these two tables we can thus estimate that the total cost of weather in the USA is at least 12+7.2=19.2 billion dollars per year.

But this is not all. In the above estimation damages from hail, wind, and non-tornadic thunderstorms are not included. According to the Extreme Weather Sourcebook 2001, the cost of crop-hail insurance loss and insured property losses from wind and thunderstorms is at least 5 billion dollars per year (and this number does not include events that cause less than 100 million dollars). If we add here the cost of cleaning efforts (a rather unknown quantity) we are looking at a lower limit of at least 25 billion dollars annually. This number does not include the effect of severe weather on industry, tourism, transportation etc. For example, utility companies can lose millions when electric outages occur from severe wind, heat, lightning, and ice storms. Car insurance companies lose millions in weather related accidents that are not necessarily part of major disasters. Uninsured property damage or loss is also not included in the above lists. Hidden costs like these can push the lower limit of weather damages in the US well above 30 billion dollars per year.

The U.S. Department of Energy estimates that approximately \$1 trillion of the \$7 trillion economy is subject to weather risk. The earnings of a large number of companies depend on how warmer or colder the winters and summers will be, whether rainfall will be above or below normal, whether a heat wave or flooding will occur and so on. According to a report dated April 17, 2001 by the US Public Interest Research Group in the United States, weather-related natural disasters in the 1990s took nearly 4,000 lives and caused nearly \$200 billion in economic loss. Worldwide, the weather disaster toll was more than 330,000 lives and more than \$646 billion in economic loss. Almost one third of the economic damages occurred in the United States. Given the state-of-the-art monitoring and warning systems in the States these figures attest to how more frequently the United States is affected by severe weather compared to the rest of the world. The great unevenness observed in the lives taken is due to the fact that most of these deaths have occurred in countries with no infrastructure, like in Bangladesh, where people live in low lands prone to flooding and where warning systems and evacuation plans are nonexistent or not applied properly. Had hurricane Katrina occurred in Bangladesh, we would be mourning hundred of thousands of people.

Part IV

Does the USA have the worst weather on the planet?

"…wildest weather in the cosmos"

The History Channel (USA)

Did you ever wonder which region on Earth has the worst weather? We demonstrated that the United States is subject to all weather disasters. But does this make it the worst place for weather? This is a loaded question because the answer depends on the criteria used to define the worst or best weather. In my opinion, the worst place is one which is significantly populated and is the subject to all possible weather calamities and disasters while at the same time it resides in a latitude belt where climate is not supposed to be treacherous. The worst place is a place where sudden shifts occur at all time scales with no relief. Cold today, warm tomorrow, drought this year, floods next year, blizzards in the winter, tornadoes in the spring, hurricanes in the summer and fall, storms all year around. For this 'honor' places where one permanent unfriendly climatic condition prevails, should not qualify. For example, the Sahara desert is hot and dry all the time. Nothing happens in Sahara. Sahara is a dead place, and that is why it is uninhabitable. Similarly Antarctica and Greenland are polar uninhabited places. Siberia is very cold in the winter time but it has no tornadoes, no hurricanes, no significant flooding, no severe thunderstorms, and no droughts. Areas like these will not qualify for the worst weather on Earth even though nobody wants to live there.

In the course of this book we discussed many weather conditions that will make life miserable. In order of presentation they were:

1) exposure to all possible air masses, sudden temperature shifts
2) sharp temperature differences between winter and summer
3) midlatitude storms, blizzards
4) severe thunderstorms, lightning, hail
5) tornadoes
6) hurricanes
7) floods
8) droughts, heat waves
9) El Nino
10) Weather extreme world records, climate type variability
11) Ice ages
12) Global warming
13) unpredictability of weather
14) economic impact

The following table summarizes the regions on Earth that are affected by each of these weather conditions.

Clearly, all these condition apply to the area of the world where the United States is located. There is not even one weather calamity that does not occur in the United States. In addition, for some of these conditions (exposure to all possible air masses, tornadoes, weather extreme records and climate type variability), it appears that the United States is the capital of the world. No other regions of comparable size can compete with the United State for the worst weather on Earth. Economic aspects also support this conclusion. Estimation of various agencies indicate that one seventh of the United States' economy is subject to weather disasters and that in the last decade of the 20th century one third of the global economic damages were charged to the United States. Figure 65 shows the disaster declaration in the United States by county. Basically every county at some time has been declared a disaster area. Monroe County in Florida and Caddo County in Oklahoma have been declared a disaster area a record of 13 times.

Regions with greatest normalized thermal amplitude	Northeastern Siberia, Northern China, Mongolia, Kazakhstan, United States
Regions open to all possible air masses	United States
Regions with severe midlatitude storms	United States, Northern Europe, Russia, Central-eastern Asia (Manchuria, Korea, Japan)
Regions with high severe thunderstorm potential	Central Africa, United States, South America, Northern India and neighbors
Regions mostly affected by tornadoes	United States, Europe
Regions mostly affected by hurricanes	China, Southeastern Asia, United States, Australia, the Caribbean, Mexico
Regions mostly affected by floods	China, Southeast Asia, United States, India, Europe, Central America, Southeast South America
Regions mostly affected by drought	United States, Europe (including Ukraine and parts of Russia), China, the Sahel, Eastern Australia, parts of South America and Africa
Regions mostly affected by El Nino	Indonesia, regions in South America, Australia, United States, Canada
Regions mostly affected by NAO and PDO	United States, Canada, Europe
Regions with great climate type variability	United States, Central Asia
Region with most extreme weather records (according to Guinness book)	United States
Regions mostly affected during ice ages	Scandinavia, Northern Russia, Canada, United States
Regions mostly affected by global warming	Most places including the United States

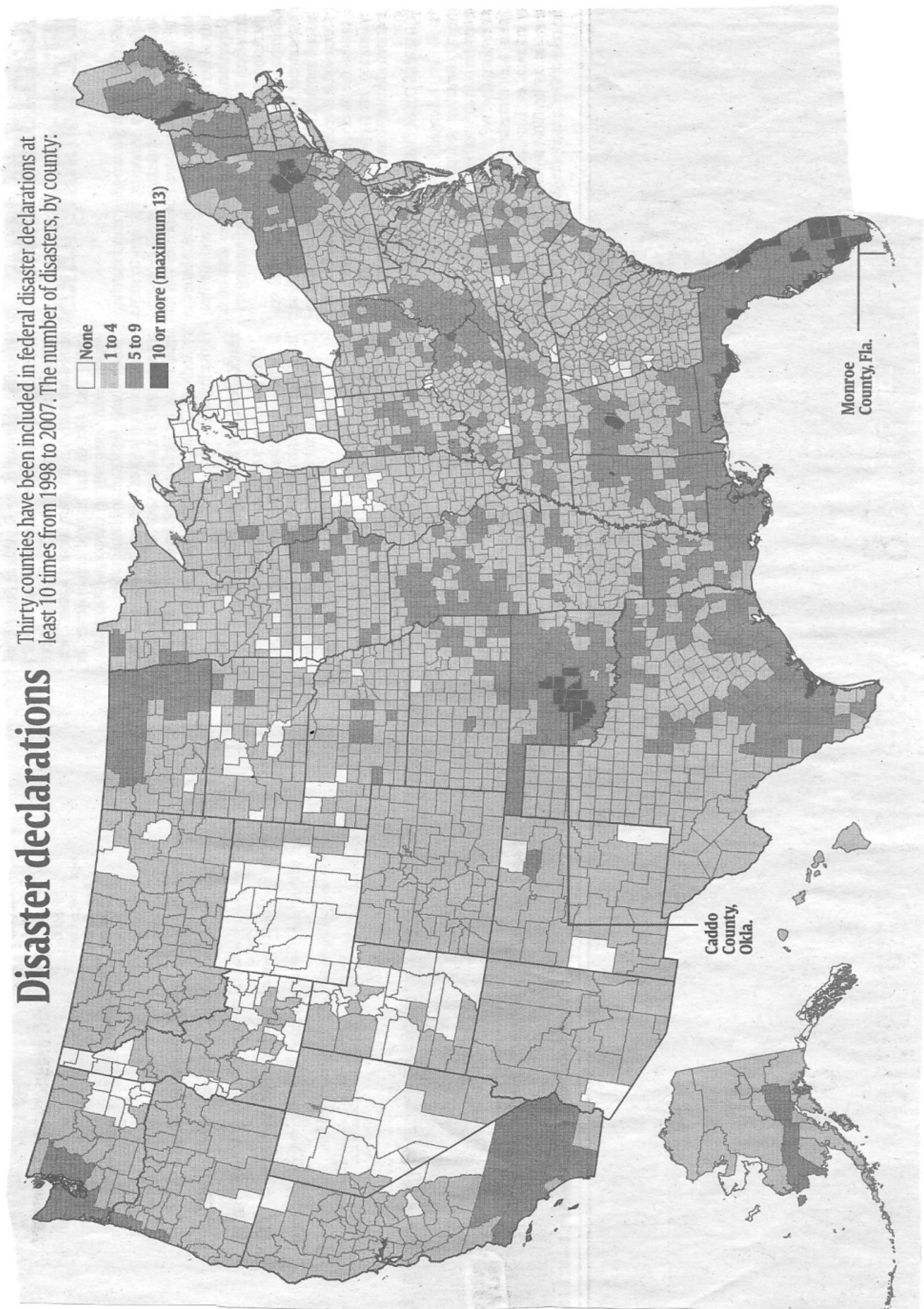


Figure 65: Disaster declarations by county. Source: Federal Emergency Management Agency.

Acknowledgements

I would like to thank all the scientists and nonscientists who provided figures or permitted me to use their material. I thank the University Cooperation for Atmospheric Research (UCAR) for providing the mythology information about the Sun. I am grateful to the National Oceanic and Atmospheric Administration (NOAA) for their fantastic web site, where I found most of the information, data and figures used in this book. All information that is not otherwise credited comes from NOAA sources.

Units we need to remember:

1 mile = 1.6 Km

1 Km = 1000 m

1 m = 100 cm

1 kg = 1000 g $\approx$ 2 lb

Celsius to Fahrenheit

$$C = (F-32)/1.8$$

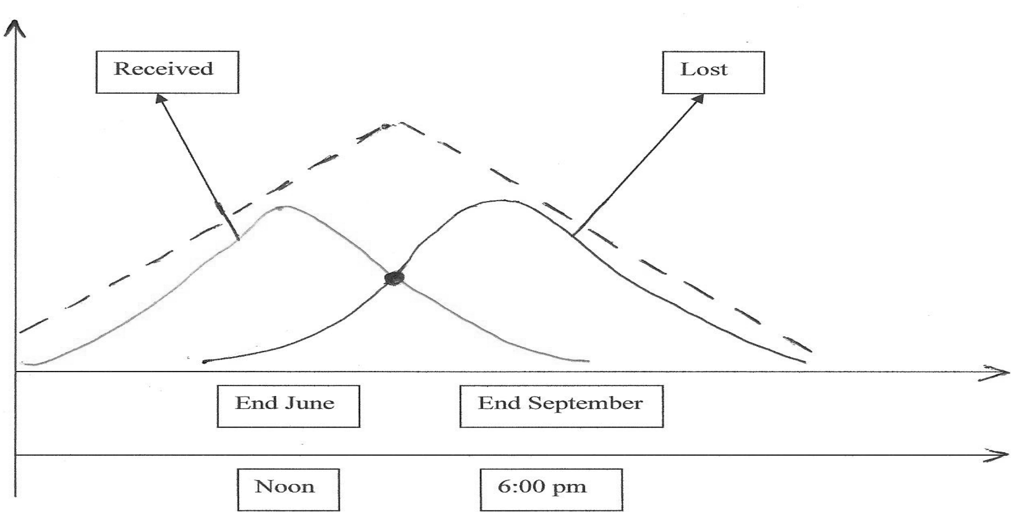
Or to a good approximation

$$C = (F-30)/2$$

APPENDIX 1

Seasonal and daily lags

We have often discussed that when an object absorbs radiation it warms up and then it radiates back heat. In the figure below the red line is the radiation received at the surface as a function of the month. Since the northern hemisphere is facing most directly the sun at the aphelion and least directly at the perihelion it receives the maximum amount of radiation at the end of June and the minimum amount at the end of December. This variation is shown in the figure below by the red curve. Warming up and radiating back takes some time, so if we were on the same graph to plot the radiation lost (emitted into the atmosphere and space), then this curve (in black) will look like the red curve but it will be shifted to the right with its maximum (fasted losing rate) occurring some time in September. The maximum temperature in the year (broken lines) will occur where these two curves intersect (some time mid to end of August). The explanation is simple. Think of the radiation received as your salary, the radiation lost as your expenses, and temperature as the amount of your saving account. As long as your salary is bigger than your expenses, regardless of the difference, your savings grow. If at some point you spend as much as your salary your savings amount stays the same. If then you start spending more than you receive you have to use your savings and the savings amount goes down. This difference in time between the maximum radiation received and the maximum temperature observed is called the *seasonal lag*. The same principle applies to the maximum temperature time during a day. During any day of the year and any place in the planet the sun is overhead at noon. That means that the maximum radiation received at any place is at noon. The maximum radiation lost occurs as we approach the evening (around 6:00 pm) making the time of maximum temperature around 3:00 pm. This is the *daily lag*.



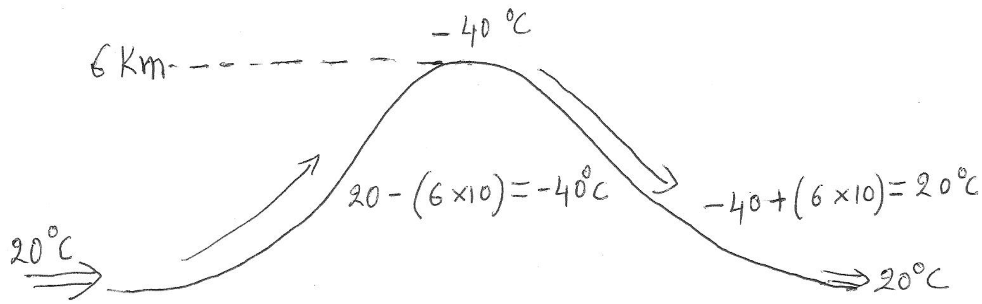
APPENDIX 2

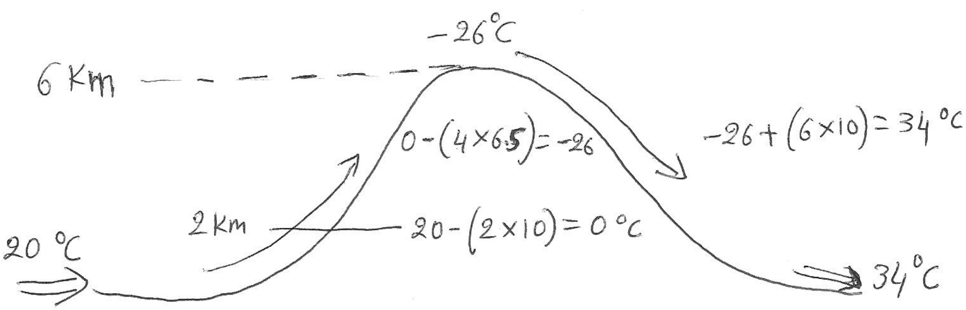
Dry and moist rates and regional climate

We know by now that when the air rises it cools and its relative humidity increases. When it reaches saturation further cooling causes the excess vapor to condense and the formation of clouds begins. Since condensation releases heat into the environment from now on the cooling of rising air will not be the same. Because the air still rises, and expands, and spends energy, its temperature will have to decrease but because of the added heat from condensation the cooling is at a lower rate than that when the air is dry (unsaturated). For this reason we have two cooling rates. The dry rate, which is 10 0C/Km, and the moist rate, which is 6.5 ^{0}C/Km. This difference has a great impact in defining local climate in areas where there is mountains. Mountains (such as the Rocky Mountains) provide a natural lifting mechanism for the air that is flowing from the Pacific Ocean. Because this air has a high content of water vapor (since it is travelling over water), even if it is unsaturated when it begins its ascent, it will soon become saturated and at some level condensation on the windward side of the mountain will begin. Below this level the air will be cooling at the dry rate. But above this level there will be clouds and precipitation and the cooling will be at the moist rate. If the mountain is relatively high, by the time the air has reached the top it would have precipitated out all its moisture. Thus, when it begins it descent on the leeward side it is very dry and it will be warming at the dry rate all the way down. These differences between the windward and the leeward sides create great differences in local climates.

Let's consider a mountain 6 Km high and a temperature of the air when it begins its ascent on the windward side of 20 ^{0}C If we assume that there will be no condensation all the way to the top then the parcel will cool at the rate of 10 ^{0}C/Km for all 6 Km. Thus, its temperature at the top will be 20-(6x10)= -40 ^{0}C and it will be the same air it was in the beginning (in its water vapor content). As it goes down on the leeward side it warms at the dry air of 10 ^{0}C/Km. Thus, as it ends its descent its temperature will be -40+(6x10) = 20 ^{0}C. It follows that in this situation both sides are exposed to the same conditions (top of figure below).

However, this is not what is happening in reality. At some level in the windward side there will be condensation. Then, there will be a dry rate cooling below this level and a moist rate cooling above it. Let's assume that this level in our example is at 2 Km. Then, the temperature at 2 Km will be 20-(2x10) = 0 ^{0}C. For the next 4 Km the air will be cooling at 6.5 ^{0}C/Km. Thus, at the top of the mountain the temperature is 0-(4x6.5) = -26 ^{0}C. At this point the rising air has formed clouds and precipitation and has been depleted of its water vapor. There is hardly any water or water vapor in it. Thus, when the air begins its decent it will be warming at the dry rate all the way! Thus its temperature when the descent ends will be -26+(6x10)= 34 ^{0}C (bottom of figure below). It follows that in such a scenario the air on the east side is warmer and drier that in the west side. This explains why California is wet and green and New Mexico and Arizona are practically deserts.


-40 °C
6 Km
20 - (6 × 10) = -40°C
-40 + (6 × 10) = 20°C
20°C
20°C


-26°C
6 Km
0 - (4 × 6.5) = -26
-26 + (6 × 10) = 34°C
2 Km
20 - (2 × 10) = 0 °C
20 °C
34°C

APPENDIX 3

<u>Cumulus</u>: *Cauliflower or cotton ball looking clouds. Fair weather clouds.*

<u>Cumulonimbus</u>: *Great vertical development, with severe weather. Because of their great vertical extend their tops reach the stratosphere. The stratosphere acts like a "lid" not allowing the cloud to penetrate it. As a result the cloud top spreads forming an "anvil".*

<u>Cirrus</u>: Feather looking clouds, thin, composed mainly of ice crystals.

<u>Cirrocumulus</u>: Thin, make wave like patterns, composed mainly of ice crystals.

Cirrostratus: Thin, look like a fine veil, composed mainly of ice crystals, form halos around the sun or the moon.

Altocumulus: Patches or layers of roll-like clouds. A denser, thicker version of cirrocumulus.

Altostratus: Look like a dense veil, the disk of the sun is often visible.

Stratus: Low level uniform cloud covering usually covering the whole sky. Not associated with significant precipitation. Fog is nothing else than a stratus cloud very close to the ground.

Nimbostratus: *Low level clouds, look like stratus, but bring steady and often heavy rain.*

Stratocumulus: *Low level irregular masses of clouds.*

An example of cloud formation during a lake breeze (Milwaukee, WI, Lake Michigan).

APPENDIX 4

Can a butterfly in Brazil spin a tornado in Kansas?

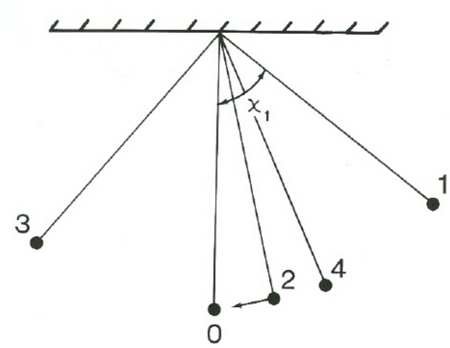
Writing a book on weather cannot be complete if the issue of prediction is not discussed. Weather prediction is part of our everyday life. Before a ball game, before we water the lawn, before we leave our homes for work, when we plan to travel, we look at the weather forecast. Every aspect of our life is closely connected to weather nowadays and forecasting the weather is simply priceless. Predicting the weather is not just for our personal convenience. Predictability of weather impacts us in many ways. A good prediction and an early warning of a severe event can save lives and reduce damages. The economic benefits of weather forecasting are immense. One trillion dollars of the US economy is tied to weather. Having a forecast (and not necessarily 100% accurate) saves the United States billions of dollars per year. Countries can plan their energy budget more efficiently if they know that the coming winter will be colder or warmer than normal. Construction companies save millions when guided by weather forecasts. The transportation industry can plan for alternatives. Farmers can change their strategies if they are aware of a coming drought. People can prepare to face an impending flood.

But, while weather forecasting has become part of our lives, it has also become a source of frustration because often, weather predictions go wrong. Have you ever wondered why weather forecasts cannot be always right and why can we not extend them more than a week (at best) into the future? Next, we will try to explain why unpredictability of weather is yet one more weather 'calamity', which, like all weather phenomena and disaster discussed in this book, happens naturally.

Predicting the future has been a major obsession of human beings since we can remember. We still read the horoscopes and we still pay charlatans to tell us all the 'good' things that are just about to happen to us. When it comes to weather, forecasting began by correlating astronomical and meteorological events with seasonal changes in the weather. As early as the 7th century B. C., the Babylonians used cloud characteristics and optical phenomena like haloes in order to predict short-term weather changes. By the 3rd century B.C. Chinese astronomers had devised a calendar that divided the year into 24 festivals, each festival associated with a distinct weather type. In around 340 B.C., the Greek philosopher Aristotle wrote Μετεωρολογικά (Of Meteorology), a book that was to become the authority in weather theory for the next 2000 years. In this book Aristotle suggested some of the modern ideas about weather prediction. For example, in Book I he writes that "The same parts of earth are not always moist or dry, but they change…But we must suppose that these changes follow some order and cycle..." Even tough some of his theories were way off target, today's weather forecasting indeed relies on order (rules) and cycles (periodicities) in climate. Around 100 B.C., Andronicus the Cyrrhus, a Greek astronomer, built the Tower of Winds, an octagonal structure carved with figures on each side that represented the eight principal winds. A bronze figure of Triton (the mythological demigod of the sea) on the top of the Tower would move with the wind and point to the quarter, which the wind blew from. This was indeed the first weathervane and from this model the custom of placing weathervanes on steeples is derived. Andronicus used his tower for weather forecasting by linking time and wind direction.

Indeed, for some event to be predicted it has to obey some rules, follow some pattern, which we can decipher and then extrapolate into the future. For example, the regular path of the Earth around the Sun allows us to predict with confidence that in August it will be warmer than in January. Embedded in this regularity, however, we have the every day weather events all over the world, which move around and interact. This makes the every day picture very complicated and ever changing. Finding patterns in these pictures becomes very difficult. In the case of physical systems (like the climate system) there is some hope. The system obeys the laws of physics and as such many of its features can be expressed as equations that describe the time changes in variables like pressure, temperature, moisture etc. Such systems are called *dynamical systems*. In order to make a prediction of the state of a dynamical system in the future, the only thing that is required is to know how to solve the equations and also to know a staring point (the initial condition). But even in this case there are plenty of problems. For some reason, nature does not want to be very predictable.

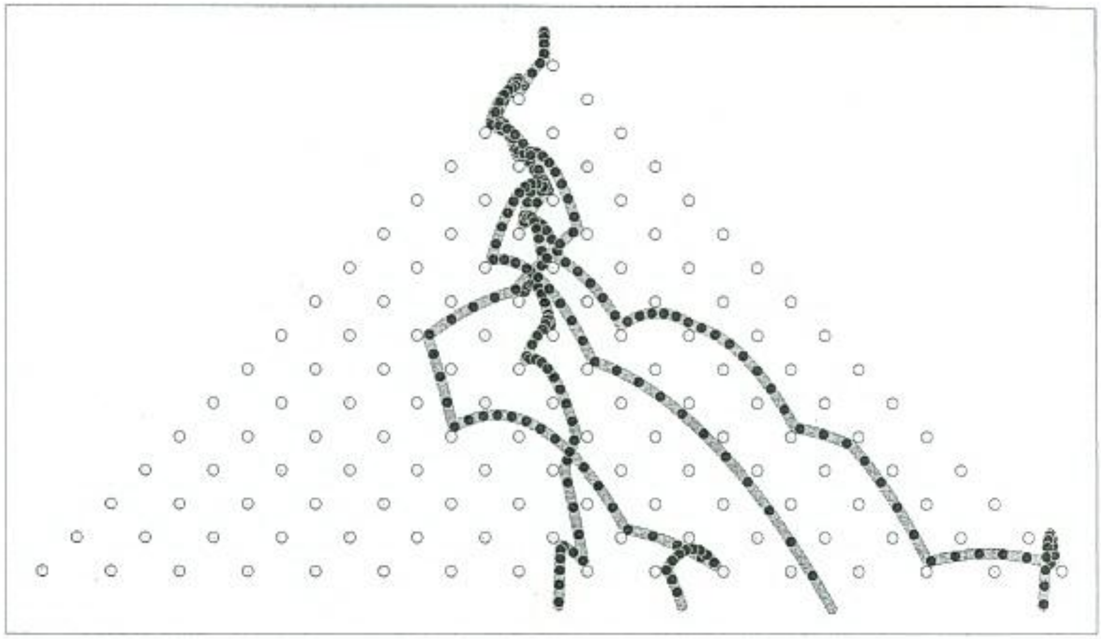
Consider a pendulum that is allowed to swing back and forth from some initial position, as shown below.



Also consider that this system is isolated and not subjected to any external influences. The parameters that define this pendulum are the length of the string holding the small ball and the mass of the ball. These parameters do not change as the pendulum swings back and forth. What changes, is the speed (v) and the position (the angle x) of the ball. Thus, position and speed are the variables of the system. In this case Newtonian physics provides the rules (equations) that describe the evolution of this system from any initial position (or initial condition). Let us assume that the pendulum is taken to position 1 and is held there. Then, at position 1 its initial state is $x=x_1$ and $v=0$. At this point the pendulum has a certain amount of energy. The total amount of energy of a system is the sum of its potential and kinetic energy. When the system is at rest its kinetic energy is zero and thus all the energy is potential energy. Thus, potential energy relates to position only. Now let the pendulum swing. As it moves toward position O its speed increases due to gravity acceleration. Some of the original potential energy is now transformed to kinetic energy. After a while (position 2), the pendulum will be closer to position O and will have a speed greater than zero. As it crosses position O its speed decreases because now gravity acts in a direction opposite to the motion. At some point (position 3) the speed of the pendulum will become zero again. At this point its kinetic energy is zero and the pendulum has now again only potential energy. However, the amount of potential energy now is not the same as originally because during the motion some of the energy has to be spent to overcome the presence of friction. Since potential energy relates to position only, less potential energy means that position 3 is not symmetric to position 1 with respect to position O but it is closer to O. Once the pendulum reaches position 3 it will begin to swing back increasing its speed until it crosses position O once again, thereafter decreasing its speed, which will become zero again at position 4, which for the reasons explained above will be closer to O than both points 1 and 3. Eventually, the pendulum, having spent all its energy to friction, will rest at position O.

Now, what do you think will happen if instead of point 1 we chose to hold the pendulum at some other arbitrary initial position? Since we know from experience that no matter how we set the pendulum in motion it will always rest at the same final position, we can confidently say that the final state of the pendulum will always be the same regardless of the initial position. This makes this simple system very predictable. We can always predict that the pendulum will rest at point O.

Next, consider the pegboard shown below also known as Galton board or quincunx board. All pegs are of the same size and stick out of the board in exactly the same way. The pegs are arranged in a symmetrical way. Thus the system is simple and its geometry very ordered. The figure shows the paths followed by four identical balls dropped from initial positions differing by only one part in a thousand. As they fall they bounce whenever they hit a peg and eventually are collected at the bottom. As we can see while the initial position is for all practical purposes the same, the final state is widely different. In fact, if you ever played this game you know that it is very difficult to predict the final position of a ball. The problem here is that this system is extremely sensitive to the initial condition. Even if you try your best to place the ball at the same point, you will always be off by a very small amount. *You can never be sure about the initial condition.* Even the slightest deviation can cause the system to evolve differently. In fact, in this particular example small differences in direction are amplified by almost a factor of two at each bounce. Even if the balls take as little as six bounces their initial difference in the direction they dropped has amplified by a factor of 2^6 or 64 times. This amplification of tiny differences in the initial conditions is the property of complex nonlinear systems rather of than linear systems that do not amplify differences in the initial conditions. This sensitivity to the initial condition, which has been termed *chaos*, makes the final outcome unpredictable. Of course, one may argue that some devise may be thought that will place the ball at exactly the same position every time. In this case the path will be the same and even though very complicated it will be predictable. Thus, one may argue, sensitivity to the initial conditions is not a condition for unpredictability. This is a strong argument but there is a little problem with it.



Source: Wolfram Research Inc.

.

Consider the following simple stepwise mathematical operation, which can be easily carried out with a calculator.

Step 1: Start with an initial value between 0 and 1 but not 0.5.
Step 2: Subtract the value from 1.
Step 3: Multiply the result in step 2 by the value.
Step 4: Multiply the result in step 3 by the number 4. Now you have a new value.
Step 5: Repeat steps 2, 3, and 4 with the new value. Now you get another value.
Step 6: Repeat steps 2, 3, and 4 with the new value. Now you get another value.

-
-

Step n: Repeat steps 2, 3, and 4 with the new value. Now you get another value.

This is an *iterative process* where the same operation is repeated using every time the result of the previous step as the starting point. The above operation is a simple mathematical model. The only parameter is the number 4 in step 4. However, it is a nonlinear process and very sensitive to the initial value. But, unlike the previous physical example this one is a mathematical one and as such one can fix the initial condition. Thus, here there can be no uncertainty about the initial condition. For example, we can start with an initial value equal to 0.4. Then, after executing step 2, we will have a value of 0.6. After step 3, we will have a value of 0.24. Finally, after step 4 we will have a new value of 0.96. With this new value we start over and after step 2 we have a value of 0.04. After step 3 we have a value of 0.0384 and after step 4 we have our new value of 0.1536.

Repeating steps 2, 3, and 4 with this new value gives the next new value, which is equal to 0.52002816. Thus, so far we have the following sequence of new values:

Initial value: 0.4
Next value: 0.96
Next value: 0.1536
Next value: 0.52002816

What do you observe? The digits after the decimal point increase (in fact double) with every iteration. After seven iterations the result carries 128 digits. After twelve iterations there are 2,048 digits! The number of digits is actually given by 2^n, where n is the number of iterations. Calculating exactly out to only 100 steps will require a computer that will carry calculations with 2^{100} decimal points. This number is approximately equal to 10^{30}, which is more than one trillion times greater than the age of the universe in seconds! No computer has ever been developed (or will be developed any time soon) to handle even a thousand digits. So what does the computer do when the iteration reaches the point where the digits are more than the digits the computer can carry? It simply rounds off the result or it chops off the extra digits. That in effect, makes the result an approximation to what the result would have been if the computer had the ability to carry calculations with unlimited number of digits. This approximation will now play the role of an error in the initial condition or of a fluctuation, which will be amplified and soon lead to an evolution that will be completely different than the actual one. *Thus, only if we had infinite precision and infinite power we will be able to predict such systems accurately.* Because we do not have that, for systems that are sensitive to the initial conditions, the exact state of the system after a short time cannot be known. The outcome of such systems after that time is simply random as small fluctuations amplify enough to dominate the evolution of the system. Thus, a future state is unpredictable.

Chaos and sensitivity to the initial condition are not properties of simple mechanical or mathematical systems. Chaos and sensitivity to the initial condition is widespread in nature. Back in the early 17th century, the German astronomer Johannes Kepler published his first law, which stated that the orbit of an object around an attracting body is an ellipse with the attracting body located at one of the foci (like figure 17).

The ellipse remains constant in space, the speed, however, of the orbiting body varies. According to Newton's gravitational law, the force of attraction is proportional to the product of the masses of the two objects and inversely proportional to the square of their distance. Since the orbit is an ellipse the distance between the two bodies is not the same at all times. As such the gravitational pull varies; it is greatest at the pericenter and smallest at the apocenter. From Newton's second law it then follows that the speed of the orbiting object varies accordingly. Nevertheless, the position and speed of the orbiting object are determined at any time and they are regular. They repeat exactly after a fixed time interval.

The situation, however, becomes a bit more complicated when there are more than two bodies in the picture. For example, Earth attracts the moon while the sun attracts both.

What is the motion of the moon in this case? You will probably not believe it but the problem has no analytic solution! In other words we are not yet able to find a solution using standard mathematical approaches. The only way to solve such problems is numerically. In this case we simply assume a numerical solution to the problem and we check if the equations are satisfied. If they are not we try a different solution until the equations are satisfied with an acceptable accuracy. This procedure can today be done efficiently with a computer. At the time of Kepler and Newton, however, this was not possible and both of them, while aware of the problem, saw this irregularity as a nuisance. It was not until the early 20th century when the French multi-scientist Henri Poincare showed that the numerical solution to the three-body problem is very irregular and very sensitive to the initial condition. In fact Poincare discovered chaos but due to the unavailability of computers he could not study this problem in detail. Nevertheless, for the first time in the history of science it was realized that irregular behavior can be observed in very simple systems and that sensitivity to the initial conditions will make the behavior of the system practically unpredictable.

The theory of chaos had to wait several decades until the development of fast computers allowed such calculations. Then, in 1963, Edward Lorenz, an atmospheric scientist at MIT, who was trying to explain why weather is unpredictable, reduced the complicated physics of the atmospheric circulation into three simple nonlinear differential equations (a differential equation describes changes of a variable in time), which described the behavior of a fluid layer heated from below. This is an approximation of what happens basically every day in the lower atmosphere. Once the sun rises, the surface absorbs solar radiation and gets warm. Subsequently, the air above the surface gets warm by contact with the warmer surface and rises. This rising motion leads to turbulent motion. When Lorenz solved the equations he found that this system is sensitive to the initial conditions. Evolutions from two slightly different initial conditions soon diverged and followed different paths. Lorenz coined this sensitivity the *butterfly effect*. The flapping of a butterfly's wings disturbs the air and this tiny fluctuation in the atmosphere grows and possibly causes a weather event somewhere else in the world, which would have not happened if it were not for this fluctuation. Lorenz published his results in the highly respectable *Journal of Atmospheric Sciences* in 1963 [13]. At that time, however, meteorologists were occupied with other problems and did not pay attention to this remarkable paper. It took more than a decade before mathematicians and physicists discovered the paper and then the theory of chaos took off and developed to one of the most important scientific theories.

We should mention here that the unpredictability associated with chaos in natural systems, like weather for example, is more complicated than that of an abstract mathematical system, like the example described previously, where the rules and the initial condition can be specified exactly. In general, it is logical to assume that in systems like climate many subsystems operate according to their own rules and interact

---

[13] Lorenz, E.N., Deterministic Nonperiodic Flow. *J. Atmos. Sci*. **20**, 130-141, 1963.

between each other. As subsystems interact they exchange information. Information received by one subsystem from another may interfere with its rules, thus producing an unexpected result. Such interactions, especially in a large number of subsystems, create an extremely complex behavior that cannot be described adequately by general equations. In addition, in natural systems we have to *measure* the initial condition. For example, to make a weather prediction we measure the temperature, pressure, moisture, and other variables and then we set the system (equations) in motion and wait to see what happens. But, as you know, measurements are subject to error. Every time I travel to my office I pass places where digital thermometers show temperature. Somehow they all differ. This may be due to the natural variability of the temperature field, but I have noticed that the two thermometers in my house also never agree. Instruments are simply not exact. This will cause an uncertainty in the measurements used to specify the initial condition of the atmosphere. In this case we will start with an error. That error will couple with the round-off error introduced by the computer and things will get out of control fast. Not to mention that the initial state of the atmosphere is measured only at certain locations, thereby missing a lot of information in between. This results not only in an inexact initial condition but also in an incomplete one. So, next time the forecaster messes up the prediction give him or her a break! Even though many improvements have been made since Increase A. Lapham delivered the first official weather prediction for the United States Weather Service (then called Signal Corps) on November 8, 1870, we still have a long way to go.

In order to improve forecasts and minimize economic and life loss, a good infrastructure must exist. This infrastructure must provide as much weather related information as possible. Today weather radars and satellites do this effectively. Radars measure precipitation. Like the radars detecting airplanes, weather radars detect raindrops or other forms of precipitation. The principle behind their operation is simple. As we discussed in the beginning of this book, when a radiation of a given wavelength encounters an object of a size comparable to the wavelength, it is scattered back. The average size of raindrops is of the order of 2-4 millimeters (about $1/8^{th}$ of an inch). This falls in the range of microwave radiation. When microwave radiation emitted by weather radar encounters precipitation, is scattered back and is received by the antenna and is recorded. The amount of radiation scattered back depends on the amount of precipitation present. Intense precipitation scatters a lot of this radiation. Note that weather radars do not 'see' clouds but only the precipitation inside them. Cloud droplets are much smaller than raindrops (about 100 times in radius). Because of that they are much smaller than the wavelength of the radiation, which simply goes around them without being scattered. In addition modern radars provide information about rotation inside the clouds, which can be used for early tornado warning. In a similar way, weather satellites use properties of different types of radiation to 'sense' many weather variables from space. Sensing weather from space is desirable because weather satellites from high in the atmosphere can 'see' a large part of the planet, unlike radars on the ground, which can only scan a circular area of about 150 miles in diameter. Because of weather satellites, weather systems everywhere on the planet can be identified and followed, and because of radars precipitation inside them can be located. This setup provides the information needed when a strong storm or a hurricane is approaching. Before radars and satellites there was very little information about weather systems, especially over the oceans. Due to inaccurate weather report in the early 20th century the average life expectancy of an airmail pilot was only about four years! Many more people lost their lives in tornadoes and hurricanes early in the 20th than do today. For example, about 10,000 people died with the category 4 Galveston hurricane in 1900, but only 50 people died with category 5 hurricane Andrew in 1992.

Despite advances in weather observing technology, predicting changes in weather is limited to about 4-7 days in advance. An interesting question that has not been addressed by atmospheric scientists yet is whether predictability depends on geography. In other words are there regions in the world where prediction is less accurate than others? Simple logic would suggest that regions which experience great weather variability (like the United States) will be less predictable, whereas areas associated with the permanent high pressure systems around the 30 N and 30 S latitudes will be more predictable. However, this is not straightforward. Part of the problem is that assessing predictability requires comparisons between forecasts and what actually happens for many years, and systematic model predictions to address this problem go back only about ten to fifteen years. The limited research in this area indicates, however, that the United States is not one of the preferred (higher predictability) regions, which appear to be regions in the northeast Pacific and Northeast Atlantic oceans. Also, it has been suggested that the presence of the Rocky Mountains adds 'noise' to forecasts, thereby decreasing their accuracy. Regardless where models can predict better, they all do a poor job in predicting small-scale events such as thunderstorm and tornado development. From this point of view, since the United States is leading the world in these two categories, it may be the most affected by limited predictability.

About the author

Anastasios Tsonis is a Distinguished Professor in the Department of Mathematical Sciences at the University of Wisconsin-Milwaukee. His research interests include Chaos theory, Climate dynamics, and Networks. He is the authors of more than 130 peer reviewed scientific publications and of nine books. Four of these books are research books, two are textbooks (including this one), one book is a popular science book entitled *Randomnicity: Rules and Randomness in the Realm of the Infinite,* another book is a translation into English of the epic Greek poem *Kyra Frossini*, and his last one is a mathematical novel entitled *Parallel*.

Which place on Earth has the most challenging weather?

This textbook is not a mainstream textbook for Atmospheric Sciences. It is a new kind of textbook written to read like a novel while presenting the science with historic facts and with every day examples.

ISBN 9781502385598
90000 >
9 781502 385598