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The Science of Extreme Weather

Course Guidebook

Professor Eric R. Snodgrass
University of Illinois at Urbana-Champaign

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4840 Westfields Boulevard, Suite 500
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Phone: 1-800-832-2412
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Eric R. Snodgrass, M.S.

Director of Undergraduate Studies
for the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

Mr. Eric R. Snodgrass is the Director of Undergraduate Studies for the Department of Atmospheric Sciences at the University of Illinois at Urbana-Champaign. He received his bachelor's degree in Geography from Western Illinois University and his master's degree in Atmospheric Sciences from the University of Illinois at Urbana-Champaign.

Each year, Mr. Snodgrass guides more than 1,500 students through the wild side of weather in his course entitled Severe and Hazardous Weather. He also teaches advanced courses, including General Physical Meteorology, Meteorological Instrumentation, and Economics of Weather, as well as Renewable and Alternative Energy for the Environmental Sustainability program. In addition, he supervises numerous capstone research projects.

Mr. Snodgrass advises all undergraduate majors and minors in the Department of Atmospheric Sciences (approximately 100 students) and supervises graduate teaching assistants and master's students. He serves on numerous committees and boards on campus, including the Student Sustainability Committee and the provost's Teaching Advancement Board and Task Force on Enhancing Student Learning in Large-Enrollment Courses.

Mr. Snodgrass's research initiatives focus on K–12 science education as well as weather forecasting applications in financial markets. He is a cofounder of Global Weather and Climate Logistics, a private company that provides logistical guidance and solutions to weather-sensitive financial institutions. His company merged with Agrible, a precision farm management and predictive analytics company, where he is also a cofounder and principal atmospheric scientist.

At the University of Illinois, Mr. Snodgrass has received the College of Liberal Arts and Sciences Award for Excellence in Undergraduate Teaching and the Campus Award for Excellence in Undergraduate Teaching. In addition, his online version of Severe and Hazardous Weather was named the best online course of 2012 by the University Professional and Continuing Education Association. His current research efforts focus on weather risk involving landfalling tropical cyclones and global agricultural yield projections. ■

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This series of lectures is intended to increase your understanding of the principles of weather-related emergency preparedness and storm chasing. The weather-related emergency preparedness and storm-chasing information provided in these lectures is for informational purposes only and not for the purpose of providing specific advice. The Teaching Company does not encourage storm chasing. You should contact an expert to obtain advice with respect to any particular weather-related emergency preparedness activities or situations.

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Table of Contents

INTRODUCTION

LECTURE GUIDES

SUPPLEMENTAL MATERIAL

The Science of
EXTREME WEATHER

Severe weather is ubiquitous. It is paramount that we study and understand high-impact meteorology because our lives are constantly impacted by the weather our atmosphere produces. This course will provide both the breadth and depth you seek to understand, and even predict, severe weather events. Throughout the course, historical examples are used to showcase the vivid and awe-inspiring power of the atmosphere.

You will learn about extreme variations in temperature as you investigate arctic cold waves, the polar vortex, heat bursts, and deadly heat waves. You will go on a journey to understand how wind forms and why it can accelerate to hurricane force in just seconds. You will discover how water in the Earth's atmosphere ultimately powers each weather system through familiar processes, such as condensation and evaporation. You will learn how to use the latest scientific instrumentation, such as dual-polarization radar and multispectral satellite imaging, to observe the evolution of storm systems and identify their most powerful features.

Severe thunderstorms are often the most feared of all types of hazardous weather. This fear will be redirected toward admiration as you learn how the atmosphere is capable of suspending billions of gallons of water within each storm cell. You will dissect each storm type and learn how they produce lightning and thunder. You will discover why some storms spin and produce large hail and tornadoes, while others race across the land as long, arcing lines with damaging straight-line winds.

Most importantly, through these lectures, you will develop the skills necessary to forecast and predict the type and severity of severe storms. Then, when they happen, you will know how to track them on radar and watch for hook echoes, velocity couplets, bow echoes, hail cores, and debris balls. You will go on virtual storm chases, where the atmospheric processes that give birth to tornadoes will be pieced together. You will discover the latest scientific theory on tornado-strengthening processes and, most importantly, learn how to stay safe should you ever find yourself in the path of one.

Winter cyclones can produce a wide variety of impactful weather. They are large, and from space they appear as a 2000-mile-wide spinning vortex of clouds. When one moves across the United States, its northern edge pushes into Canada while its tail stretches south into Mexico. You will learn how these monstrous storm systems blend air from different source regions to create a variety of winter weather conditions.

Blizzards are a formidable force in our atmosphere. They can shut down a region for days and bury cities in feet of snow. You will discover the ingredients that must mix to form a blizzard, which has the power to immobilize entire states. These same storm systems are capable of producing sting jets that race across parts of Europe with driving winds that can top 100 miles per hour.

You will discover the thermodynamics of an ice storm and learn how supercooled water can encase trees, power lines, and roadways in several inches of ice. You will learn how to recognize and predict winter precipitation types, such as sleet and ice pellets versus heavy snow and rain. Then, you will dive into the science of extreme snow by discovering the lake-effect process. You will know how to monitor these events with radar imagery and forecast the position of the hyperfocused bands of snow that can drop more than 10 feet of snow in just a few days.

Earth's deadliest and most impactful forms of weather happen when the atmosphere overwhelms an area with water or deprives it of this precious resource. Globally, drought is the deadliest form of weather. You will learn how drought has done more to shape human history than any other weather type. You will learn how to predict drought and how to measure its impact on the economy. Then, you will investigate the power of a flood. From flash flooding to coastal flooding, floodwater causes the most insured loss each year across the globe.

Tropical cyclones are considered the greatest storm systems on Earth. You will learn how typhoons and hurricanes form, track, and produce such incredible winds. You will discover why hurricanes have eyes and how to forecast their position and strength. You will peer deeply into the structure of a hurricane and learn how it creates storm surge torrential rain.

Your study of the tropics will lead you to the discovery of the teleconnections of Earth's weather systems. You will learn how large-scale circulations, such as El Niño and La Niña, impact weather across the entire globe. You will use this knowledge to predict future weather conditions and become well versed in the meteorology of long-range weather prediction.

Severe weather is happening somewhere on Earth each day. This course will empower you by teaching you the science that drives extreme weather. Most importantly, you will know how to stay safe as you observe the amazing weather Earth produces.

LECTURE 1

Extreme Weather Is Everywhere

Every day, severe weather is happening somewhere on Earth. The goal of this course is to explain the science of extreme weather. You will discover why certain locations are more susceptible to severe weather than others. Another goal of the course is to teach you how to survive severe weather. Both as a tool for survival and for understanding the science, you will also learn how to use the most technologically advanced techniques to observe and forecast extreme weather.

Why Does Earth Have Weather?

» Earth is a sphere receiving energy from a nearby star, the Sun, whose distance and energy output are ideal for Earth. The Sun bathes us in visible light, which is essential to nearly all processes that occur on Earth—especially photosynthesis. It is also the reason that Earth has weather.

» The Sun's energy is more than plentiful, but it is not evenly distributed across Earth's spherical shape. The tropics receive more energy from the Sun than they can radiate back to space, while the polar regions are in deficit.

» This one simple fact drives atmospheric circulations. Earth's atmosphere creates large-scale, powerful winds that attempt to reduce the global disparity in heating and move toward a global equilibrium.

» Without large-scale storms to move Earth's heat around, the equator would become much hotter and drier than it is, and the poles would remain much colder than they are. Without hurricanes, midlatitude cyclones, and other major storms, the atmosphere of Earth would not stay mixed, and temperatures would become far more extreme.

» The atmosphere is the medium through which these global tensions are tamed. One of the most fascinating things about Earth's atmosphere is how thin it is. In truth, Earth is barely habitable. We must stay pretty close to the surface and away from the polar regions of Earth. Go much above the surface of the Earth, or too close to the poles, and the air temperatures are so cold that human life is only possible with the help of modern technology.

TROPICAL CYCLONE DIANNE

- The composition of Earth's atmosphere is also famously unique in our solar system. Instead of being made of almost entirely carbon dioxide like our neighbors, 99% of the air we breathe is a combination of nitrogen and oxygen. Carbon dioxide only makes up about 400 parts per million—about 0.04%. Yet Earth's temperature is extremely sensitive to trace gases in our atmosphere.

- If our planet's atmosphere were made of only nitrogen and oxygen, Earth would be a much different place. These gases let in the Sun's light without much interaction. About the only thing that happens is some of the blue light is scattered, resulting in rich blue skies.

- Letting all that light through allows Earth to warm up quite a bit. However, when the Earth in turn radiates its thermal energy back into the atmosphere toward space, oxygen and nitrogen allow it to pass through without capturing any of that energy. As a result, the heat would be lost to space.

- The consequence is that if Earth's atmosphere were only made of nitrogen and oxygen, our globally averaged temperature would plummet 60° to an average temperature of 0° Fahrenheit (F), or –18° Celsius (C).

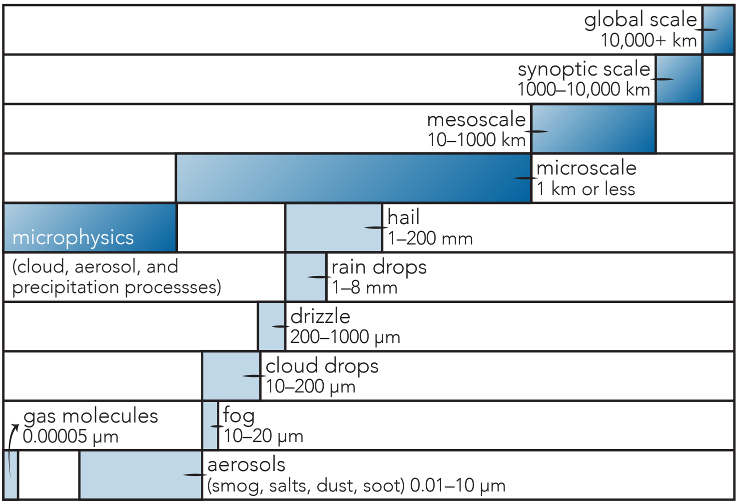
- Earth's trace gases—primarily water vapor, carbon dioxide, and methane—perform an essential task. Just like nitrogen and oxygen, these gases let the Sun's light in, but as the Earth's thermal energy tries to escape, these gases, called greenhouse gases, absorb the outgoing energy and retain it in the atmosphere.

- In addition, water vapor plays other critical roles in weather that are often overlooked. Without the phase change of this gas into a liquid, no heat could be supplied to a developing storm. Without this heat release, the storm would not be buoyant or rise to create rain.

» Water is also the only natural substance to change through all three phases (solid, liquid, and gas) in our atmosphere, and it is those phase changes that power Earth's weather systems.

The Scale of Weather

» Earth's weather systems are born out of an interaction between processes that occur across 18 orders of magnitude of size.



» Microscale events—those that form the building blocks of clouds—evolve into mesoscale events. Microscale meteorology refers to weather events that are approximately 1 kilometer in size, while the mesoscale refers to weather events that span 10 kilometers to 1000 kilometers in size.

» For example, a single cumulus cloud is a microscale weather event. A mesoscale weather event would include a long line of thunderstorms or a hurricane. Midlatitude cyclones are much bigger than hurricanes and are therefore on the synoptic scale, where weather events stretch to 10,000 kilometers.

» The largest scale is the global scale. A feature like the jet stream—which circumnavigates the entire Northern Hemisphere—is an example of a weather process that occurs on a global scale. The jet stream is a vital player in Earth's extreme weather and climate; in fact, it controls the weather for more than half of the global population.

» All of the smaller-scale weather processes wouldn't occur without much larger parts of the weather system being set into motion. Without the global-scale jet stream, there would be no midlatitude cyclones. Without the midlatitude cyclones, there would be no fronts, ice storms, blizzards, or thunderstorms.

» At the same time, large-scale weather features such as drought, El Niño, hurricanes, and the polar vortex are the result of countless interactions and feedbacks on much smaller scales. Each part of the system works together, across 18 orders of magnitude, to build Earth's most extreme weather. This is why weather is so complex—and why it's remarkable that we understand it so well.

Weather in the United States

» The United States has arguably the most diverse weather. With the exception of winter, states from Louisiana to South Carolina in the southeastern United States have severe heat and humidity that can be practically unbearable in the summer. Also, severe thunderstorm activity is high year-round. Lightning fatalities are highest in the Southeast, and tornadoes can happen during any month.

» During late summer and fall, all attention is given to the Gulf of Mexico, the Caribbean, and the Atlantic, because hurricanes can spin up quickly. States such as Florida, North Carolina, Louisiana, and Texas bear the full brunt of landfalling tropical cyclones and suffer the greatest losses.

- In the winter, any snow in the Southeast becomes an example of extreme weather. Even a 2-inch snowfall event can close schools for several days and cause thousands of car accidents.

- In the Northeast, the region's population density can present challenges when adverse weather settles in. With more than 100 million people along the East Coast, a blizzard can lock this region down for days.

- In the summer, heat waves increase the load on the power grid to the point of failure. In the fall, winter, and spring, powerful low-pressure systems called northeasters ride northward along the coast, causing beach erosion, flooding, and massive blizzard events.

- In the Midwest, summers can be oppressively hot. During spring and summer, this region is subjected to frequent squall lines of thunderstorms capable of stripping shingles from rooftops, flattening new crops, and tearing large branches from trees. Winter is often wet, with repeated ice storms and snowfall events.

» However, being between the warm Gulf of Mexico and cold Canadian Prairie, the Midwest is subject to the freeze-thaw cycle, which effectively destroys roads and bridges as water seeps into cracks and expands as it freezes.

» The Great Plains are very similar to the Midwest, except that spring and summer thunderstorms are the most severe on the planet. Each year, supercell thunderstorms erupt into the troposphere with the energy to produce the world's most powerful tornadoes. At the same time, these storms give birth to hail the size of grapefruit and straight-line winds that can level a barn.

» The northern plains are home to the most intense blizzards in the United States. Arctic air slides southward and wraps itself into developing winter storms. The result is bitterly cold air combined with heavy snow and winds that occasionally approach hurricane force.

» The mountains in the West produce their own set of meteorological challenges. In the summer, they are a part of America's playground, but thunderstorms form among their peaks. Flash flooding can happen in an instant and send a wall of water rushing through the canyons that will sweep away everything in its path. In the winter, a west wind can produce a pleasantly warm and comfortable day, but the chinook winds can accelerate to speeds greater than 100 miles per hour.

SEVERE WEATHER WARNINGS

If a tornado is coming toward your house, opening your windows is one of the most dangerous things you can do. Hiding under a bridge is also extremely dangerous.

If you think you are about to get struck by lightning, running is not wise, and neither is hiding under a tree. Your car might offer the best protection.

- Deep in the mountains, avalanches and windstorms can be awesome and terrifying. Air is forced to carve paths through the valleys and up steep slopes, where it builds clouds capable of producing several feet of snow in a single day. Additionally, windchill temperatures in the mountains can drop to −40°F to −60°F.

- In the Pacific Northwest, the shifting weather patterns can make this region a land of plenty one season and a land of great need the next. Winds from the west can feed great ribbons of moisture from the Pacific Ocean that rise over the mountains and produce an abundance of rain and snow.

- As one of the United States's wettest locations, cities near the mountain chain's feet spend most of the year under clouds. It is common in these locations to receive more than 100 inches of rainfall per year.

- On the other side of the mountain chains, a rain shadow prevails. In central Washington and Oregon as well as southern Idaho, fewer than 10 inches of rain will fall on average. Such extremes make this region sensitive to both drought and flood.

- With a significant part of its land north of the Artic Circle, winter is unrelenting in central and northern Alaska, where the Sun barely shines but for a few precious hours each day, and sometimes not at all.

- In the desert Southwest of the United States, picking the right elevation is the key to picking the right climate. The desert Southwest is also very vulnerable to flash flooding. With such intense heat and dry weather, the desert ground becomes as hard as concrete. When the monsoonal thunderstorms arrive in late summer, flash flooding through dry riverbeds can create a torrent mudflow in just moments.

- Along the southern California coast—specifically, San Diego and nearby coastal cities—clear skies prevail for more than half the days of each year. Temperatures in the winter cool into the upper 60s, and in the summer, the average highs are in the mid-70s to upper 70s.

- Tornadoes, hail, and other thunderstorm activity are rare, because this area misses most of the ingredients they need to form. Snow doesn't fall here, and while the remnants of an eastern Pacific hurricane can make it this far north, all it brings is a little rain—no wind or storm surge.

SUGGESTED READING

The following web page, which is housed on the University of Illinois servers, contains recommended links for weather information:

https://www.atmos.illinois.edu/~snodgrss/Ag_Wx.html.

QUESTIONS TO CONSIDER

1. What makes a region vulnerable to severe weather? Has severe weather impacted the location that you have chosen to live?

2. Deaths from severe weather have decreased over the last 100 years, despite the rapid increase in population. Why is the fatality rate decreasing, even though more people are exposed to severe weather due to population growth?

Temperature Extremes and Cold-Air Outbreaks

Earth's extreme weather is a direct consequence of the contrast in temperatures across the planet. In this lecture, you will learn about the temperature ranges that exist on Earth. You will also learn about the consequences of having a round planet that rotates around a tilted axis and explore what this tilt means for extreme weather on Earth. In addition, you will learn about the polar vortex and how it relates to extremely cold weather.

Earth's Temperature Ranges

» Everything that has mass is constantly vibrating at a molecular level—even solid objects. That molecular vibration, including the kinetic energy of molecules in a substance and the vibrational movement of the molecules themselves, is what we call temperature. Hot objects have very high molecular kinetic energy; cold objects have lower kinetic energy.

» To stop all molecular vibration entirely would mean to get so cold that no kinetic energy exists—a temperature of absolute zero. That temperature, which has been approached very closely but never fully reached, is about 2/3 of a degree beyond –459°F, which is a little beyond –273°C.

» With no heat, strange quantum effects occur that could change a substance's makeup. It may cease to exist.

- On Earth, air temperatures are all about the distribution of the Sun's energy. On the Sun's surface, the temperature is approximately 11,500°F, or 6000°C. A star at that temperature emits its peak energy as visible light. Visible light is not just how we see; it's also the dominant wavelength for our Sun.

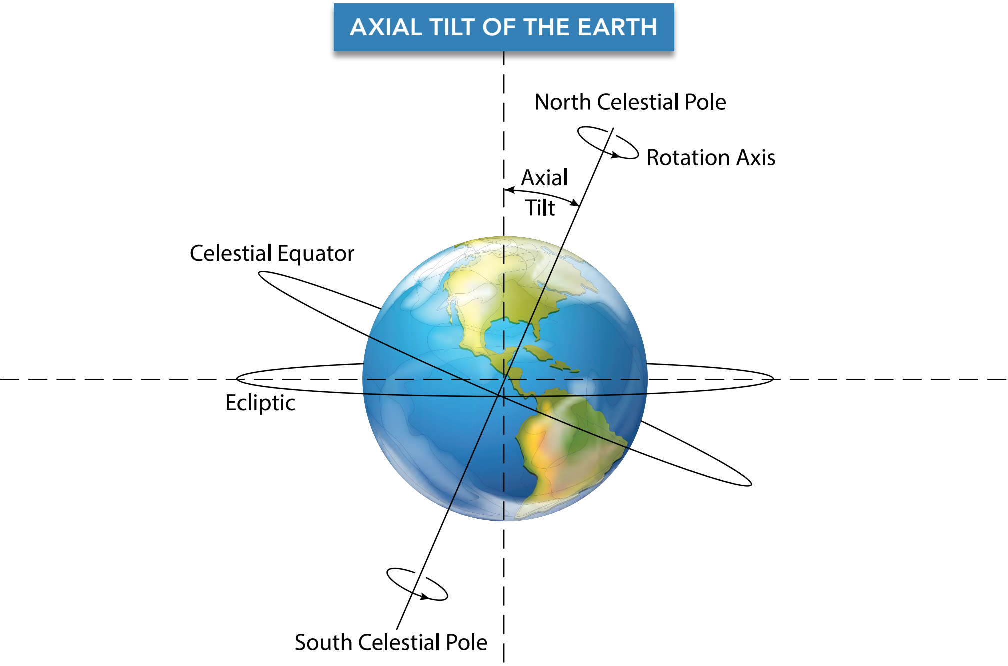
- We are bombarded with enormous quantities of sunlight. With this much energy coming to Earth every day, it's no wonder that Earth's range in temperature is so dramatic. As this energy is distributed across our round planet, Earth's complex terrain and highly variable surface types unevenly spread this energy around.

- Earth's average surface temperature is 60°F, or almost 16°C, but the world record for the highest air temperature is 134°F, or almost 57°C, which was recorded in Death Valley, California. Earth's coldest temperature was recorded near the South Pole in the heart of winter: −129°F, or −89°C. This means that Earth has a total range of air temperatures that span 263°F, or 146°C.

Earth's Shape, Tilt, and Orbit

- Earth's large dynamic range in temperature is a direct consequence of its shape, tilt, and orbit. The directness of the Sun's rays changes significantly throughout the year. If the axis around which Earth rotates had no tilt, we would not have such pronounced seasons, and temperature fluctuations throughout the year would be very small.

- Earth's axial tilt is currently about 23.5°. Because of this tilt, Earth has seasons. There are 4 distinct days each year that mark the change of Earth's seasons. Starting on March 21—the vernal, or spring, equinox—the Sun's rays shine directly on the equator. On that day at noon, if you were standing on the equator, you would be shadowless. On that day, the Sun rises and sets exactly to the east and west.



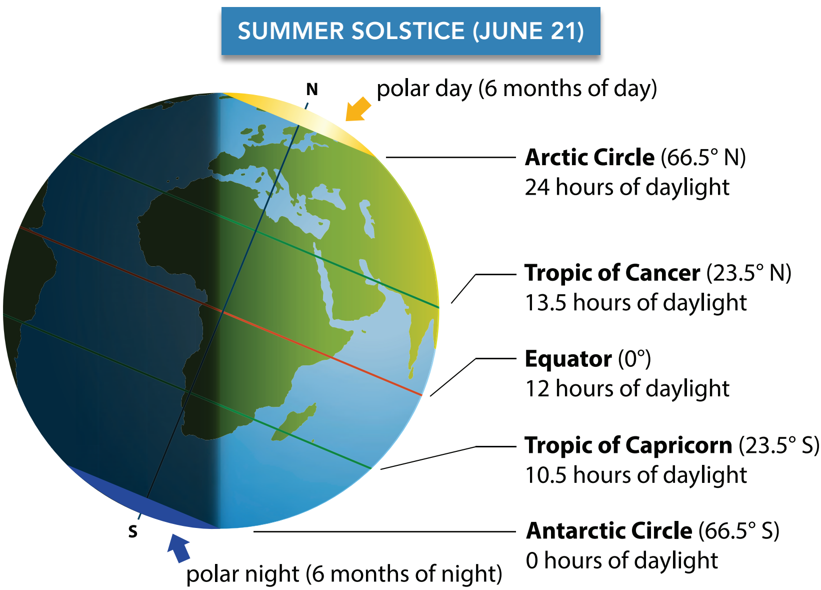
- Equinox means "equal night," which means that every location on Earth, except the North and South Poles, experience 12 hours of darkness and 12 hours of daylight.

- If you were on the North Pole on this day, the Sun would rise above the horizon and not set for another 6 months. While the rest of the Northern Hemisphere continues to gain daylight hours and warm up in spring, the Sun at the North Pole never sets below the horizon.

- By June 21, the Sun's rays reach their northernmost latitude and strike directly on the Tropic of Cancer, and summer begins in the Northern Hemisphere. This day is called the summer solstice. Solstice means "Sun stop." This is the farthest north the direct rays of the Sun will ever reach.

» An interesting consequence of living north of the Tropic of Cancer is that the Sun is always in the southern sky at noon. This means that if you live north of the Tropic of Cancer, you will never experience sunlight directly overhead. This is the longest day in the Northern Hemisphere in terms of daylight hours. On the North Pole, the Sun has not set for 3 months.

» The more the Earth tilts, the greater the seasonal variations in weather, because we are altering the Sun angles throughout the year more dramatically. Additionally, if you live north of the Arctic Circle, the Sun does not set on June 21 at all.

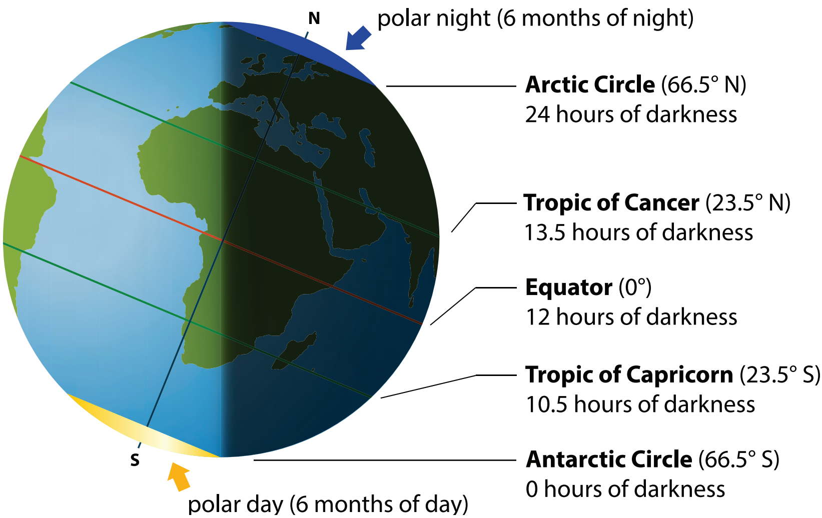


» Around July 4th, the Earth is the farthest it gets from the Sun in its orbit. However, it is still quite warm in the Northern Hemisphere on this day because this hemisphere is tilted directly at the Sun during this time of year. As such, much more concentrated light hits this hemisphere.

» As the autumnal, or fall, equinox arrives on September 21, the Sun, which has been out on the North Pole for 6 months, sets, and 6 months of darkness arrive. The Northern Hemisphere ends summer and begins fall and continues the loss of daylight hours. However, the Southern Hemisphere starts spring, and the Sun rises on the South Pole to begin 6 straight months of sunshine there.

» Winter arrives on December 21, the shortest day of the year in terms of daylight hours for the Northern Hemisphere. On this day, the Sun's rays are directly on the Tropic of Capricorn.

WINTER SOLSTICE (DECEMBER 21)



» As January 4 arrives, the Earth passes as close to the Sun as it can in its orbit. The Northern Hemisphere is cold despite its closer proximity to the Sun because it is tilted away from the Sun's direct rays. In the Southern Hemisphere, the seasons are opposite.

» Additionally, seasonal variations in most locations are less extreme than their Northern Hemisphere counterparts. The reason for this is due to the ratio of land area to ocean area. There is much more ocean area when compared to land area in the Southern Hemisphere, unlike in the Northern Hemisphere. The result is that the oceans moderate the seasons.

AVOIDING HYPOTHERMIA

From 2003 to 2013, an average of more than 1300 people died from hypothermia in the United States each year. The easiest ways to reduce these deaths are to have a plan for when you are out in bitterly cold weather and keep a winter survival kit in your car.

» On the other hand, the Earth is physically closer to the Sun during the Southern Hemisphere summer and farther away in the winter. This pushes winters to be colder and summers to be warmer than they would be otherwise. Of these two effects, the ratio of land to water is dominant.

» Earth's seasons are not all the same length. In fact, Northern Hemisphere winter is the shortest season, at just 89 days, while summer is the longest season, at nearly 94 days.

Fluctuations in Temperature

» Local topography can sometimes produce dynamic fluctuations in temperature over the distance of a short drive. Living along a coastline that is mountainous is a perfect setup for experiencing large changes in air temperature.

» In San Francisco, California, the cool ocean currents in the Pacific Ocean heavily moderate the climate. Winters are very mild, with high temperatures in the 50s and 60s. Summers are relatively cool, with high temperatures averaging in the mid-70s.

» But just east of the coast is the Central Valley of California. In a matter of minutes, the cool coastal climate is replaced with desertlike heat. The elevation along the coast effectively isolates the Central Valley, keeping cooler air to the west and warmer air to the east. It's not uncommon in the summer to have temperatures in San Francisco in the 60s while the Central Valley soars over 100°F.

» Hawaii is famous for its incredibly diverse climate. With 8 different climate zones, you can experience a desert with nearly 100° heat, a tropical rainforest with 300+ inches of rain annually, and, if you come on the right day, a blizzard.

» While large changes in temperature can occur throughout the year, change can happen very quickly for a single location on any given day. For example, heat bursts are common in regions with regular thunderstorm activity but relatively dry climates, such as the Great Plains of the United States and parts of central Australia.

» Whereas a heat burst is a brief extreme change in temperature, a heat wave can be a long, drawn-out, and sometimes deadly affair. Heat-related fatalities are likely the deadliest form of weather on Earth.

» The Great Plains of the United States are the perfect battleground for colliding air masses from the tropical and polar regions on Earth. While extreme heat can build 100°F temperatures deep into Canada in the summer, the vast Arctic prairie can unleash vigorous and powerful cold fronts in the depths of winter. Cold-air outbreaks form frequently in the midlatitudes.

» Winter storms frequently track across the United States and Europe in the winter. As they strengthen, the counterclockwise flow of the winds around these low-pressure systems draws bitterly cold air from the north southward. There, it collides with warmer air to create cold fronts.

- These fronts are the trigger and source of lift in the atmosphere, which makes them a focal point for severe weather. When backed by extreme cold of the Arctic, powerful cold fronts are capable of creating such a dramatic change in weather that many people are caught off guard.

The Polar Vortex

- The polar vortex in the Northern Hemisphere refers to counterclockwise circulation patterns near the North Pole. This circulation is weak during the summer but can be quite strong in the winter. These circumpolar winds can often exceed 80 miles per hour.

- The weather phenomenon occurs in the upper troposphere and lower stratosphere—thousands of feet above the ground. Inside the vortex, the coldest air on Earth typically resides. Occasionally, pieces, or lobes, of this vortex shed or break apart and send extremely cold air southward.

- Meteorologists watch for these outbreaks by monitoring the position of the jet stream. Jet streams are narrow bands of fast-moving air that encircle the Earth. The jet stream is another belt of winds that encircles the Earth, but it is typically found south of the polar vortex, in the midlatitudes.

- The polar jet stream and polar vortex can work together in winter to create deep troughs in the jet stream. Cold-air outbreaks are accompanied by deep troughs in the flow of the jet stream that develop 6 miles, or 9 kilometers, above the surface.

- From a global perspective, these troughs appear as southward dips in the position of the jet stream. When a jet stream trough develops over an area, cold weather is always the result.

- Jet stream troughs are very common in winter, but true intrusions of the polar vortex are much less common. This is because the coldest air often stays trapped around the North Pole. When a lobe of the polar vortex does break off and heads south, it manifests itself as a large spinning mass of cold air in the upper troposphere. In contrast, the airflow through a jet stream trough dips south but still progress to the east.

- Essentially, when the polar vortex moves over an area, it may sit and spin, high above our heads, for several days or more. Normally, troughs of cold air move along much faster and are more transient. When the polar vortex lunges south, it sets up a permanent, deep trough that doesn't move for several days.

weather station	record high	record low	difference
Portland, ME	103	–39	142
Concord, NH	102	–37	139
New York	106	–15	121
Boston	102	–12	114
Baltimore, MD	105	–7	112
Philadelphia	104	–7	111
Washington, DC	105	–5	110
Charleston, SC	105	6	99
Savannah, GA	105	3	102
Jacksonville, FL	105	7	98
Miami, FL	100	30	70
San Juan, Puerto Rico	98	60	38

Provisional source: *World Book* 2016, except for Miami

SUGGESTED READING

Burt, "A Challenge to the Validity of the World Record 136.4°F [58°C] at Al Azizia, Libya."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 1, p. 1–6.

Stott, Stone, and Allen, "Human Contribution to the European Heatwave of 2003."

QUESTIONS TO CONSIDER

1. How might Earth's seasons and extreme temperature change if Earth's tilt on its axis were to change?

2. Why do annual temperature fluctuations increase with increased latitude?

LECTURE 3

Low Pressure and Earth's High Winds

Weather is fundamentally a consequence of changing air pressure. Air moves vertically whenever there are differences in air pressure. Slowly descending air produces higher air pressure. Higher air pressure creates clear and calm conditions. Violently ascending air is often the result of low air pressure, and it is the contrast of high and low air pressure that creates the Earth's most powerful storms. As you will learn in this lecture, understanding where in the atmosphere that air ascends or descends unlocks many of the mysteries of extreme weather.

Air Pressure

» Earth's ceaseless and often-volatile atmospheric motion is a constant reminder of the enormous global tension between temperature extremes. As a direct consequence, weather systems evolve as the atmosphere repositions itself to accommodate the uneven heating our round planet receives from the Sun. This leads to fluctuations in air pressure, which are at the heart of every weather event.

» Meteorologists constantly monitor Earth for changes in air pressure. They understand that with changing air pressure comes changing weather. These fluctuations drive wind on Earth.

» Unlike Earth's nearest neighbors, the typical atmospheric pressure at ground level on Earth is survivable. The pressure is low enough that we are not crushed by the weight of the atmosphere, but it is also high enough that each breath fills our lungs with life-giving oxygen and nitrogen.

- Humans can survive a large range of air pressure, but our bodies will respond to these changes in interesting ways. The first indication that the pressure has changed is felt in the ear, when the ear "pops," which is when a small tube in your ear eventually brings the air inside your ear back into equilibrium with the outside air.

- If air pressure drops too low, the human body experiences hypoxia, or oxygen starvation. Spending too long at such low pressure can cause death.

- Given how essential oxygen is, you might be surprised to learn that most of the space in a room is actually empty space. In fact, less than 1% of the total volume of a room is physically taken up by air. The rest is open and free space. However, the small fraction of the total space that is occupied by air exerts an enormous force.

- Air pressure is defined as the force exerted by the air per unit area, such as a square inch.

- Our atmosphere is a mixture of gases that are held on Earth's surface by gravity. These gases are compressed against the surface. As a result, air pressure decreases exponentially with altitude. At all times and for any given location, the highest air pressure is found on the surface of the Earth.

- As you ascend in the atmosphere, the pressure decreases rapidly. The top of Earth's atmosphere is commonly found at an altitude of 120 kilometers, or about 75 miles, above sea level. If you were to ascend to half that height, 99.9% of all the air is still beneath you.

- Go only 1/10 of the way up, to an altitude of 7.5 miles, where commercial jets fly, and 75% of all the air is still beneath you. At that altitude, you would need to take 3 or 4 breaths of air to get the same volume of air in your lungs as you would at sea level.

- If you were to add it all up, the weight of the atmosphere is a staggering 11.6 million billion pounds. This enormous pressure is the result of every square inch weighing approximately 14.7 pounds at sea level.

- It is only when there is a pressure difference, or a pressure change, that we get to experience how powerful the force of the air really is. This difference is called a pressure gradient. Large gradients in pressure in the atmosphere create a powerful force in the wind.

- There are many caves on Earth that open to ocean. Many of these caves are open to the air during low tide, but at high tide, the mouth of some caves becomes completely submerged, trapping air inside. When the cave becomes sealed at high tide, in one instant, a dense fog can form, but in the next moment, the fog can disappear.

- When the mouth of the cave is under water, the air inside the cave is sealed in. This air soon becomes saturated with water vapor, because water vapor is evaporating from the ocean water in the cave.

- When a wave rolls in, the amount of water in the cave increases. This compresses the air in the cave, which leads to a small but measurable warming of the air. This in turn promotes the evaporation of more water into the air in the cave. When the wave rolls out, the volume available for air in the cave increases.

- So, the air expands in the cave, which causes the air to briefly cool. And because this expanding and cooling air is saturated, an instant cloud forms in the cave.

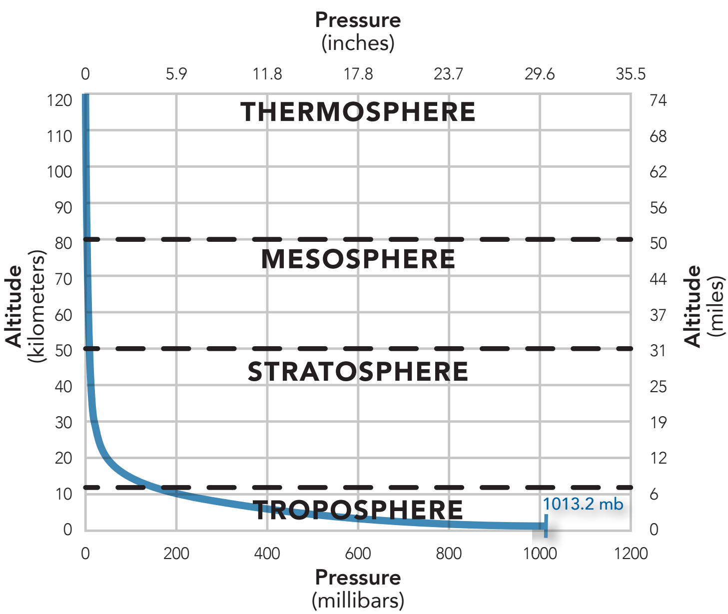
- This demonstrates the impact of differential pressure. Differences in pressure give us everything from the ferocious winds of a tornado, to the incredible speeds of the jet stream, to the rapid circulation of hurricanes, to the explosive descent of a microburst, to the howling of a blizzard.

Measuring Air Pressure

» Meteorologists will often refer to the air pressure in the units of bars or millibars. A millibar is 1 thousandth of a bar, and standard atmospheric pressure found at sea level, also called 1 atmosphere, is 1013.25 millibars (which is equivalent to 14.7 pounds per square inch). This number represents the force applied per unit area at sea level.

» In the metric system, there is a tiny unit of pressure called the pascal: 101,325 pascals is equivalent to 1 atmosphere or 1 bar, and 1 hectopascal is equivalent to 1 millibar.

» Some meteorologists still refer to air pressure in terms of inches of mercury. This is a reference to an early design of the barometer, an instrument that measures air pressure. Under standard sea-level pressure, the mercury will rise 29.92 inches in a vacuum tube.



- A pressure of 1084 millibars set the record in December 1968 in Siberia. The extremely cold and dense air that resides there in the winter built a dome of high air pressure that bested the record set in the United States in 1963 at 1064 millibars. These high-pressure domes bring clear skies and light winds, but the temperature is extremely cold, which increases the density of the air and helps the atmosphere achieve these high-pressure records.

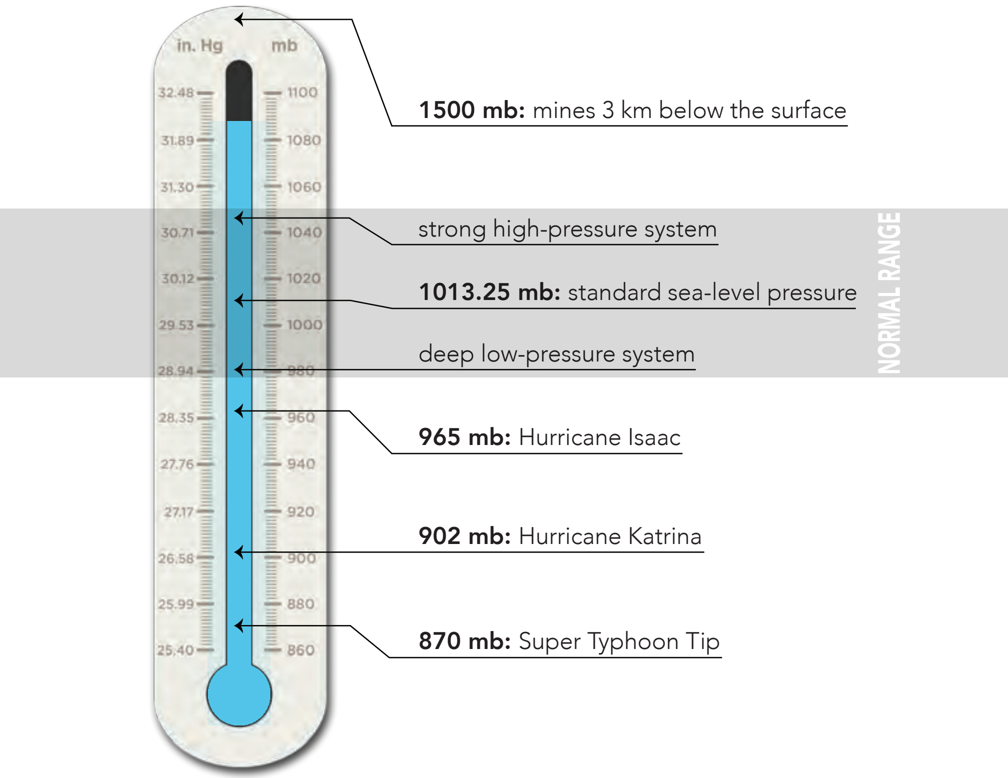
- Humans have experienced much higher air pressure than this on Earth. The deepest mines on Earth extend more than 3 kilometers below the surface. Air pressure in these mines can build as high as 1500 millibars.

- The record for the lowest air pressure ever measured at sea level was found in the center of the most powerful tropical cyclone on record: Super Typhoon Tip. The air pressure fell to 870 millibars at Tip's most intense stage. This drop in pressure produced winds that approached 200 miles per hour.

- High air-pressure systems typically bring lighter winds, relatively clear skies, and nice weather conditions. These types of weather conditions are common when the air pressure builds above about 1020 millibars.

- In contrast, low air pressure is associated with deteriorating weather. Strong winter storms often have central pressures below 990 millibars and can occasionally dip below 975 millibars. To find sea-level pressures lower than this, we have to look into the eyes of hurricanes.

- Hurricane Katrina in 2005 intensified to a category 5 strength hurricane before it hit Louisiana. The central pressure in Katrina fell to 902 millibars, which produced winds of 175 miles per hour. Katrina's damage estimates topped $200 billion.



Air Pressure and Wind

» Changes in air pressure result in changes in wind speed. Simply put, air moves on Earth due to changes in air pressure. It always moves from higher air pressure to lower air pressure. Getting the air to move vertically is very difficult. Gravity is always pulling the air toward the center of the Earth, which compresses the air against the Earth's surface.

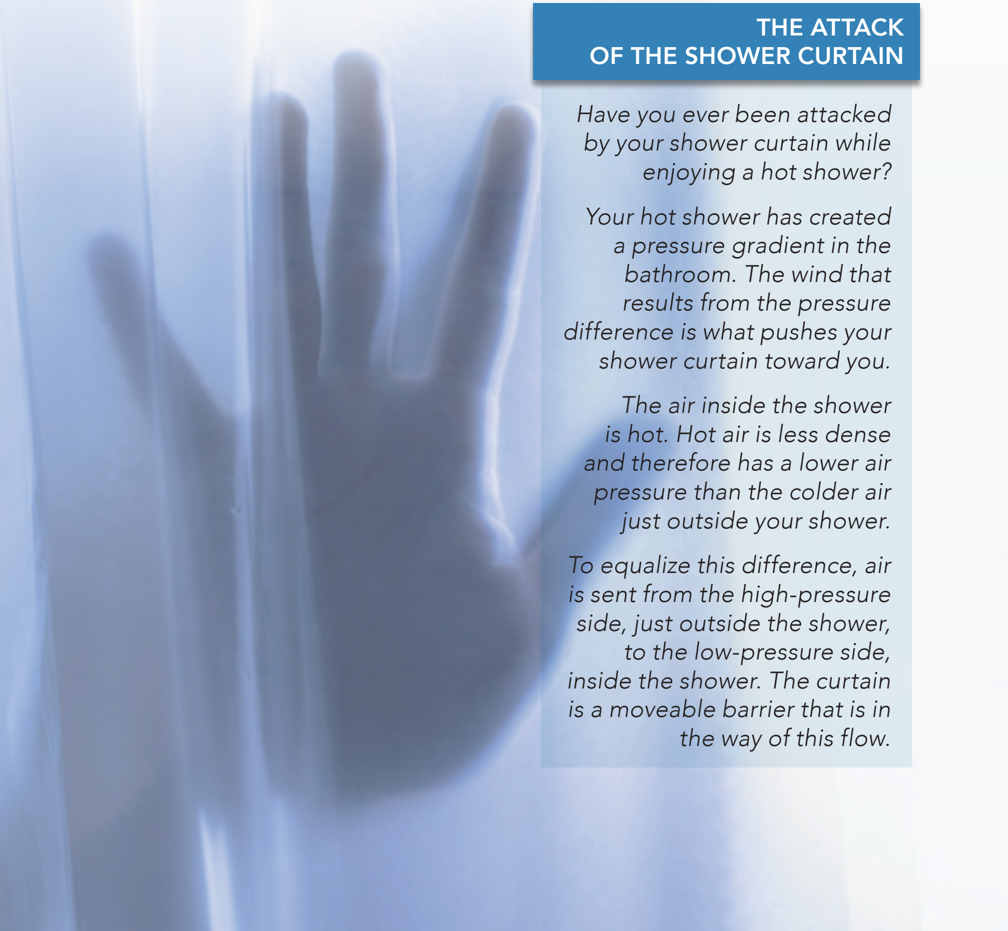
- If gravity were to somehow shut off, the air would decompress and race away from Earth's surface into space. Air resists doing this because gravity is always holding it in place. The highest air pressure at any given location is found on the ground. Air pressure also decreases rapidly, exponentially, with height. This means that there is higher air pressure near the ground and lower air pressure aloft.

- Because air wants to move from higher pressure to lower pressure, the air is always trying to escape from Earth's surface. But gravity keeps this vertical pressure gradient in check. This balance between gravity and the vertical pressure gradient is called hydrostatic balance.

- When the air is out of hydrostatic balance, like it is in a thunderstorm, things get very interesting. When air is forced to ascend, it expands as the pressure decreases. Expansion of the air leads to cooling. Cooling of the air leads to condensation. And condensation builds clouds.

- Vertical air motion is difficult because of gravity. In contrast, horizontal variations in air pressure are what cause the wind to blow. Pockets of high and low air pressure develop and decay across Earth every day. Wind is the flow of air from the high-pressure regions into the low-pressure regions.

- Deep low-pressure systems are constantly being filled with air from surrounding higher air pressure. Wind is the result of a difference in pressure between two locations, which is referred to as a pressure gradient. The strong vertical pressure gradient is nearly always balanced by gravity. Horizontal pressure gradients cause the wind to blow.



THE ATTACK OF THE SHOWER CURTAIN

Have you ever been attacked by your shower curtain while enjoying a hot shower?

Your hot shower has created a pressure gradient in the bathroom. The wind that results from the pressure difference is what pushes your shower curtain toward you.

The air inside the shower is hot. Hot air is less dense and therefore has a lower air pressure than the colder air just outside your shower.

To equalize this difference, air is sent from the high-pressure side, just outside the shower, to the low-pressure side, inside the shower. The curtain is a moveable barrier that is in the way of this flow.

- How can we monitor these pressure differences to forecast the wind speed and direction? Knowing this information is important for forecasting wind-power generation or severe wind damage. It can be used to find a tail wind that will improve your gas mileage or warn you if there might be a crosswind that can blow your car off the road.

- How do we forecast the wind? We start with a map of sea-level pressure. On these maps, pressure is contoured into lines of constant pressure called isobars. The spacing of these isobars represents the pressure gradient.

- To determine wind speed, our numerical models calculate the pressure gradient, account for friction, and produce a wind speed map. These precise and accurate forecasts of wind are a direct consequence of our ability to model the dynamics of changing air pressure.

SUGGESTED READING

Mount Washington Observatory, "World Record Wind."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 1, p. 6–8 and 14–15.

QUESTIONS TO CONSIDER

1. Why does the wind blow? What influences wind speed?

2. Why is low air pressure associated with nearly all types of severe weather?

LECTURE 4

Extreme Humidity, Rain, and Fog

Earth is saturated with water, and this fact is the basis for nearly all of Earth's extreme weather. Water is the only substance that naturally exists in all three phases in our atmosphere. It readily converts between a gas called water vapor, a liquid, and a solid called ice. And it is the energy associated with water's phase changes that powers many of Earth's most extreme weather events. In this lecture, you will learn about extreme rainfall, humidity, and fog.

Water on Earth

» While Earth's atmosphere contains very little water, the Earth's surface is nearly covered with it. Approximately 70% of Earth is covered in water: 97% of this water is found in Earth's vast oceans, and 2.4% is locked away as ice, most of which is found in Earth's ice caps. What remains on the surface makes up our liquid freshwater supply in rivers, lakes, streams, and ponds.

» Groundwater, which is easily brought to the surface and supplies a large percentage of the world's population with drinking water, is found in much greater quantities than the freshwater in rivers, lakes, and streams—in fact, more than 25 times the amount found in liquid freshwater sources on Earth's surface.

» Roughly the same is true for Earth's total water, salty and fresh. It is commonly thought that the oceans are the Earth's largest reservoir of water. But our oceans are dwarfed by the sheer quantity of water found in the Earth's crust and mantle, where more than 10 times the amount of water found in the ocean resides.


MONSOON SEASON IN HO CHI MINH CITY, VIETNAM

- The water in the crust and mantle are not underground oceans. For the most part, they are chemically locked away in minerals. But this water can reach the surface, for example, when it's outgassed in volcanic eruptions.

- Geologists have long studied the science behind megafloods known as outburst floods. A common cause for them is the sudden release of meltwater from a retreating glacier. Such floods can reshape the landscape forever.

- Water is vital to our survival on Earth. Without our oceans, the Earth's temperature would swing so wildly each day that nighttime temperatures would be bitterly cold and afternoon temperatures would scorch most of the tropics and even the midlatitudes. Seasonal fluctuations in temperature would also be much more extreme.

- But water's high thermal inertia—which is a measure of the energy required to change its temperature—keeps Earth's climate moderated. Additionally, the oceans are a large reservoir for carbon dioxide, a powerful greenhouse gas. Most importantly, as water changes phase from a solid to a liquid to a gas, the energy it consumes in this process fuels weather on Earth.

- World records for one month and one year of rainfall were set in the 19th century in the village of Cherrapunji, India. In just one month, July 1861, more than 30 feet of rain fell, averaging a foot of rain every day for a month. And that rainy July was also the concluding month for a record-setting year of rain (from August 1860 to July 1861) that had totaled almost 87 feet of rain (1042 inches).

- In stark contrast, Earth's driest places receive so little rain that it is practically negligible. Next to the Andes Mountains is the Atacama Desert. The village of Arica receives on average 1 millimeter of rain each year. Nearby locations have gone for centuries without measurable precipitation, and some riverbeds have not had enough rain for flowing water in more than 120,000 years.

ATACAMA DESERT

Water Vapor

» Measuring and tracking water vapor throughout the atmosphere is essential to accurately predicting the behavior of the weather. Water vapor fuels severe weather. Wherever water vapor is abundant, vast amounts of energy are on tap to produce nature's most extreme storms. Where water vapor is lacking, we also find Earth's driest deserts.

» Unlike other gases, water vapor can readily change phase in our atmosphere and condense into liquid water. Water vapor is the highest energy state for water, so to step down to its liquid phase or to freeze into ice, energy must be released.

» The energy in water vapor is called latent heat. It is latent, or hidden, because the energy is stored in the kinetic energy of the water vapor molecule. When this heat is released into the atmosphere through condensation, freezing, or deposition, it gives air the power to rise.

» The energy required to vaporize 1 gallon of water is 10 million joules—roughly equivalent to 4.5 sticks of dynamite. If that amount of energy is released in an instant, there is an explosion. Every cloud contains many gallons of water vapor, so the latent heat available in just one fluffy, peaceful-looking cumulus cloud is enormous.

» A full-fledged storm system is even bigger. For example, the energy stored in Hurricane Katrina's clouds, which came from warm water that evaporated and rose from the ocean beneath, was equivalent to 6,700 quadrillion joules of energy, or 72,000 atomic bombs. But unlike a bomb, which releases all of its energy very quickly, the hurricane releases it slowly, over days.

- This energy manifests itself in huge waves, torrential rains, and powerful winds. The so-called blast radius of a hurricane is 5 orders of magnitude larger than one of the first atomic bombs. It is this energy that fuels storms, by providing them with heat, which makes them buoyant in our atmosphere.

- This heat, and the resulting buoyancy, support the enormous weight of thunderstorms. Even a small storm contains hundreds of millions of gallons of liquid water and ice.

Relative Humidity

- Like any physical object, our bodies can cool by radiating heat away. We can also cool off using convection of air currents. We can also conduct heat directly into other objects.

- But as biological organisms, our most important defense against extreme heat is sweating, which uses the power of evaporative cooling. The evaporation of the sweat requires energy for the water to achieve a higher energy state—water vapor. Our skin provides this energy. As the sweat evaporates, the heat from our skin is carried away, and we feel cooler.

- But the amount of evaporation is dependent on the relative humidity of the air. For example, when the relative humidity stands at 100%, no evaporative cooling can take place.

- The relative humidity is one of the most confusing terms in atmospheric science because it is a ratio of two weather variables that can easily change: the amount of water vapor in the room and the total amount of water vapor the room could contain if completely saturated.

- What makes relative humidity a tricky variable is that cold air is easy to saturate. Cold air simply cannot contain much water vapor, and therefore it is easy to saturate cold air with water vapor.

» The relative humidity is relative to temperature. The relationship between temperature and humidity gives rise to the concept of heat index, which combines the impacts of heat and humidity to reveal a "feels like" temperature, or apparent temperature. It accounts for the mechanisms our body uses to stay cool, primarily through sweating, and predicts the discomfort felt when heat and humidity rise.

NOAA'S NATIONAL WEATHER SERVICE HEAT INDEX

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	118	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of heat disorders with prolonged exposure or strenuous activity

CAUTION	Fatigue possible with prolonged exposure and/or physical activity.
EXTREME CAUTION	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
DANGER	Sunsroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical actzivity.
EXTREME DANGER	Heatsroke or sunstroke likely.

HIGH-HEAT AND HIGH-HUMIDITY WARNING

If you are exerting yourself during a combination of high heat and high humidity, you need to watch out for worsening symptoms, in the following order.

- *Heat cramps: Muscles in your leg or abdomen may begin to spasm.*
- *Heat exhaustion: Blood flow rushes to the skin, leaving too little for your vital organs, which can lead to dizziness, nausea, and a weak pulse.*
- *Heatstroke (also known as sunstroke): Body temperature rises sharply and can be fatal, as the body loses its ability to cool itself and the brain may not function normally. Wrap in wet cloths or lie in a cool bath.*

Extreme Fog

- As the Sun sets each night, the heat stored in the Earth's surface is radiated back through the atmosphere toward space. The air near the surface cools, which reverses the typical temperature profile of the atmosphere during the day, where temperatures cool with height.
- A temperature inversion is defined as a layer of the atmosphere where the temperature warms with height. Inversions are strongest and most frequent when the skies are clear at night.
- Clouds are very efficient at absorbing Earth's emitted thermal radiation and radiating back toward the Earth's surface. Therefore, cloudy nights are often much warmer than clear nights.

» The floor of the Grand Canyon can cool so quickly that the air becomes saturated with water vapor. The condensation results in a 500-foot-thick fog that transforms the Grand Canyon into a rolling sea of dense fog. Fog that forms in this way is called radiation fog because the Earth radiatively cools the air to the point of saturation.

» Unlike the radiation fog in the Grand Canyon, the fog in San Francisco is much more common. From September through March, these incredible dense fogs roll in off the Pacific Ocean and fill San Francisco Bay.

» The meteorological makeup of this fog originates in the Pacific marine layer. The main characteristic of this layer is a shallow temperature inversion that forms over the cooler waters of the Pacific. Above this layer, air slowly descends and warms as it descends, trapping the cooler air near the surface.

» As this air moves, or advects, toward the California coast, it encounters the colder ocean currents that flow from the northwest along the California coast. As the marine layer cools even more, it saturates, producing a dense advection fog that pushes into the California coast.

» All fog is essentially a cloud that forms on the Earth's surface. These clouds form in supersaturated air with relative humidity over 100%. Cloud droplets are very small and measure between 20 and 100 millionths of a meter each. For a cloud droplet to form, water needs something to condense on.

» If the atmosphere were perfectly clean and pristine, no clouds would ever form. Water vapor needs something to condense on, and it is impurities in the atmosphere—such as salts, soot, ash, dust, aerosols, and other tiny particles—that serve as the site onto which water vapor will condense.

» Without these particles, the relative humidity would need to be several hundred percent for 2 water vapor molecules to combine and form liquid water.

» Light has a lot of difficulty passing through clouds and fog because the tiny droplets scatter the light in all directions. As a result, when a thick fog forms, visibility through the fog can be reduced to a few feet at best.

SUGGESTED READING

Bohren, *Clouds in a Glass of Beer.*

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 1, p. 9–14.

Samenow, "Unbearable Heat and Humidity in Iran City Were 'Completely Normal,' Says Local."

QUESTIONS TO CONSIDER

1. What controls the amount of moisture in the atmosphere, and why is water not evenly distributed across the Earth?

2. Relative humidity is extremely important for human comfort. What is relative humidity, and what is it relative to?

3. Heavy fogs often form right after a severe storm passes over an area and drops a large amount of hail. Why would a fog form under these conditions?

LECTURE 5

How Radar Reveals Storms

Radar has transformed how we track and predict severe weather—especially tornadic thunderstorms. Data from the U.S. National Weather Service shows that even though the number of powerful tornadoes has remained largely unchanged since the 1940s, the number of deaths due to tornadoes has fallen sharply, even as population has grown, ever since the introduction of radar in the 1950s. As you will learn in this lecture, weather radar has transformed the science and practice of extreme weather meteorology, allowing us to see under and through each storm.

Radar Technology

» Radar technology has revolutionized the forecasting of severe storms and saved many lives. The revolution began on the evening of April 9, 1953, when Don Staggs and Glenn Stout, two meteorologists at the Illinois State Water Survey, were looking at black-and-white images of radar echoes near Champaign, Illinois.

» They identified a powerful supercell thunderstorm. Supercells are small, but very powerful, rotating thunderstorms that frequently produce strong tornadoes. An interesting hook shape slowly emerged as the radar collected echoes from the rainfall within the storm. They called it a hook echo because it looked like a fishhook was protruding from the back side of the storm.

» They recorded the position of this strange feature so that they could see if there was any evidence of what it was once the storm ended. The next day, they discovered that just north of Champaign a tornado had passed from west to east across the county. Staggs and Stout had discovered the first tornadic signature on radar.

» Just under 3 years after the hook echo was discovered, the first successful radar forecast of a tornado took place in Bryan, Texas, on April 5, 1956—predicted 30 minutes before the tornado actually hit.

» Meanwhile, Dr. Theodore Fujita at the University of Chicago published an analysis of Staggs and Stout's data, which later helped him formulate his now-widely-used Fujita scale for ranking tornado damage.

» Radar technology has improved significantly over the years. Color radar displays began in 1974, making it easier to distinguish the different levels of precipitation intensity. A new Doppler radar network was installed in the early 1990s, making it possible to track the wind speed and direction within a storm—a key factor in determining whether a storm is rotating.

Development of Weather Radar

» Radar is a device that sends focused microwave radio signals into the atmosphere and collects the reflection of these waves from objects the beam intersects. Its original design did not include the detection of precipitation.

» World War II marks the first widespread use of radar technology. Its primary purpose was to detect enemy aircraft long before they could be seen or heard. The first radar systems used low-frequency waves of 200 megahertz and 400 megahertz, but the Allies secretly developed so-called microwave radars with higher frequencies of 3000 megahertz and 10,000 megahertz.

» Weather was a nuisance to these early microwave radar systems. Radar echoes from rain would cover the imagery, preventing radar operators from detecting enemy aircraft. This discovery led the Allies to conduct many of their missions under the cover of bad weather, effectively preventing the radars used by the opposition from seeing the attack.

» After the discovery of the hook echo in 1953, and the first successful tornado prediction in 1956, the U.S. government built and deployed a network of weather radars across the United States in the late 1950s to detect precipitation.

» This radar network was upgraded in the 1980s with a next-generation radar network called NEXRAD. Each radar in the NEXRAD system is housed within a radome, which is designed to protect the radar from adverse weather, such as strong winds, lightning, and ice accumulation, as well as from critters, such as birds and bats.

» Inside each radome is a large 30-foot-diameter dish, which both transmits and receives the radar signal. The dish rotates on a large pedestal and broadcasts its signal in a radial pattern. This is why the radar data we see on television and the Internet is revealed by a sweeping line that fills a circle.

NEXRAD RADAR STATION

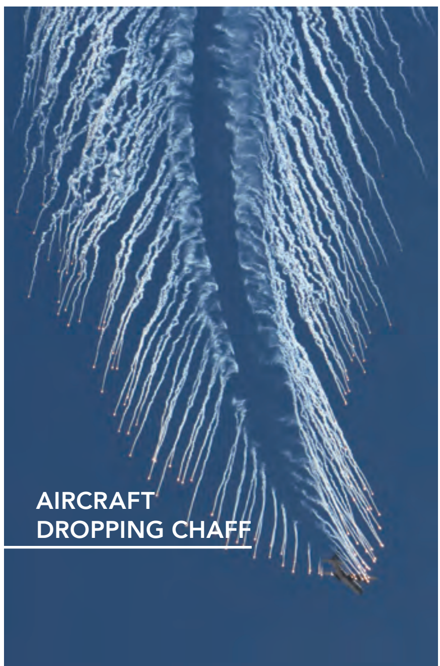
Gaps in Radar Coverage

» In the United States, the eastern United States has the best radar coverage, with most locations scanned by several radars at once.

» Radar coverage in the western United States is challenging due to mountains blocking the radar beams. The ideal scanning strategy to measure precipitation is to scan as low in the sky as possible, and mountains make this very difficult. As a result, the radar network's ability to monitor precipitation intensity and amount in the west is more limited.

» Some locations are purposefully not scanned by the NEXRAD radars. In Nevada, one of the largest military bases in the United States prevents inadvertent spying by broadcasting a microwave signal to block or blind the local radars. When the U.S. government is testing equipment, such as new aircraft technology, they don't want the local NEXRAD radars observing what is going on.

» Another thing the military uses for security is chaff, which is used by aircraft to protect them from radar-guided missiles. It consists of small pieces of aluminum that are sprayed from the plane. The aluminum reflects the radar signal and makes it difficult to track the aircraft with radar.

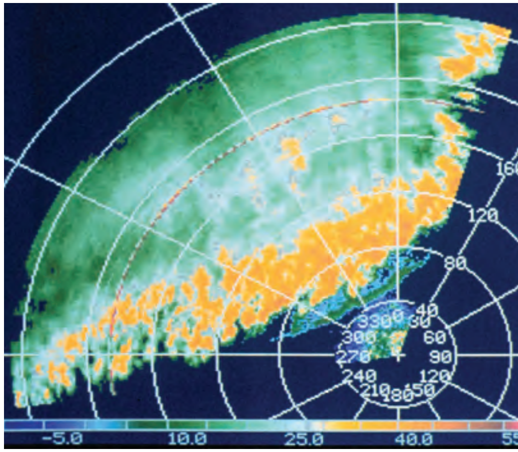


AIRCRAFT DROPPING CHAFF

How Weather Radar Works

- Rain gauges ultimately provide the most accurate and precise rainfall estimates. But the rainfall data they collect is only valid for the minutely small opening at the top of each gauge. Rainfall amounts vary greatly with time and space.

- Radar provides an elegant and simple solution to monitoring rainfall from a distance, across an entire region. The radar broadcasts a powerful and focused microwave signal from its antenna as it scans in a circular pattern. These microwaves are scattered and reflected by raindrops, and some of that energy is directed back to the radar dish, where it is collected.



- The amount of power returned to the radar is proportional to the size of the raindrops and the number of raindrops it scans. The more raindrops the radar scans, and the bigger the raindrops, the more intense the precipitation will be.

- Microwaves can pass through the atmosphere without being absorbed by the gases in the atmosphere—much like the way that visible light can shine through our atmosphere without being absorbed by the gases in the atmosphere.

- Unlike visible light, the majority of radar beams pass through clouds, rain, and snow to see storms behind storms. This allows the signal to pass through the atmosphere unattenuated, which in turn allows the radar to scan over great distances—more than 200 miles in some cases.

- But weather radar is different from a microwave oven. Weather radars operate at a power level equivalent to 1000 times that of a standard microwave oven, yet they are not cooking raindrops. Instead of continually blasting the rain with microwaves, which would cook it, weather radar sends out a single, focused, short-lived pulse that lasts roughly one millionth of a second. This is called a pulsed Doppler radar.

- The radar dish then watches and waits for a thousandth of a second for some of that microwave pulse to be reflected or scattered back to the dish, where it is collected. The amount of energy it collects is directly proportional to the number of raindrops and their size inside of a contributing volume. The contributing volume is essentially a slice through the atmosphere. You can see these slices by looking at each pixel on a radar display.

- The amount of reflected energy lets us derive the intensity of the rainfall. And we can tell where the rain is and its coverage using the antenna's azimuthal angle (the angle compared to true north), the elevation angle, and the time it takes for the radar echoes to return to the dish. Together, these properties tell us exactly where the rain is.

- The radar system is extremely sensitive. The radar signal is broadcast at 1 megawatt, or 1 million watts, but the echoes from the individual raindrops are very weak. The power received from these echoes is often as low as 10^{-16} watts.

Doppler Technology

- Storm Total Precipitation products are among the most useful tools that make use of weather radar. These radar images are extremely valuable for detecting both extreme rainfall and drought, and they are incredibly valuable to the agricultural community, because they are used to detect regions where crops are water stressed.

- Radar's ability to detect the instantaneous intensity, accumulated amount, and type of precipitation is only part of its great utility. But it was the upgrade to the use of Doppler technology in 1988 that added the ability for radars to detect the speed and direction of the winds within storms.

- You are probably familiar with the Doppler effect. We hear it every time a car or train passes by. As the vehicle approaches, the sound of the engine has a higher pitch, but after it passes, that pitch lowers. The sound waves are much closer in spacing as the vehicle approaches, so the pitch of the sound is higher. As the vehicle moves away, the sound waves are spreading, and the pitch is lower.

- Radars do not detect sound. But the same phenomenon occurs with visible light and microwaves. If the raindrops are being blown toward or away from the radar dish, the frequency and phase of the microwave signal will be shifted. Doppler radars can detect this shift and use it to determine the wind speed.

- Doppler shifts can only be measured when the precipitation is moving with some component of its motion toward or away from the radar. Precipitation that is moving perpendicularly to the radar beam will not produce a Doppler shift in the frequency or phase of the microwave. Therefore, the radar detects the highest values of the wind when looking directly into the wind or directly away.

- Radar meteorologists issue Doppler-indicated tornado warnings. Advanced warning from radar saves many lives each year. Doppler technology also helps radar meteorologists warn of strong straight-line winds.

- In 2008, the NEXRAD radars were upgraded to superhigh resolution, which increased the radar resolution by 4 times. The resolution upgrade allows for the precise targeting of hail cores and tornadoes by sampling these regions of the storm with greater clarity. Better resolution also provides much more accurate rainfall estimates.

» From 2010 to 2013, dual-polarization capabilities were added to U.S. weather radars. Also known as "dual-pol," these newer radars enhance the radar's ability to detect precipitation by sending 2 pulses—one with its electric field horizontally oriented and the other vertically oriented. The ratio of these 2 pulses can be used to accurately detect precipitation type.

SUGGESTED READING

National Weather Service, "Doppler Radar."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 2, p. 26–31.

Rinehart, *Radar for Meteorologists*.

QUESTIONS TO CONSIDER

1 Doppler radar uses a color scale to indicate precipitation intensity. What colors are associated with hail, and how does the Doppler radar estimate rainfall rate using this color scale?

2 Radar is an excellent tool for detecting tornadoes within storms. What do radar meteorologists look for when trying to identify whether a storm is producing a tornado?

How Satellites Track Severe Weather

Space-based observations of Earth's extreme weather are essential to our survival. Without them, weather can surprise us and catch us off guard, causing disaster. As global populations grow, more people will be exposed to life-threatening weather. Our satellite network is designed to seek out and find these conditions and warn us days in advance. In this lecture, you will learn how heading into space with satellites lets us study Earth's extreme weather systems.

Satellite History

» The North American Aerospace Defense Command (NORAD), the National Aeronautics and Space Administration (NASA), the U.S. Space Surveillance Network, and others track objects in orbit around Earth.

» Each agency reports a slightly different number, but since the start of the space race in the 1950s, there have been tens of thousands of objects launched into Earth's orbit. Of these, about 40 are U.S. satellites capable of weather observation.

» The TIROS-1 Satellite captured the first satellite image after being launched into space on April 1, 1960. The image is of low quality and lacks color, but it marks the beginning of an era of space-based observation of Earth.

- The U.S. government funded the creation of a meteorological satellite network in the mid-1970s, and immediately began saving lives. Before 1975, landfalling hurricanes, even weak hurricanes, could potentially kill hundreds of people. After 1975, satellites provided advanced warnings, and evacuation orders were posted days in advance.

- Even with such technology, a well-forecast disaster is still possible. Hurricane Katrina was well forecast, and satellite observations helped pin down Katrina's exact path days before landfall. Evacuation orders were made, but New Orleans was and is a very vulnerable city, and many people who chose not to evacuate or couldn't lost their lives.

Geostationary Satellites

- Our satellite network captures stunning images of Earth's weather systems, revolutionizing our understanding of weather. We are able to see an entire weather system from above and watch it evolve at very high time resolution. Satellite imagery allows us to connect weather systems all over the globe and examine their interactions.

- There are 2 distinct configurations of satellite orbits. Many are clustered very close to Earth, while a second group is found in a large circular outer ring.

- Geostationary orbit is the orbit used by so-called operational satellites—those that continually monitor the same region on Earth from space. These are the satellites that inhabit the outer ring of satellites around Earth.

- This orbit is unique because the orbital period of the satellite matches the rotation of the Earth. At a special distance of 36,000 kilometers, the satellite's speed in orbit is such that the centrifugal force, which flings the satellite away from Earth, is matched by gravity, pulling it back toward Earth.

- This balance means that the satellite's orbital speed matches the rotational speed of the Earth, allowing it to remain in a stationary orbital plane around Earth. The advantage is that the satellite looks at the same part of Earth all the time and can see nearly half of the Earth at once.

- The disadvantage is that this orbit is only achieved at a distance of 36,000 kilometers from Earth's surface. At that distance, it is difficult to capture high-resolution images of Earth.

- The United States typically operates 2 geostationary weather satellites, called the Geostationary Operational Environmental Satellites (GOES). The specific satellites are swapped out about every 10 years, but there is always a GOES East and a GOES West.

- Together, the 2 satellites observe from 20° W to 165° E longitude, providing full scans of the United States every 15 minutes and full-disk images every 30 minutes.

- In preparation for the 2016 launch of the GOES-R satellites, the already-operational GOES satellites performed several rapid-scan tests. Under normal operation, GOES satellites transmit a new, fresh, full-disk image back to Earth every 15 minutes. The rapid-scan technology allows the satellite to image a certain part of the world with 1-minute time resolution—that's an image every minute.

- Rapid-scan mode allows meteorologists to observe the evolution of a storm system with extremely high time resolution. GOES satellites launched after 2016 have this capability as a baseline feature.

- Geostationary satellites excel in providing excellent spatial coverage and very high time resolution, but the greatest pitfalls in these images are spatial resolution and lack of color.

- Before the launch of the GOES-R satellites in 2016, GOES satellites viewed Earth with panchromatic, visible channels, meaning that all visible light is reported with no color distinction. Collecting multiple bands of color is very data intensive, which slows the transmission of data back to Earth.

- The highest resolution available from our GOES satellites is 1 kilometer. The result is that many smaller weather features and land surface features are not resolvable by GOES satellites. Thankfully, the GOES satellites have a complementary group of satellite observations from low-earth-orbiting or polar-orbiting satellites.

Low-Earth-Orbiting Satellites

- Low-earth-orbiting satellites are much closer to Earth and therefore maintain much higher spatial resolution. At an altitude of just 705 kilometers, NASA's Earth Observing System (EOS) Terra satellite platform orbits the Earth from pole to pole while the Earth spins beneath it.

- Each instrument onboard EOS Terra takes advantage of its close orbit to sample the Earth at high spatial resolution. The highest-resolution instrument on Terra is called ASTER. ASTER's resolution is 66 times better than the GOES satellite, with each pixel covering only 15 meters.

- Low-earth-orbiting satellites like Terra have multispectral visible channels, which provide stunning color images. An instrument named MODIS, which is onboard EOS Terra, is moving at an incredible speed so that it can stay in low earth orbit. The satellite can orbit Earth in approximately 99 minutes, which means that it is moving at roughly 16,700 miles per hour.

- Not all low-earth-orbiting satellites orbit from pole to pole. There is a satellite platform whose orbit hovers near the equator that is called the Tropical Rainfall Measuring Mission (TRMM).

This satellite constantly monitors the properties of Earth's water budget in the tropics. TRMM's instruments capture stunning 3-dimensional images of Earth's weather systems.

» Meteorologists use images like these to assess hurricane strength by looking for deep, active tropical thunderstorms. These storms fuel the hurricane by releasing enormous quantities of latent heat, which deepen the hurricane's central pressure.

» Since the 1960s, other low-earth-orbiting satellites operated by the U.S. government have maintained spatial resolutions that are about 2 orders of magnitude better than operational meteorological satellites.

» The highest-spatial-resolution satellite data that has been publicly available for free since 1972 comes from the Landsat satellites. Their spatial resolution is 10 meters. If the government has maintained this technological superiority, current satellites that are used for military reconnaissance are able to image the Earth with a spatial resolution of approximately 1 centimeter.

» Most satellites are designed to be passive instruments. Passive satellites simply collect light that is scattered, reflected, or emitted toward the sensors. Active remote sensing involves sending a signal of light and then collecting the reflected or scattered light.

» Visible satellite channels are passive. If they used active remote sensing techniques, they would have to produce a flash of light with the intensity of the Sun to get a picture of Earth from 36,000 kilometers away.

» Because we wouldn't want an intense flash of light every 15 minutes throughout the night, reminding us that the satellites are taking our picture, the visible light channels are unable to resolve imagery of Earth at night, unless there is a light source.

- Visible satellite channels work just like a digital camera. They are sensitive to the same light as our eyes. Objects in their field of view are distinguished by color and albedo.

- Albedo is a measure of light that is reflected off an object compared to the amount of light that was incident on the object. High-albedo objects are bright, while low-albedo objects appear dark. Therefore, on a visible satellite image, clouds appear very bright due to their high albedo. The land surface is dark because it is not as reflective.

- Without sunlight, visible satellite channels are unable to see clouds. But they can still see at night, because of the lighting of Earth's cities. In the United States, large cities, such as Chicago, New York, Detroit, Atlanta, and Los Angeles, are easily seen.

- The Suomi polar-orbiting satellite has also been able use a combination of visible and infrared sensing to capture views of hurricanes and other storms at night.

- During the day, visible satellite imagery offers the highest-resolution view of Earth's weather systems. Earth's weather doesn't rest at night and wait for the next day. To observe storms at night, thermal infrared satellite cameras were developed.

- These channels measure emitted, long-wave, thermal infrared radiation from the Earth and clouds instead of measuring reflected visible light from the Sun. This technology provides 24/7 observation of Earth's weather from space.

- Hurricanes can move significant distances overnight, and with infrared technology, we can monitor every change from space while the Sun is down.

- How are satellites able to measure the heat of clouds from space? All objects radiate light according to their temperature. Very hot objects, such as our Sun or an incandescent lightbulb, are so hot that they produce visible light. Much colder objects—such as the Earth, clouds, and even our bodies—also emit light, but at a much longer wavelength, in the infrared part of the electromagnetic spectrum.

- The hotter an object is, the more radiation it emits. Clouds are very cold objects in the sky, so with an infrared camera, they appear as very dark objects. But on an infrared satellite image, clouds appear very bright, while the much warmer Earth around the clouds appears dark. If more energy is being emitted by the warmer Earth, then why is the cloud bright and the Earth dark?

- To our eyes, clouds are white, but to an infrared camera, they are cold and therefore appear dark. Looking at an infrared image of a cloud field, where the clouds are the darkest features, would be really confusing.

- To remedy this situation, and to help satellite meteorologists properly interpret infrared images, all of these images are inverted. What measures as cold will appear bright, while objects that are warm will appear dark. Unless you have access to the raw infrared satellite data, every infrared satellite image you see has been inverted.

SUGGESTED READING

NASA, *NASA Worldview*.

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 2, p. 34–37.

QUESTIONS TO CONSIDER:

1. What are some of the limitations and advantages of using geostationary satellites to observe severe weather on Earth?
2. What is the biggest advantage of having thermal infrared satellite channels?

Anatomy of a Lightning Strike

Moment for moment, lightning is probably the most extreme of all extreme weather phenomena. By its simplest definition, lightning is a large electrical discharge—a spark. The typical strike is about 3 to 6 miles long, but some strikes have been measured in excess of 30 miles. The lightning strike is only about as wide as your thumb, though. Each day on Earth, there are approximately 9 million lightning strikes, or about 100 strikes per second. Lightning is a very frequent weather phenomenon, and the odds of lightning impacting your life are very high. In this lecture, you will learn about lightning.

Lightning Detection

» Lightning detection in the United States is accomplished through the National Lightning Detection Network (NLDN). Since the late 1980s, this network has been collecting the time and location of every strike in the United States.

» They estimate that between 20,000,000 and 30,000,000 strikes occur in the contiguous United States each year. The reason for the spread in the numbers is that some strikes occur at the same time and are difficult to separate in the data.

» Lightning is detected with a vast network of instruments. Each sensor is sensitive to the large electromagnetic blast generated by each strike. If a lightning strike occurs near a sensor, a large blast of electromagnetic energy radiates isotropically away from the strike location. This blast radiates away at about 1/3 the speed of light and in a few moments passes over one of the sensors.

» The sensor records the time at the exact moment the blast of radiation passes over. When 3 or more sensors detect the same blast, the position of the strike can be triangulated.

» This works much in the same way as a GPS sensor in your car—that is, for the position of your car to be found, at least 3 satellites must lock on to your GPS sensor to triangulate your position.

» The NLDN then maps the locations of the lightning strikes. The strike position data have been used to make lightning flash density maps.

Lightning around the World

» In the United States, the number of strikes increases as you get closer to the Gulf of Mexico, due to conditions that are warm, humid, and unstable for most of the year. Florida is the lightning capital of the United States. Some parts of Florida have more than 100 days of thunderstorm activity each year. Parts of central Florida have greater than 8 strikes per square kilometer per year.

» In terms of the world, in central Africa, the flash density is greater than 50 strikes per square kilometer per year, and in the heart of the African rainforest, thunderstorms are very frequent.

» Lightning in Canada tends to be concentrated along its southern border with the United States. This is because thunderstorm frequency decreases significantly with latitude in North America, as does the length of the warm season, during which thunderstorms form.

» Furthermore, the farther north you go in North America, the farther removed you become from a large, warm body of water. Warm, humid conditions are needed to create frequent thunderstorms, and northern Canada rarely experiences this type of weather.

- In Europe, lightning activity tends to be concentrated around the Mediterranean and eastern Russia. Northern Europe's climate favors more stable atmospheric conditions, which inhibit frequent thunderstorm activity.
- Lightning strike frequency is much higher in northern Australia. This part of the country spends a significant amount of time each year near the stormy intertropical convergence zone, which is a zone of low air pressure, frequent rain, and storms that encircles the Earth near the equator.
- The location that receives more lightning than any other place on Earth is northern Venezuela, where the Catatumbo River flows into Lake Maracaibo. The air above the mouth of this river destabilizes each day. The winds that flow across the lake converge and lift the air to create thunderstorms. This region experiences up to 160 nights per year with thunderstorm activity. Some storms last for 10 hours or more and produce hundreds of strikes per hour.

How Do Clouds Become Electrified?

- Electrons carry a negative charge and orbit the nucleus of the atom. Protons carry a positive charge and combine with neutrons in the nucleus. If the number of electrons matches the number of protons, the atom is said to be neutral. An ion is an atom with too few or too many electrons.
- Electrons are mobile—they can easily be stripped away from the atom. Protons are not as mobile. If they move, the whole atom moves, too. Like charges repel, and opposite charges attract.
- Electricity is a flow of electrons. An electric field is the attraction force between two charge centers when they are separated. The electric field is aligned positive to negative, and its strength is dependent on the size of the charge centers.

- Conductors are materials that contain movable charges. Good conductors are copper wire, silver, and gold. Water is a good conductor, too. Insulators are materials that resist moving charges. Good insulators are made of glass or porcelain. Air is also a good insulator.

- In a thunderstorm, just before the cloud produces a lightning strike, a positive charge center builds near the top of the cumulonimbus cloud, while negative charges accumulate near the bottom. In response to negative charge accumulating on the bottom of the cloud, positive charges tend to collect on tall ground objects, such as trees. Before the storm arrives, the ground and tree are neutrally charged.

- Like charges repel. The negatively charged cloud base pushes the negative charges on the surface away, leaving a net positive charge on the tree.

- The electric field between the tree and the cloud can exceed 1 million volts per meter. Just before the lightning strike occurs, the electric field reaches 3 million volts per meter.

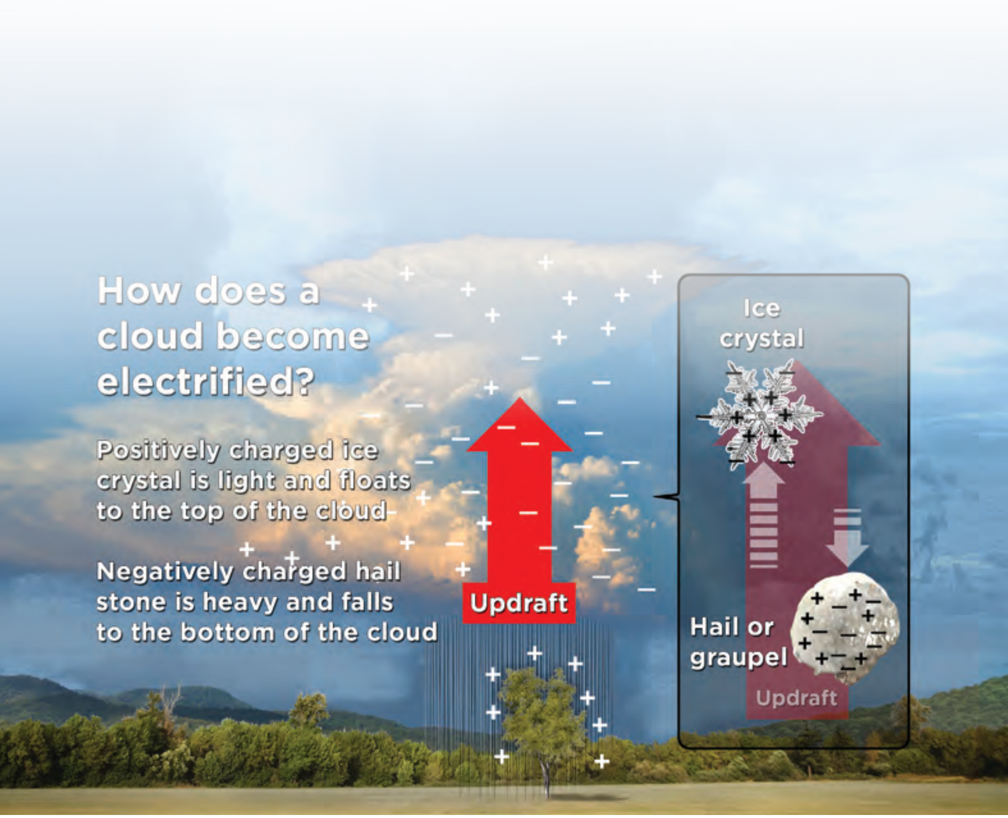
- When the electric field surpasses 3 million volts per meter, dielectric breakdown occurs, which means that the air switches from being an insulator to a conductor of electricity.

- This is one of the reasons why lightning is so powerful. It must pass through air, which is normally an excellent insulator. For air to become a conductor, the electric field must be enormous.

- How does the cloud produce such a large electric field? Without ice, a cloud cannot become electrified and cannot produce lightning. Ice can form in several different ways within a storm. All ice crystals are 6 sided at their molecular level.

» Individual ice crystals grow in different shapes, and the majority of those shapes fall into a few primary categories. Ice crystals in shapes called plates, columns, needles, and dendrites have a large surface area compared to their mass and are easily lifted through the updraft of a thunderstorm.

» In contrast, other habits, or species, of ice form as supercooled water accretes onto the surface of an ice crystal. This process gives birth to graupel, which is a small, soft, spongy type of hail. Unlike the ice crystal, a piece of graupel has a small surface area compared to its mass and therefore falls through the updraft.



» The different types of ice therefore become vertically sorted in the cloud. The lighter ice crystals float to the top, while the heavier graupel and hail accumulate near the bottom of the cloud.

» As ice crystals grow, the electrons tend to gather along the periphery of the crystal. These crystals are very good at transferring these electrons to any objects with which they collide.

» Graupel is different in that the distribution of electrons is more even throughout the entire piece of ice. The even charge distribution in graupel versus the uneven distribution in ice crystals is crucial to understanding how clouds become electrified.

» Ice crystals and graupel coexist in the storm. As they form in the updraft, the lighter ice crystals rise rapidly through the storm. The heavier graupel falls very slowly through this same updraft. There are countless collisions as they pass each other.

» Each collision results in the transfer of electrons from the ice crystal to the graupel. The loss of the electron leaves the ice crystal with a net positive charge. The graupel, now having extra electrons, has a net negative charge. The heavier graupel falls to the base of the cloud. The lighter ice crystals float to the top.

» This process results in the buildup of a positive charge center at the top of the cloud and a negative charge center near the base. The buildup of this electric field can happen very quickly. Just moments after a discharge—the lightning strike—the cloud can recharge.

The Power of Lightning

» The most powerful lightning strikes contain 10 billion joules of energy. An average home could be powered for about 6 months if all the energy from a powerful strike of lightning could be captured, stored, and used.

» Why aren't we using lightning as an energy source?

1. It is unpredictable. While we can accurately detect lightning, we cannot predict exactly where it will strike.

2. It is fast. The strike duration is measured in millionths of a second.

3. It is big. We do not have battery systems or capacitors that can take that much charge so quickly and store it.

4. It is wastefully hot. The biggest problem is that only 1/1000 of the total energy of the strike is electrical. The rest is heat. A typical strike has a temperature of 30,000°C, or 54,000°F, which is 5 times hotter than the surface of the Sun.

» Storing the energy from the strike is not feasible, and even if you could capture the part that is electrical, you would only get about 6 hours of energy for your home.

Types of Lightning Strikes

» A fully charged cloud is capable of producing a variety of lightning strikes. An intracloud strike arcs between charge centers within the same cloud. A cloud-to-cloud strike occurs when the strike travels between charge centers in different clouds. Cloud-to-air strikes can also occur. This happens when the strike discharges into the air surrounding the cloud.

» About 80% of all lightning strikes are of these first three varieties, all of which stay in the sky. The strike we need to worry about is the cloud-to-ground lightning strike. Lightning is not one of the criteria used by the National Weather Service to designate a storm as severe, because frequent cloud-to-ground lightning strikes are a part of every thunderstorm.

THE DANGER OF TREES AND LIGHTNING

Trees are frequent targets of lightning strikes. They are tall, and their roots provide an excellent conduit for the electricity to flow into the ground. Never take shelter from lightning under a tree. Nearly 15% of all lightning-strike victims are under trees. When lightning hits a tree, it can kill you in many ways.

The worst situation is when the tree's bark is relatively dry. The lightning is looking for a conductor to pass through as it flows into the tree. If the bark is dry, it will enter the center of the tree, where the water and sap are found. Here, the lightning will superheat the water, forcing it to rapidly expand. The result is that the tree will explode. If you are nearby, the debris from the exploding tree could kill you.

If the bark of the tree is wet, the energy from the strike tends to stay in the bark as it races downward into the ground. The bark will often peel back as the lightning passes through it, but the tree can survive the event. It will wear the scar of the strike, though.

The danger for humans is a side flash. The lightning can jump up to 6 feet away from the tree and strike you if you are standing nearby. Nearly all of the energy can be diverted from the tree into your body.

SUGGESTED READING

NSSL: The National Severe Storms Laboratory, "NSSL Research: Lightning."

MacGorman and Rust, *The Electrical Nature of Storms*.

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 21, p. 383–399.

QUESTIONS TO CONSIDER

1. In the United States, Florida has both the most frequent lightning strikes as well as the highest number of fatalities from lightning. Why does Florida have such frequent thunderstorm activity?

2. Lightning cannot form if the storm does not have a strong updraft or contain ice. Why is ice the crucial ingredient for lightning formation?

Lightning Extremes and Survival

Given how powerful lightning is, why does anyone survive a lightning strike? And what can you do to improve your odds if you are caught in a storm? In this lecture, you will learn why it is possible for people to survive a direct hit from lightning. You will also learn about less common, but far more extreme, forms of lightning. Compared to ordinary strikes, the strikes from extreme lightning are 10 times more powerful.

Types of Extreme Lightning

» A positive-polarity lightning strike occurs when negative charges from the ground reach up toward positive charges in the upper parts of the cloud. Positive-polarity lightning strikes are much rarer than negative-polarity strikes. Only about 5% of all cloud-to-ground strikes are positive-polarity strikes. They are powerful. Many positive-polarity strikes have been measured to contain more than 10 times the power of a negative polarity strike.

» The more common negative-polarity strike begins in the lower parts of the storm. This type of lightning is called negative polarity because of the net transfer of negative charges from the cloud to ground.

» In addition to forming between a cloud in a storm and the ground, lightning also forms above the storm. Most people have never witnessed these types of lightning because we cannot see above the storm.

- Positive-polarity strikes often create gigantic jets, sprites, and elves that shoot upward in the upper layers of the atmosphere. These types of lightning often take on a red or blue hue and are very brief. They are just as brief as the cloud-to-ground strikes, but rather than creating an arcing spark of electricity, these lightning events appear more like fireworks.

- Lightning can take on other shapes, too. For example, about 1 in 500 people claim to have seen ball lightning, which has been described to look like a bright ball of light that is between the size of a softball and basketball.

FROM LIGHTNING TO THUNDER

You might have been taught to count the number of seconds between when you see lightning and when you hear thunder to estimate how far away a lightning strike is.

The speed of sound, which is also the speed of thunder, is approximately 750 miles per hour. If you convert this to miles per second, sound will travel 1 mile every 5 seconds.

Start counting when you see lightning. If you get to 5 and hear thunder, the lightning is 1 mile away from you. Each second is 0.2 of a mile. If you get to 8, the lightning is 1.6 miles away from you.

- People say that ball lightning smells of sulfur, like rotten eggs. It can last for several seconds while it floats, bounces, and rolls around. It can also easily start fires, and some have reported that it can burn its way through walls and windows.

- Have you ever seen a nearby lightning strike that leaves a bead-like string of light behind after the strike is over? Meteorologists call this bead lightning. It forms when part of the lightning channel remains ionized after the return stroke. The ionization gives off light for a few moments after the strike ends.

Thunder

» Sometimes you can be so far away from a lightning strike that you will never hear the thunder. All lightning produces thunder, but lightning can be far enough away that you see it, but never hear it.

» Why is this? First, sound waves refract, or bend, upward in the lower atmosphere. Second, the Earth is curved. Third, sound waves dissipate as they travel away from their source. The result is that sound waves from a distant strike either pass over your head or have dissipated to the point that you can no longer hear them.

» It is possible to see lightning from storms that are many miles away but never hear thunder. This type of lightning is called heat lightning. This type of lightning often looks like someone far away is taking pictures at night with a bright flash. Heat lightning is a misnomer; it is just lightning from a distant storm that is seen but not heard.

» What is thunder, and why does lightning produce it? The lightning strike is an incredibly hot event. Each strike can heat the air to a temperature 5 times hotter than the surface of the Sun. This rapid heating of the column of air that surrounds the strike causes it to expand rapidly as a huge sound wave.

» Initially, this wave is supersonic. This sound wave is so powerful that if you stand right next to a lightning strike, the thunder can throw you several feet. The supersonic wave slows down to the speed of sound and propagates radially away from the strike.

» If you are standing near the strike, you will hear a brief, high-pitched, very loud crack of thunder. The sound of thunder changes as you move farther and farther away from the strike. Higher-pitched sound waves dissipate quickly and refract upward, leaving the lower-pitched sound.

- » The duration of thunder also increases as you get father from the strike. This is because of echo from trees, buildings, mountains, or the clouds themselves. Essentially, the farther you are from the lightning strike, the lower the pitch, the quieter the sound, and the longer it will rumble.

When Lightning Strikes

- » Your odds of being struck by lightning this year are 1 in 700,000. You have a better chance of getting struck than winning the lottery.

- » How many people are struck and killed by lightning each year in the United States? The 10-year average from 2005 to 2014 was 32 fatalities.

- » Since 1940, there has been a clear downward trend of the number of fatalities each year from lightning, despite rapid population growth during this time. Why is this?

- » First, it is important to realize that over this entire time period, about the same number of people are struck per year—about 600. In the 1940s, up to 80% of the people would die. Today, less than 10% die after being struck. The biggest changes are in medical technology.

- » When you are struck by lightning, if the strike stays in your skin and does not cross your chest or head, there is a very high likelihood that you will survive. You may only have superficial burns. Some people heal from these burns in just a few hours.

- » If the strike passes near your heart, you may go into ventricular fibrillation. You will basically have a heart attack and need to be defibrillated.

- Touching a person who was just struck by lightning will not electrocute you. In fact, you should touch the person immediately to check for a pulse and regular breathing. If the person is in cardiac arrest, give him or her CPR immediately.

- One of the reasons why fewer and fewer people are dying from lightning strikes is because of the common knowledge of CPR.

- Lightning research has also helped hospitals know how to treat lightning victims. They immediately check for irregular signals from the heart to the brain that might signal a waiting heart attack after the victim is struck.

- We can add to this a significant increase in lightning safety. Lightning detection systems are common in outdoor public places such as parks and playgrounds and also at construction sites. These detectors use small electric field mills to generate an electric field that is higher than the background atmosphere electric field. An approaching storm will alter this electric field significantly, and the system will warn people of the potential for lightning.

- From 2006 to 2014, 55 women were killed by lightning, compared to 232 men. More than 80% of the victims were male.

- Statistically, 98% of lightning fatalities are outdoors. Of the remaining 2%, the majority of these victims were indoors on corded telephones. Phone lines are not sufficiently grounded enough to prevent the lightning strike from traveling through them and striking you during a conversation. With the advent and wide spread of cell phones, this statistic is getting smaller with time.

- Long-term lightning strike statistics show that 40% of the locations of people that were struck goes unreported; 28% are in open fields, such as sports fields, parks, and farm fields; 14% of all victims are under trees; 8% are boating, fishing, or swimming; and 5% are on golf courses.

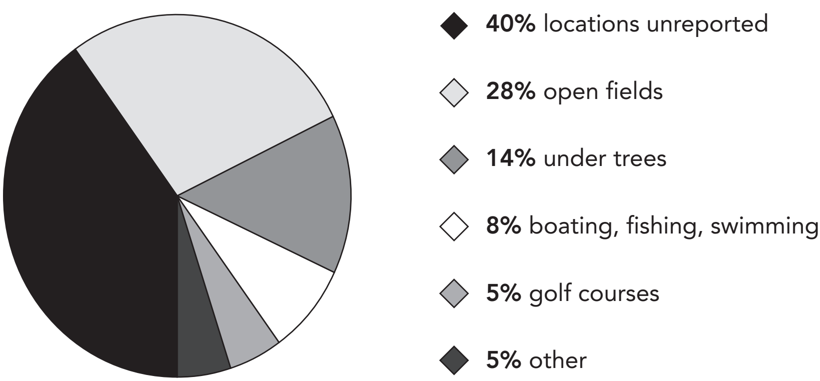
» The state with the most deaths in 2012 was Florida. From 1959 to 2014, Florida has had twice as many lightning fatalities as the second-place state, Texas. Over this time period, 10% of all lightning fatalities were in Florida. Year-round thunderstorm activity combined with a high population makes the citizens of Florida very vulnerable to lightning strikes.

» Outdoor risky behaviors are easy to identify. Warm-weather sporting events such as soccer, golf, fishing, boating, swimming, and baseball put you at great risk.

» You don't have to be struck directly to suffer the impacts of a lightning strike. When the lightning strikes the ground, the energy spreads out radially from the point of contact. A ground strike can be just as lethal as a direct hit.

» Large animals are most susceptible to the dangers of a ground strike. If a lightning bolt were to strike the ground, as much as a million volts may enter the ground. This voltage will dissipate with distance from the strike point. A few feet away, the voltage might drop to 800,000 volts. A few more feet away, it might be as low as 600,000 volts.

LOCATIONS OF LIGHTNING STRIKES



» The problem for large animals, such as cows or horses, is that 2 of their legs could be standing where the voltage is 800,000 volts, while the other 2 legs are standing where it is 600,000 volts. The difference in voltage will drive a current through the animal, past its heart, and kill it.

» Humans are fortunate that our legs never get too far apart. As a result, the voltage difference is smaller, and it is less likely that a ground strike could kill a human compared to a larger animal.

AND THE AWARD GOES TO…

Roy Cleveland Sullivan, a park ranger at Shenandoah National Park, is the current record holder for surviving the most lightning strikes. He has been struck on 7 different occasions and survived them all. Lightning has hit him nearly everywhere on his body.

Lightning Safety

» What should you do if you are stuck outdoors and think you are about to be struck by lightning? First, you need to recognize the signals. You will feel it. Your skin will tingle and your hair will stand up on end. If this happens and you cannot take shelter in a building or car, you should do the following.

- Do not run. If you run, you might actually run toward the area where the charge buildup is the largest. When you run through that area, you could be all the lightning needs to complete the circuit and strike.

- Instead, put your feet together and crouch down low to the ground. Balance on the balls of your feet. Make the contact area between your shoes and the ground as small as possible. Wait there until the sensation goes away.

- Do not lay down. If you lay down, you increase your chance of being hit by a ground strike.

- Probably the safest place to be during a storm with a lot of lightning is in a car. The car's metal body and chassis behave as a Faraday cage, which is a metal enclosure where the interior of the enclosure is protected from the electricity passing through the metal surrounding. The electricity resists entering the car due to static cancellation and because the interior is not full of a conducting material.

- This is probably not the case if you drive a convertible with the top down or if you have a car with a plastic, fiberglass, or carbon fiber shell.

- Airplanes behave in a very similar way. Aircraft are just as safe as cars because they also act as a Faraday cage. The aluminum skin of the aircraft acts as a continuous conductor. The electricity of the strike passes through the skin, leaving the rest of the plane relatively unharmed.

- Many people have installed lightning rods to protect their homes from a direct strike. The lightning rod simply serves as a connection point and conductor for the lightning to use to get to the ground. The lightning rod offers a path of least resistance compared to other parts of your home. Lightning rods do not attract lightning, nor do they dissipate the charge within a storm. All they do is provide a pathway for the energy to get to the ground.

SUGGESTED READING

National Weather Service, "The Positive and Negative Side of Lightning."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 21, p. 383–399.

QUESTIONS TO CONSIDER

1. Why are men struck by lightning more often than women?

2. Why does counting the seconds between when you see a lightning strike and when you hear thunder allow you to calculate the distance to a strike?

LECTURE 9

Thunderstorm Formation and Weather Balloons

Thunderstorms are the key to understanding many forms of extreme weather. From lightning and thunder, to hail, downbursts, flash floods, and tornadoes, thunderstorms are the parent storm system for much of Earth's destructive and powerful displays of weather. Whether you are frightened by severe thunderstorms and just want to avoid them, or you're fascinated and would like to better understand what you're seeing, this lecture will teach you how meteorologists predict thunderstorms and related severe weather and identify exactly where such storms will strike.

Thunderstorms

- Thunderstorms happen all over the world. Measured in terms of days per year, thunderstorms are most frequent in the tropics. For example, Lake Victoria in Uganda has more than 240 days of thunderstorms each year.

- For most of the Northern Hemisphere, March through September is the most active time of year for severe thunderstorm activity. Conversely, Australia sees most of its severe thunderstorms during November through February, which are the warmest months in the Southern Hemisphere.

- U.S. thunderstorms are most frequent in Florida. In general, thunderstorm frequency is highest near the Gulf of Mexico, which is warm enough, and humid enough, to produce a lot of thunderstorms. U.S. thunderstorm activity is lowest along the West Coast, Intermountain West, and Northeast.

- The Front Range of the Rocky Mountains in Colorado and northern New Mexico serves as a site where frequent summertime thunderstorm activity is initiated by forcing warm, moist, unstable air vertically into the atmosphere. These storms roll out into the Great Plains and up into southern Ontario, where they can be seen for miles in the clear air.

- In Europe, the greatest concentration of thunderstorms is generally to the east and south near Italy, Austria, Hungary, Romania, and the small countries that border the Mediterranean, another great reservoir for warm moisture. By contrast, the United Kingdom sees much less thunderstorm activity, due to the influence of cooler, more stable air from the North Atlantic.

- Thunderstorms threaten human life daily on Earth. In the United States alone, the 10-year average for thunderstorm-related deaths is 225 deaths each year. These fatalities are the result of hail, wind, lightning, tornadoes, and flash floods combined.

- In terms of property damage, these same severe weather threats produce insured losses totaling $12.5 billion, according to the National Oceanic and Atmospheric Administration. An additional $2.4 billion in crop insurance is paid out in an average year for damage to crops—primarily for hail, wind, and floods.

Atmosphere Stability

- The clouds that produce thunderstorms are called cumulonimbus clouds. Three ingredients are needed to make a cumulonimbus cloud and subsequently a thunderstorm: an unstable atmosphere, trigger mechanism, and adequate surface moisture.

- Without the destabilization of the atmosphere, no storm can form. Stability is defined as the resistance to change. Stable objects require a lot of energy to move from their initial position.

» In the atmosphere, getting a great deal of air and water to rise requires that the atmosphere be unstable. That means that the air in a storm was able to accelerate upward, away from its initial position.

» Meteorologists have developed a theory called parcel theory to help explain the thermodynamics of rising air. A parcel is defined as a volume of air that we are going to track as it moves around in the atmosphere.

» Heat transfer between parcels is slow, so in practice, the parcels do not mix very much. Because the parcel of air does not mix much with the environment that surrounds it, parcels can have different temperature characteristics than the environment that surrounds them.

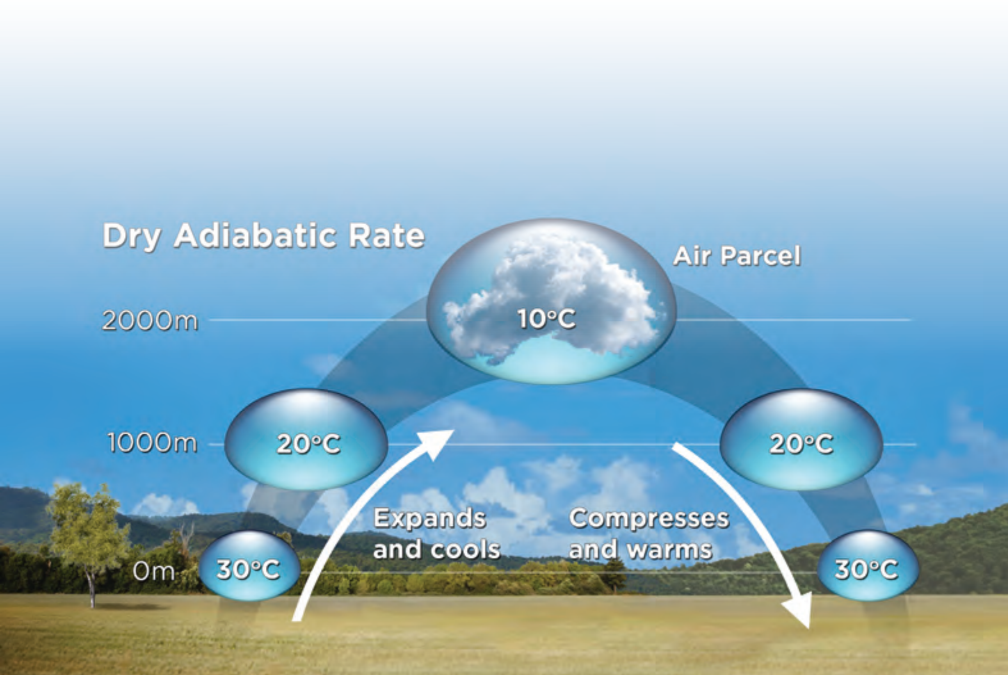
» If the parcel is warmer than the environment, the atmosphere is said to be unstable. Unstable atmospheres are those that are capable of creating thunderstorms.

» We call the process by which the parcel does not mix with its environment an adiabatic process. Essentially, an adiabatic process is an idealized process, where there is no mixing of the air from outside the parcel into the parcel.

» The first law of thermodynamics explains how a parcel of air will cool when lifted into the atmosphere. The cooling is a result of the expansion of the size of the parcel.

» As a parcel of air ascends, it expands in size as the atmospheric pressure around the parcel decreases. We can calculate exactly how fast this cooling happens using the first law of thermodynamics. When solved, we learn that for every kilometer a parcel of air ascends, it cools 10°C. This cooling rate is called the dry adiabatic lapse rate.

- When dry air descends in the atmosphere, it warms at the same rate. The warming is a consequence of the compression.
- If the rising parcel of air cools to its dew-point temperature, the air becomes saturated and condensation begins. The condensation begins to build a cloud inside of the parcel.
- Condensation releases a lot of latent heat as the water vapor becomes a liquid. This heat is pumped into the parcel and therefore slows its cooling rate.
- Therefore, if a parcel of air is rising into the atmosphere and at the same time it is saturated and producing a cloud, the cooling rate drops to just 6°C per kilometer.



Weather Balloons

- Every day, twice a day, meteorologists at the National Weather Service launch weather balloons, in the morning and evening, to assess whether the atmosphere is unstable. Each balloon carries an instrument pack called a rawinsonde that measures temperature, relative humidity, height, pressure, and wind speed and direction as it ascends.

- Most weather balloons successfully ascend into the stratosphere before the balloon eventually pops. Therefore, each weather balloon gives us a full thermodynamic profile of the troposphere.

- Every day, hundreds of weather balloons are launched at roughly the same time all over the world: midnight and noon, Greenwich time. As soon as all of the data are collected, computer programs begin drawing parcel lines on what are called sounding diagrams to determine if and where the atmosphere is supportive of severe thunderstorm development.

- Even though no storms had formed when the balloons were launched, we can plot the hypothetical parcel line on top of the data collected by the weather balloons. Meteorologists look for a few key features on these soundings to determine the stability of the atmosphere and the characteristics of potential storms.

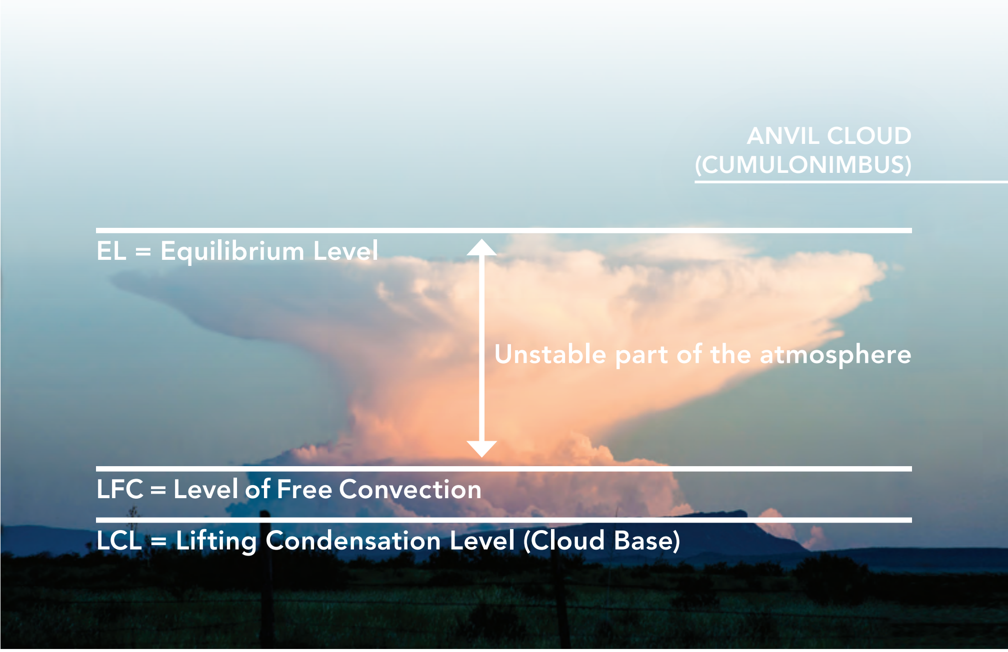
- Have you ever noticed that cumulus clouds, including big cumulonimbus clouds, often have nearly flat bottoms at the base of the cloud? This flat base marks the point at which a rising parcel of air first becomes saturated. This point is called the lifting condensation level because it is the point a parcel must be lifted to for condensation to occur.

- On the sounding, this point is identified by examining the parcel line and looking for a kink in the shape of the line.

» Next, meteorologists look for the first time, starting from the bottom of the diagram, where the parcel line becomes warmer than the surrounding environment. This point, which is called the level of free convection, is found where the parcel line crosses over the environmental temperature line. This point indicates the base of the unstable layer in the atmosphere.

» From the level of free convection to the next point, called the equilibrium level, the atmosphere is unstable and is primed for thunderstorm development. The equilibrium level marks the top of the storm where the anvil clouds forms.

» Anvil clouds occur when the rapidly rising air in the updraft of the storm hits the stable layer of air above the equilibrium level. Anvil clouds get their name because they look just like the top of a blacksmith's anvil.



» The last two tools for assessing the stability of the atmosphere are both indexes. One atmospheric index uses temperature to measure instability and is called the lifted index. It is calculated by subtracting the parcel temperature from the environmental temperature at 500 millibars, which is roughly halfway up the troposphere.

» If this index is negative, the atmosphere is unstable, because it tells us that the parcel is warmer than its environment and is therefore buoyant at that level. The more negative this number becomes, the more unstable the atmosphere is.

» Another index measures how much energy is available to the storm and is called the convective available potential energy (CAPE). It is found by looking for the positive area between the parcel line and the environmental temperature line on the soundings. The more CAPE there is, the more powerful the storm can become.

» A more advanced way that atmospheric scientists present a sounding diagram is called a skew-T, log-P diagram, pioneered in the late 1940s.

Trigger Mechanism

» Assessing the stability of the atmosphere is a crucial first step in predicting thunderstorms. The second ingredient in severe thunderstorm formation is a trigger mechanism. Some sort of boundary, or front, is needed to cause parcels of air to rise into the atmosphere. Something must give the parcel its initial vertical push so that it can use the potential energy—the CAPE—stored in the unstable atmosphere.

» Fronts are boundaries between air masses of different characteristics. When a front passes, we expect the weather to change. Such fronts are also focal points for severe weather.

» There are 5 types of fronts that initiate thunderstorm development.

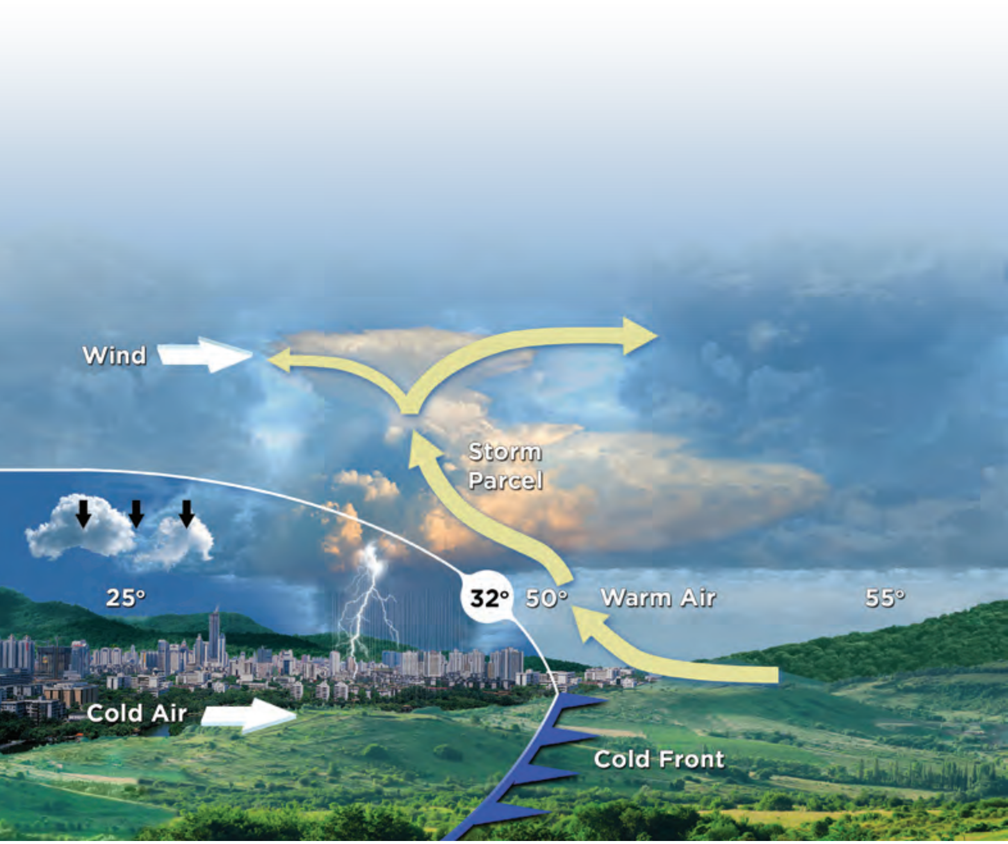
1. Most people are familiar with weather fronts, such as cold fronts or warm fronts. At the collision point of cold, dry air and warm, moist air, the warm, moist air is thrust vertically over the cold, dry air. This occurs because the warm, moist air is much less dense than the cold, dry air. If the atmosphere is unstable, the parcels that are forced to rise over the front form thunderstorms.

2. Storms can be triggered by a collision of high-humidity air and low-humidity air. The collision results in the formation of the dry line, one of the most notorious fronts in the creation of severe thunderstorms. The dry line gets its name because the air on one side of the front has high humidity, while the air on the other side is extremely dry.

3. Mountains serve as permanent fronts. Air flowing over the mountain is forced to rise, and as the parcels of air expand, they cool, which leads to clouds and condensation. If the atmosphere above the mountains is unstable, the clouds develop vertically and form huge cumulonimbus clouds.

4. Another trigger is the boundary between land and water. In the summer, the land of the Florida Peninsula gets very hot while the surrounding waters stay relatively cool. Locally higher air pressure builds over the cooler water because the cooler air is denser. Low air pressure builds over the heat of the land, and a pressure gradient forms. Winds flow from the high pressure toward the low pressure. Over water, the air flows quickly, because the water surface is smooth compared to the land. The roughness of the land forces the air to slow down. This causes the air to converge, and air is forced to rise. This rising air enters an unstable atmosphere and develops into afternoon thunderstorms.

5 Even differences within flat land can cause air to rise. The Sun does not evenly heat the land. Some regions become hotter than others. This can be caused by the orientation of the surface to the Sun: More direct light equals more solar heating. Some areas may be darker than surrounding regions. Dark areas absorb more of the Sun's energy and therefore heat up more than the surrounding area. Warm bubbles of air, called thermals, will form and rise into the sky. These thermals can result in the development of thunderstorms.



Surface Moisture

- » In addition to instability and a trigger, the third ingredient to make a storm is what ultimately supplies all of the heat to the storm.
- » Clouds form due to condensation, which not only gathers moisture, but also releases enormous quantities of heat. This heat powers the storm by destabilizing the atmosphere. This heat is released into the parcel, making it warmer than its surroundings. Without adequate surface moisture, thunderstorms won't form.
- » The majority of the moisture for thunderstorms in the United States comes from the Gulf of Mexico, which is a mostly shallow and warm body of water. Its tropical location allows for strong solar heating throughout the year. This heating promotes the evaporation of water from its surface that can be transported into the United States. There are no large physical barriers to impede the transport of this moisture northward.

SUGGESTED READING

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes*.

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 2, p. 18–25, and chap. 18, p. 306–331.

QUESTIONS TO CONSIDER

1. How are clouds, which are full of billions of gallons of water, able to remain buoyant in the atmosphere?
2. Meteorologists use 2 metrics to assess the stability of the atmosphere. Why are negative lifted index values and positive convective available potential energy (CAPE) values associated with thunderstorm development?

LECTURE 10

Wind Shear and Severe Thunderstorms

What takes an ordinary thunderstorm to its severe limits? Some thunderstorms are capable of producing incredible destruction, while others simply put on a brief display of moderate rain with a little lightning and thunder. The reason for the increased severity of some storms is due to one additional ingredient: wind shear, which is the change in wind speed and direction with height. As you will learn in this lecture, severe thunderstorms require strong wind shear.

Wind Shear

- Thunderstorm formation requires three ingredients: an unstable atmosphere, a trigger mechanism, and adequate surface moisture. These ingredients, when combined, will produce a convective event, where a cumulonimbus cloud will form. Atmospheric scientists refer to these events as ordinary convection, or ordinary thunderstorms.

- Ordinary thunderstorms go through 3 distinct stages of development: the cumulus stage, the mature stage, and the dissipation stage.

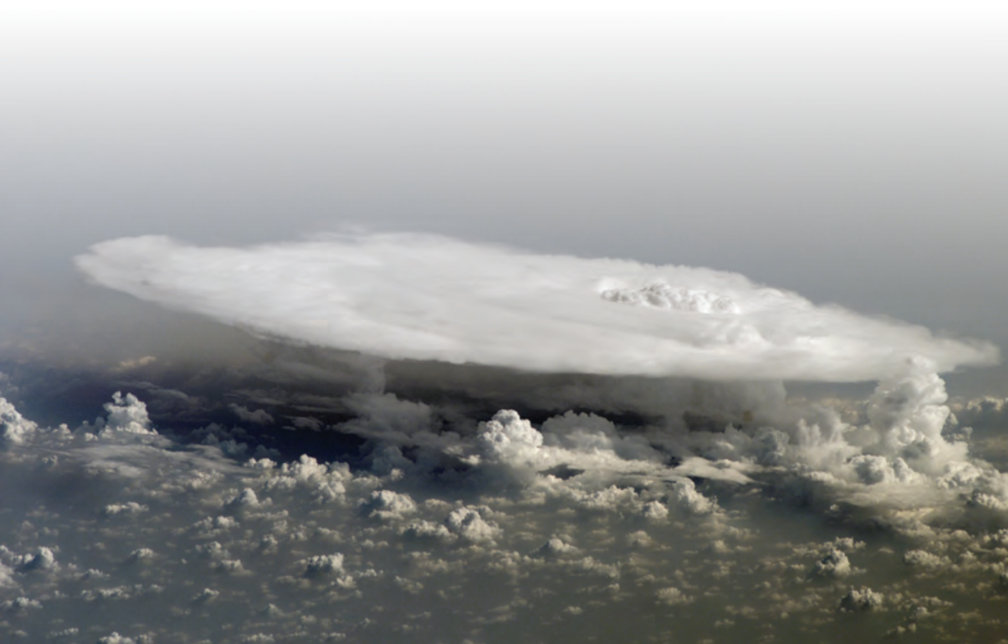
- The cumulus stage is marked by the distinctive formation of an updraft. Updrafts are vertically oriented currents of air that lift warm, moist parcels of air through the lower levels of the troposphere.

- As the parcels of air rise, they expand and cool. Condensation occurs when the parcel temperature cools to its dew-point temperature, saturating the air within. The base of the cloud forms with a nearly flat bottom, but above this, the clouds bubble buoyantly into the sky in the destabilized atmosphere. These updrafts are very turbulent.

- In some supercell thunderstorms, the updrafts approach 150 miles per hour. These updrafts are able to support huge globes of hail the size of grapefruit.

- Mature storms stretch from cloud base to the equilibrium level. This level often coincides with the position of the tropopause. The updraft is stopped at this level by the extremely stable air that is found above this point. Instead of continuing its vertical ascent, the updraft air is forced to spread horizontally and exhaust outward, forming a familiar cloud type called the anvil cloud.

- Anvils get their name because they turn the shape of the storm into that of a blacksmith's anvil. All thunderstorms produce anvils. The size and shape of the anvil can be used to assess the strength of the storm beneath it. Basically, the bigger the anvil, the more powerful the storm is beneath it.



» The key feature of the mature stage of the storm is the formation of a downdraft. Basically, what goes up must come back down. The rapidly rising air within the updraft cools, forcing condensation of water vapor onto tiny impurities, including dust particles, soot, ash, aerosols, and salt particles. Cloud droplets are born from this condensation process and begin to grow as condensation continues.

» In mature thunderstorms, the updraft carries the cloud droplets to altitudes where the temperature drops below freezing. At this point, some of the cloud droplets begin to freeze, and ice crystals begin to grow—but some of the cloud droplets, and even some of the raindrops, don't freeze, and instead they supercool.

» Water does not always freeze when the temperature drops before 32°F or 0°C. In fact, pure water can remain in its liquid state at temperatures as cold as −40°F. Water needs help to freeze.

» For pure water to freeze, the temperature of the water must cool down enough that the water molecules have lost enough energy that when a hydrogen bond is created, it doesn't break apart. Once that happens, other water molecules attach themselves with these permanent bonds and create a latticelike structure of rigidly locked molecules that we call ice.

» If there are certain impurities in the water, this whole process can happen at warmer temperatures. The impurities help lock the first few molecules into place so that others can latch on and grow the ice structure. However, these impurities are only effective once the temperatures get several degrees below the 32°F.

» From the cloud base to about 1/3 of the way up into the cumulonimbus cloud, the temperatures are above freezing. From this point up, the storm is primarily composed of a mixture of supercooled water and ice. At the very top of the cloud, where temperatures are far below −40°F, the cloud is composed entirely of ice.

- All thunderstorms contain this mixture of supercooled water and ice. The combination is important for the growth of large aggregates of ice crystals we commonly call snowflakes. It is also important for the formation of hail. Supercooled water will freeze instantly when it comes in contact with an ice crystal or frozen raindrop. This is how hail begins to grow.

- Without ice and supercooled water, storms could never produce lightning. Ice is the crucial ingredient needed for cloud electrification. Without it, the static buildup of electricity is impossible within the storm.

- In mature thunderstorms, this rain process is in full swing. As raindrops grow in size—primarily by colliding with each other and coalescing—they essentially collect each other. They also form by the melting of snowflakes.

- Then, they fall out of the storm. They either get so big that the updraft can no longer support their weight, or they fall out along the sides of the updraft, where the vertical winds are weaker. This is how downdrafts form.

- As the precipitation falls, it drags the air down with it. Once it approaches the cloud edge or cloud base, this pocket of rainfall undergoes some evaporation due to its mixing with drier air. Evaporation is a cooling process. This combination of events leads to the formation of a cold, dense pocket of rapidly descending air that is loaded with precipitation.

- Ordinary storms can't survive their downdrafts. The problem is that the downdraft in an ordinary storm falls back through its updraft. If the updraft and downdraft are too closely spaced, the downdraft will block the updraft, and the storm will dissipate. Gravity will win this battle, and the downdraft will effectively cancel the updraft. The storm quickly dissipates at this stage—never having a chance to reach its severe potential.

- Most ordinary storms can go through their entire life cycle in about an hour. To reach its severe limits, the storm needs more time to develop. Wind shear is key for providing this boost in longevity.

- Wind shear is the change of wind speed and direction. It is used to prevent the storm from becoming vertically stacked, where the updraft and downdraft are colocated. Wind shear pushes up the top of the storm downstream, allowing the updraft and downdraft to separate. Now the storm has the precious time it needs to strengthen.

Predicting Severe Thunderstorms

- When all 4 ingredients combine—an unstable atmosphere, a trigger mechanism, adequate surface moisture, and wind shear—the atmosphere produces powerful, severe thunderstorms.

- The Storm Prediction Center (SPC), which is a part of the National Weather Service (NWS), exists to study, predict, and prepare the public for severe thunderstorms.

- When the SPC issues a severe thunderstorm watch or tornado watch, it means that meteorologists are watching an area for the potential development of a severe thunderstorm or tornado. They look for regions where the 4 ingredients are coming together.

- Severe thunderstorm watches and tornado watches are quite common throughout the thunderstorm season in the United States.

- Severe thunderstorm watches are most common in the region that stretches from northern Texas through Oklahoma and Kansas. This region has frequent strong thunderstorms from early spring through late fall.

- Louisiana, Mississippi, and Alabama are the states with the highest number of tornado watches each year. This part of the United States has a never-ending thunderstorm season. Being so close to the warmth of the Gulf of Mexico keeps moisture constant and temperatures very high throughout the cooler months of the year.

- Each time a large low-pressure system plows through the United States, it drapes a cold front through this region that triggers thunderstorms into unstable air. Combine this with favorable wind shear profiles for rotating storms, and tornadoes are possible here year-round.

- While a "watch" means that conditions are favorable, a "warning" means that the severe weather event is actually happening. Thunderstorms are warned as severe when one of the following events is observed.

- If a Doppler radar detects regions within the storm where the radar reflectivity exceeds 55 decibels relative to Z (dBZ, where Z represents the energy reflected back to the radar), radar meteorologists at the National Weather Service will issue a severe thunderstorm warming due to hail.

- Doppler radar can also be used to identify severe winds in excess of 50 knots, or about 58 miles per hour. Radar radial velocity images show us where parts of the storm are producing dangerously fast winds.

- We can also detect severe winds using the Automated Surface Observing System (ASOS). The U.S. government has placed more than 900 such weather stations across the United States, many of which are at airports.

- These stations are equipped with highly accurate and precise weather observation equipment that measure winds, temperature, humidity, visibility, precipitation intensity, and type. When severe storms pass over the ASOS stations, we receive instantaneous surface wind data.

» Tornado warnings are issued by one of two ways. First, if a trained storm spotter or official, such as a police officer or fireman, witnesses a tornado, the storm will be warned. However, some tornadoes form where storm spotters can not see them, or they form at night. In these situations, the NWS relies on its Doppler radar network.

» A very important change to the storm warning strategy occurred in the mid-2000s. Advances in Doppler radar technology, combined with a tremendous amount of severe thunderstorm research, has allowed meteorologists to pinpoint regions of storms that are producing severe weather.

» For complex thunderstorms, only small parts of each storm are actually capable of producing weather bad enough to reach the severe criteria.

» In the past, the NWS used a county-based warning system. This means that if a severe storm enters any part of the county, the whole county is warned. For some storms, this led to the unnecessary warning of thousands of people.

» County-based warning systems produce a lot of false alarms. Using this method for decades has made many citizens less responsive to warnings, especially tornado warnings. With the newer storm-based warning system, unnecessary warnings have been drastically reduced.

» Each year, the SPC collects storm report information, and on average they receive between 20,000 and 30,000 reports each year. These reports are broken down into 3 categories: hail reports, severe wind reports, and tornado reports.

- On average, there are 1200 reports of tornadoes each year across the United States. Hail reports typically total around 10,000 each year. The most common form of severe weather in the United States is wind; on average, 15,000 reports are recorded each year.

- The many lives that are saved each year because of weather forecasting is a direct tribute to the successful identification of severe storms by the NWS, the SPC, and counterpart organizations in other parts of the world.

SUGGESTED READING

Federal Aviation Administration, *Wind Shear.*

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes.*

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather,* chap. 18, p. 306–310.

QUESTIONS TO CONSIDER

1. Storm chasers seek environments where 4 separate ingredients have come together. Can you identify those ingredients?

2. What role do impurities such as dust, ash, and aerosols play in the formation of a thunderstorm?

LECTURE 11

Squall Line Thunderstorms and Microbursts

For most people, a thunderstorm is just a thunderstorm, and the only difference between them is their severity—how fast the wind blows, how heavily the rain falls, or how frequent the lightning occurs. To a meteorologist, however, thunderstorms have personalities, characteristics, and defining qualities that shape them and organize them into distinct modes of formation. In this lecture, you will learn how meteorologists classify thunderstorms by investigating convective systems that cluster, or form organized lines of thunderstorms.

Mesoscale Convective Systems

» The most basic level of classification for thunderstorms is to determine if the storm system is composed of discrete, individual storm cells, or the storm system can be a cluster or line of storm cells. But thunderstorms can also organize themselves into large clusters called complexes, or systems, or squall lines.

» Inside the thunderstorm complex, each individual storm is able to feed off of the surrounding storms, and they work together to reinforce and sustain their updrafts. These are known as squall lines, due to the intense squall winds they can produce along a line of storms.

» Meteorologists call them mesoscale convective systems (MCS). This name conveys their larger scale: The line of storms is on the mesoscale, which ranges from 10 to 1000 kilometers. The name also conveys how these storms are organized. They are convective, meaning that the parcels of air that create these storms are buoyant and rise in unstable atmospheric conditions.

» Finally, they are a system of storms that works together, as opposed to a single-celled storm structure. All of the nanoscale and microscale events that build clouds and precipitation organize into larger-scale events, such as squall lines. Most severe thunderstorm events occur on the mesoscale in terms of their size.

» All thunderstorms must be initiated or triggered. During the summer, cold air retreats to the far northern latitudes, making large warm and cold fronts far less frequent in the midlatitudes. Meteorologists must therefore search for much subtler triggers.

» The heat of summer frequently produces thunderstorms that form on rising thermals of warm air. One ordinary thunderstorm can spark the development of a long line of severe weather if the environmental conditions are right.

» How can one ordinary non-severe storm do this? The answer lies in the behavior of the storm's outflow. Outflow forms when the downdraft of a mature storm reaches the surface and spreads out horizontally. This cool, dense pocket of air races away from the storm's periphery.

» As the outflow propagates away from the storm, it acts as a mini cold front. Inside the outflow, the air is cool and dense. Warm, humid air can be lifted over the outflow as it radiates away from the original storm.

» New storm cells are often generated on this outflow boundary. The difference between the original storm and these new cells is that the new storms are forming along a common trigger—the outflow of the original storm.

» For these storms to survive, the environment must support their development. First, the atmosphere must be unstable and have plenty of moisture. Negative lifted index values and high CAPE (convective available potential energy) combine with humid surface air to create the new cells. However, for these storms to remain linear, strong wind shear is a necessity.

» The optimal wind profile is a wind that doesn't change too much in direction with height, but it does increase in speed. This is called unidirectional wind shear.

» The new storm cells that form on the outflow of our original storm form so close together that they practically become indistinguishable from one another. Rather than existing as discrete, individual storms, they line up together and form a single unified system. This configuration of storms is generically called a squall line.

» A squall is defined as a sudden, often violent gust of wind. This name is very appropriate for this type of storm system, because it is the type that contributes the majority of the 15,000 reports of severe winds collected by the Storm Prediction Center each year.

» How does this storm produce these violent, straight-line winds? Once the line of storms is established, it has definable characteristics. Let's explore the squall line from front to back and from start to finish and discover how it reaches its severe limits.

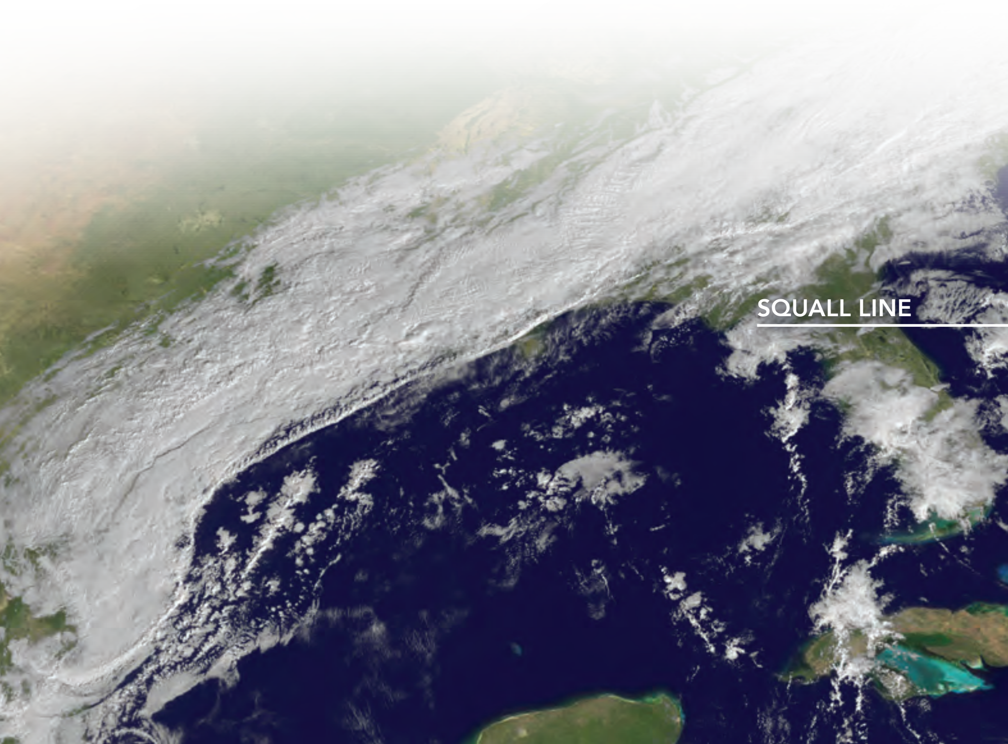
Squall Line Thunderstorms

» Thunderstorm systems like the squall line establish their own mesoscale circulations. The initial storm forms in an environment that has increasing unidirectional wind shear. A circulation forms as the faster winds aloft race over the top of slower surface winds.

» The updraft is forced to tilt downstream with the wind, and as it rises into the atmosphere, it produces small eddies, or circulations, on either side that spin up due to the rising air. The storm is capable of greatly modifying its local environment and causes the air to behave in very interesting ways.

» As the storm matures and moves forward, a downdraft and rainshaft are produced on the back side of the updraft. This is a key feature because this descending, cooler air is essential to the preservation and structure of the storm.

» A small circulation establishes between the rising air in the updraft and the sinking air in the downdraft. Let's say that there are 2 counterclockwise-spinning cells on the back side and 2 clockwise-spinning cells on the front side. This configuration helps the storm stand up vertically and strengthen its updraft.



» At this point, the storm forms its own trigger mechanism. This means that the storm can become self-sustaining because it has formed its own means by which to create new updrafts.

» The downdraft on the back side of the storm is composed of rain-filled, cool, and dense air. As it hits the ground, it diverges in all directions as an outflow of cool, dense air. This pocket of air is called the cold pool, which races underneath the updraft and out ahead of the storm. Fresh updrafts form on top of this outflow.

» When cool, dense air from the downdraft descends and spreads radially outward under the storm, shelf clouds form. As this air races out ahead of the storms, warm, humid air collides with the outflow and is lifted abruptly. The result is a shelf of clouds.

» The shelf cloud marks where the inflow of the storm meets the outflow. Shelf clouds look very ominous, because they are low hanging, move quickly, and are very dark and foreboding. When shelf clouds appear, they serve as a warning that the intense part of the storm is coming soon.

SHELF CLOUD

- Both the wind and temperature change as a shelf cloud passes. Before the cloud arrives, warm, humid air flows into the storm. As soon as it is overhead, a burst of cool air arrives, causing you to feel as though a cold front has just passed over you. This is why meteorologists often refer to this feature as a gust front.

- Mature squall lines often develop what is called a bookend vortex on the ends of the squall line. As the line advances, the storm cells at the ends of the line often curl around and form a mesoscale circulation, much like the way that water will form small eddies around your hand as you push it through.

- Be careful not to confuse these bookend vortices with tornadoes or hook echoes, as they are much too large and form by entirely different means than tornadoes. But bookend vortices do signal strong storm systems and are most commonly found in squall lines with large bow echoes, which get their name because they look like bows that have been drawn backward, ready to fire an arrow.

- A squall line can occasionally evolve into a derecho, which is a long-lived, large MCS that causes widespread damage, especially from wind. Some can stretch over 1500 miles and last more than 10 hours.

- Have you ever noticed that after the heavy rain and intense rain from a squall line passes, a period of light to moderate rain often follows the storm? Sometimes it can rain for more than an hour after the intense part of the storm blows over.

- Meteorologists call this part of the storm the trailing stratiform region. "Stratiform" means that the cloud field on the back side of the squall line is more layered, flat, and stratified.

- As warm, moist air is thrust upward into the updraft, it is carried to the back side of the storm. The flow of the air changes trajectory along the way from having a strong vertical component to its motion to having a strong horizontal component.

- On the back side of the MCS, the rain-filled downdraft air is spread out over a larger area that trails the leading edge of the storms—hence the name "trailing stratiform region."

- A telltale sign that a squall line is struggling to maintain its strength is that if the radar reflectivity values are becoming weaker with time, we know that the storm is weakening. Another feature to watch for is the spacing between the main body of the storms and the gust front. The greater this separation, the weaker the updraft, and the storm "gusts out."

Downbursts and Microbursts

- A downburst is defined as a powerful downdraft that produces damaging winds. A microburst is a very small downburst that is typically no longer than 2.5 miles wide.

- Downdrafts are a part of every thunderstorm, but why are some so powerful? The answer lies in understanding the moisture characteristics in the boundary layer, which is the lowest part of the troposphere. It extends from the surface of the Earth to an altitude of roughly 1 to 2 kilometers.

- When the downdraft of these storms falls into the boundary layer below, if the conditions are right, the descending air can quickly accelerate toward the surface to speeds over 100 miles per hour.

- Entrainment, which refers to the mixing of dry air into the downdraft, is the key. This dry air promotes two kinds of cooling processes: evaporation of raindrops and sublimation of ice crystals. If dry air is entrained into the storm in the midlevels of the atmosphere or in the boundary layer, the downdraft cools quickly and increases in density.

- The denser the downdraft air, the faster it will descend. Flying through a downburst will force a plane to lose altitude rapidly and potentially crash into the ground.

» High radar reflectivity plus fast winds on the Doppler velocity images is the signal radar meteorologists look for. This is why planes never land when radar meteorologists detect high radar reflectivity near the runway.

» It can be difficult to distinguish downburst damage from tornado damage. Both are capable of uprooting trees and destroying homes. But there is one key feature that helps us determine the source of wind damage.

» When the National Weather Service is called to assess the damage and determine if it was caused by a tornado or a downburst, they look at the patterns in the debris and damaged property. Tornadoes produce mangled, swirling patterns in the trees that they down and the houses that they destroy. Downbursts, on the other hand, produce damage patterns where damage is oriented in the same direction.

SUGGESTED READING

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes*.

National Weather Service, "Microbursts."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 18, p. 310–320, and chap. 22, p. 401–420.

QUESTIONS TO CONSIDER

1 Squall lines of thunderstorms produce shelf clouds. Can you identify this cloud type, and do you know what to do to stay safe if you ever saw one?

2 What features would you look for on a Doppler radar reflectivity and radial velocity image to identify the most severe parts of a squall line?

LECTURE 12

Supercell Thunderstorms and Hail

The topic of this lecture is the supercell thunderstorm—the most powerful thunderstorm on Earth. These storms are ferocious and damaging, and they can win the fight against even a well-constructed home. For these storms, horizontal wind shear sets the whole storm spinning. The true power of a supercell thunderstorm is in its ability to focus its rotation into a narrow, violently spinning column of air. Predicting this type of storm requires a sharp eye in recognizing the ideal wind profile.

Supercell Thunderstorms

» The triple point—typically the ideal place for supercell thunderstorm initiation—is found right next to the center of the low-pressure area where a cold front, warm front, and dry line intersect.

» Low-pressure systems use their counterclockwise rotation to draw together air masses of different temperature and moisture characteristics. They pull hot, humid air to the north from the Gulf of Mexico; hot, dry air to the east from the deserts in the southwest; and cold, dry air from Canada to the south. As these air masses collide, air is forced to rise.

» The perfect situation for a severe weather outbreak is for all 3 of these air masses to meet at the same point just south of the low-pressure center. This is the triple point. It is ideal because in one focused location, you have a powerful combination of lifting mechanisms—3 fronts—and you have an abundance of moisture streaming in from the Gulf of Mexico.

- Add to this an unstable atmosphere due to cold air already in position aloft and potential energy as measured by CAPE values will soar. Furthermore, around the low, we will find winds that not only change direction with height, but also increase dramatically in speed.

- Unlike the squall line, the supercell is a discrete storm cell. It is small—no bigger than a medium-sized county in the central United States. However, these storms are responsible for producing the largest hailstones, the most powerful straight-line winds, and the most violent tornadoes.

- Why are these storms discrete? Why do they form as separate thunderstorm cells? The answers to these questions lie in an examination of the environment in which the supercell forms.

- Once again, it is all about wind shear, which is the change in wind speed and direction with height in the atmosphere. For squall lines, winds must increase with altitude but not change too much in direction. The supercell, in contrast, relies on both a change of speed and direction to form.

- The perfect environment in the Great Plains begins with a surface wind out of the southeast. A 10- to 20-mile-per-hour wind from the southeast flows from the Gulf of Mexico, bringing high-humidity air into the storm.

- This is the fuel for the storm. The moisture in this air will release enormous quantities of heat into the storm as it condenses within the rising updrafts.

- Just above the surface, winds need to increase in speed and veer to the south. A veering wind is a wind that turns counterclockwise with height. About 1 to 1.5 kilometers above the surface, the perfect wind shear profile will include a feature called the low-level jet.

- Unlike the rear-inflow jet of the squall line, the low-level jet is a synoptic scale feature that develops before the storms appear. It is characterized by 30- to 50-mile-per-hour wind from the south or southwest that races over the top of the surface winds.

- Essentially, the faster wind in the low-level jet causes the air to tumble, and horizontally aligned tubes of spinning air begin to form between these two layers. This is the key to the formation of a supercell.

- The tubes of air resemble strands of DNA as they twist in a helical form and migrate northward. Meteorologists borrowed a term from physics, "helicity," and use this as a parameter to measure the strength of this wind-shear-induced, corkscrew-like tube of air. In the ideal supercell environment, helicity values that exceed 150 meters squared per second squared are perfect for creating rotating updrafts.

- Supercells are defined by their rotating updrafts. But how does the storm use this horizontally aligned tube of air to spin? As a thunderstorm develops in a particular region, the updraft of the storm will pull a horizontal tube of air vertically, reorienting it into an upright position. The rotation that was once horizontally aligned is now upright and spinning around a vertically oriented axis.

- Meteorologists call the rotating updraft of the supercell thunderstorm the mesocyclone. This is what ensures that these storms remain discrete, rather than in groups like the squall line.

- The middle and upper levels of the atmosphere must continue to support the storm for it to survive. At about 3 kilometers above the ground, the temperature of the environment must quickly fall. A change in temperature with altitude is called a temperature lapse rate.

» Intense supercells have environmental lapse rates that approach 10°C per kilometer—the steepest lapse rate that the environment can produce. The greater this lapse rate, the more unstable parcels of air will be as they rise into the midlevels of the atmosphere.

» Steep lapse rates lead to large CAPE values and very low lifted index values. While this signifies the destabilization of the atmosphere, the winds must also continue to evolve and change with height.

» At 5 kilometers, the best wind shear profile will include a 60- to 80-mile-per-hour west-southwest or west wind. Near the tops of these storms, at altitudes greater than 10 kilometers, which is higher than 32,000 feet, winds can approach or exceed 100 miles per hour out of the west. These winds blow the tops off the storms and create long anvil clouds that spread for miles above the storm.

» Most supercells track from the southwest to the northeast. Midlevel winds in these storms are most frequently from the west or southwest, and these winds steer the storm.

» Mature supercells produce huge anvil clouds, which form as the updraft of the storm slams into the stable base of the stratosphere and is forced to spread out horizontally. Winds at this altitude are strong, which forces the cloud to spread great distances.

» This cloud feature gets its name because it looks like a blacksmith's anvil—flat, smooth, and wide on top. The larger this cloud becomes, the more powerful the storm is beneath it.

» Beneath the anvil, mammatus clouds, one of the most visually stunning types of cloud, form.

MAMMATUS CLOUD

- The updraft transports vast amounts of moisture into the upper atmosphere, which eventually spreads out into the anvil. Anvil clouds produce rain and snow, but as this precipitation falls, it evaporates in the dry air below.

- Rain that evaporates before it reaches the ground is called virga. It is this midair evaporation that leads to the formation of mammatus clouds beneath the anvil. These bulbous-shaped clouds are the only cloud type to form in descending air.

- Saturated, precipitation-loaded air in the anvil descends, forming these bulbous-shaped cloud features as the water evaporates. Mammatus clouds look like inverted cumulus clouds. These clouds are benign, but they are most often associated with the most powerful thunderstorms.

» There is a transition to intense precipitation right next to the updraft to less and less intense precipitation as you get farther away. In fact, at the base of the updraft, no precipitation falls. This is because the updraft in the supercell is the consequence of a very unstable atmosphere. Parcels of air rapidly ascend at speeds that can exceed 100 miles per hour. Precipitation simply cannot fall back through a vertical air current of this speed.

» The environment in which the supercell forms is one of high wind shear. The air that is being lofted into the atmosphere by the updraft therefore experiences a stronger and stronger horizontal component to the wind as it ascends. This pushes the updraft downstream with height.

» It is also this reason why the precipitation intensity changes as you get farther from the updraft. Heavy precipitation particles, such as hail, are not thrown as far downstream by these strong winds. Therefore, they fall out right next to the updraft.

» Lighter precipitation particles, such as raindrops, can be thrown much farther. Therefore, far from the updraft, light rain falls, yet right next to it, heavy rain and hail fall.

» The mesocyclone is the rotating updraft of the supercell thunderstorm. This updraft not only rotates, but also leans downstream in the prevailing winds aloft. This is because faster winds in the middle and upper levels of the atmosphere displace the updrafts horizontally as they ascend.

» Supercell thunderstorm updrafts are among the most intense updrafts observed on Earth. The mesocyclone carries so much momentum as it ascends that once it reaches the top of the troposphere, where the tropopause and equilibrium level exist, it is able to briefly penetrate into the incredibly stable lower layers of the stratosphere.

» This will produce a cloud feature called an overshooting top, which appears as a large bump of cumulus clouds on top of the anvil. Only the strongest storms will produce these features.

Hail

» Supercell thunderstorms have hail. Thunderstorms are composed of a mixture of ice and liquid water. Some of this water is supercooled, meaning that its temperature is below freezing, but it is still liquid. Hail forms as supercooled water freezes on contact with ice crystals within the intense updrafts of a supercell thunderstorm.

» There are different layers of growth in hailstones. Some layers are clear while others are opaque. When a droplet of supercooled water collides with a growing hailstone, the rate at which it freezes determines the clarity of the ice.

» A hailstone that undergoes a “wet” growth stage will have a clear layer of ice built on its outer edge. The ice is clear because it froze slowly, and the air bubbles were allowed to escape.

THE LARGEST AND HEAVIEST HAILSTONE

As of 2016, the world record holder for the largest and heaviest hailstone fell in Vivian, South Dakota, in 2010. This record-setting hailstone was more than 8 inches in diameter and 19 inches in circumference and weighed in at 1.93 pounds.

» "Dry" growth occurs when the supercooled water drop freezes immediately on contact. Quick freezing prevents the bubbles from escaping and traps them in ice. The result is a buildup of opaque ice on the hailstone.

» Large hailstones take several minutes to form as they float in the powerful updrafts of supercell thunderstorms. As large hailstones form in the updraft, they often form small fingerlike spikes that protrude from the top of the stone. The bottom is smooth.

» As the stone is supported by the updraft, it is constantly being bombarded by supercooled water from below. This is due to the fact that the heavier hailstone cannot be lifted through the updraft as quickly as the smaller supercooled water drops. When the droplets splash on the bottom of the stone, they run up the sides as they freeze. Some of the water drips off the top of the stone while some freezes, forming spikes on top of the hailstone.

» A very large hailstone will eventually fall from the sky at a speed of more than 150 miles per hour. If it hits you, you will be seriously injured or perhaps killed.

SUGGESTED READING

Kennedy, Rutledge, Petersen, and Bringi, "Polarimetric Radar Observations of Hail Formation."

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes.*

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather,* chap. 18, p. 320–331, and chap. 20, p. 365–381.

Tornado Titans, "What Are Supercells?"

QUESTIONS TO CONSIDER

1. Supercells are discrete storm cells. Can you identify the reason why supercells remain single-celled storms?

2. Imagine that a supercell was approaching your location from the southwest. Can you describe the transition of precipitation intensity and type as the supercell passes over you?

Tornadoes and Their Amazing Winds

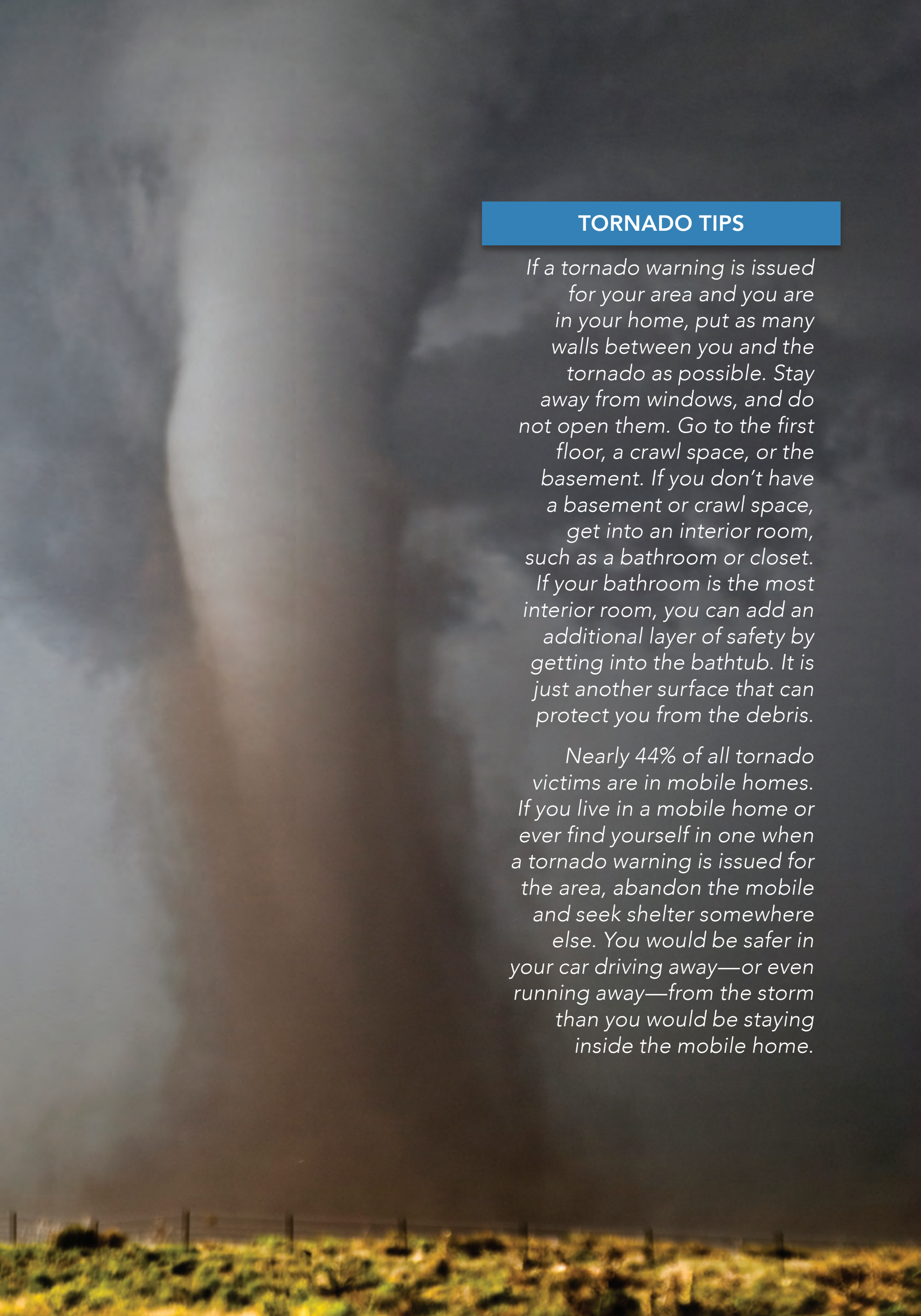
Tornadoes create Earth's most powerful winds. Blowing as fast as 200 to 300 miles per hour, tornadoes are also the most awe-inspiring and beautiful form of extreme weather. So, what exactly is a tornado? How do tornadoes form, and why do they form? Is there a reason why they form more often in some locations than others? Tornadoes are mysterious and misunderstood by many. In this lecture, you will learn all about tornadoes.

Tornadoes

» A tornado is defined as a rapidly rotating column of air that is attached to both the base of the cloud and to the ground. The precursor to a tornado is a funnel cloud, which emerges from the base of a thunderstorm, where the circulation can extend toward the ground.

» The funnel cloud is visible because it draws cloud water down with it. The name "funnel cloud" comes from their shape; they look just like an auto mechanic's funnel used to pour oil into an engine.

» Tornadoes come in a variety of shapes and sizes. Meteorologists have come up with several terms to describe them, including "elephant trunks," "stove pipes," "ropes," "cones," and "wedges." Each nickname describes what the tornado looks like. Of these, the wedge tornado is probably the most feared. These tornadoes are wider than they are tall.



TORNADO TIPS

If a tornado warning is issued for your area and you are in your home, put as many walls between you and the tornado as possible. Stay away from windows, and do not open them. Go to the first floor, a crawl space, or the basement. If you don't have a basement or crawl space, get into an interior room, such as a bathroom or closet. If your bathroom is the most interior room, you can add an additional layer of safety by getting into the bathtub. It is just another surface that can protect you from the debris.

Nearly 44% of all tornado victims are in mobile homes. If you live in a mobile home or ever find yourself in one when a tornado warning is issued for the area, abandon the mobile and seek shelter somewhere else. You would be safer in your car driving away—or even running away—from the storm than you would be staying inside the mobile home.

- Nearly 100 years of scientific research into tens of thousands of tornadoes has taught us quite a bit about how often tornadoes appear and what average tornadoes look like.

- An average tornado is typically 250 yards wide at its base. Some are much smaller—less than 100 feet across—while others can stretch more than a mile. The average tornado produces winds of 110 miles per hour, while the most powerful tornadoes produce winds 3 times this speed.

- An average tornado lasts approximately 10 minutes. During that time, its forward speed is between 20 and 40 miles per hour, and its damage track is about 4 miles long.

- While these are the average numbers, some tornadoes touch down for just moments while others survive for more than an hour. Some tornadoes can move at forward speeds that exceed 70 miles per hour, while others can remain stationary or even reverse direction.

- What is clear from these statistics is that tornadoes take on many shapes and sizes and move and spin at a large range of speeds. Where the statistics become very important is looking at tornado fatalities.

- When we break down tornadoes into 3 broad categories—weak, strong, and violent—based on wind speed, observations have shown that the vast majority are classified as weak: 69 to 85% of all tornadoes, depending on the database. Another 13 to 29% are considered strong. Only 2% are rated violent.

- Weak tornadoes are the most common, yet they are responsible for less than 5% of all tornado fatalities. In stark contrast, the 2% of all tornadoes categorized as violent are responsible for approximately 70% of all tornado fatalities.

» Regardless of the strength, when the National Weather Service issues a tornado warning, assume the worst and take cover immediately. Tornadoes are efficient killers.

Locations of Tornadoes

» A common myth is that some states in the United States never experience tornadoes. However, all states have had tornadoes.

» The National Oceanic and Atmospheric Administration (NOAA) keeps accurate records on the number of tornadoes each year per state. Even Alaska, at the very bottom of the list, has had 4 tornadoes since 1950.

» Texas leads the way, with a yearly average of 155 tornadoes. Texas is a large state in the middle of Tornado Alley—a region in the United States that is known for its tornado activity—and its sheer size is part of why it leads the nation in tornado frequency. Tornado Alley covers the states of Texas, Oklahoma, Kansas, Nebraska, North and South Dakota, eastern Colorado, Iowa, Missouri, Illinois, and Indiana. These states have a lot of tornado activity during the months of April through September.

» There is another tornado alley in the south called Dixie Alley. It includes Arkansas, Louisiana, Mississippi, Alabama, Georgia, and Tennessee. This region is vulnerable to tornadoes all year, due to its warmth in winter.

» The reason tornadoes are so frequent in these locations lies in the geography of the United States. First, the Rocky Mountains serve as a large physical barrier that perturbs the flow of the jet stream. New, powerful low-pressures systems are born in the Great Plains as the air flows off the mountains.

» In North America, warm, moist air flows unimpeded into the central United States, where it can be lifted into the unstable atmosphere by strong fronts, such as the cold front, warm front, and dry line. The wind shear profile in these alleys is ideal for supercell development. These rotating supercells are the parent storms for most tornadoes.

» Essentially, Tornado Alley and Dixie Alley in the United States, as well as other tornado-producing locations, from Argentina to Japan to most of Europe, are places where all of the ingredients for tornadoes come together most frequently.

» In the United States, there is one state that is outside of the tornado alleys that nonetheless has a lot of tornadoes. Florida ranks third in the number of tornadoes each year by state. Many of Florida's tornadoes are a type of offshore tornado called a waterspout tornado. Waterspouts are typically very weak, with wind speeds less than 100 miles per hour, and occur over water.

» Unlike the tornadoes that form in supercells, most waterspouts form as weak boundaries, such as those created by the sea breeze, and collide over open water. Horizontal wind shear along these boundaries causes a vertical column of air to start to spin. The updraft of a cumulus or cumulonimbus cloud will stretch this column vertically, causing it to tighten and spin faster.

» Waterspouts rarely produce a lot of damage, and most stay offshore. Florida's frequent thunderstorm activity and proximity to the Atlantic Ocean and Gulf of Mexico make it a great place to witness these types of tornadoes. You can also find them on the Great Lakes and in other locations.

» The United States leads the world in tornadoes, but other countries experience them, too. Most of Europe, parts of China, India, Japan, Australia, and small pockets in Africa have tornadoes. In South America, intense tornadoes are concentrated in Argentina and the southern tip of Brazil.

» The European Severe Storms Laboratory has been keeping accurate records of tornadoes in Europe and western Russia.

Taken together, all of Europe accounts for the second largest number of tornadoes on average, about 300 tornadoes per year.

» Canada is home to 5% of the world's tornadoes, with 60 to 100 reports per year. Made possible by a northward migration of the same triple-point factors that create tornadoes in the United States, most of the Canadian tornadoes are in southern Alberta, Saskatchewan, Manitoba, and southeastern Ontario and Quebec.

» However, the United States is home to more than 75% of the world's tornadoes. The United States's unique geography combined with its midlatitude location makes it the global gathering place for tornado activity.

» The United States has a lot of tornadoes, but tornadoes are actually quite rare. The United States averages approximately 1300 each year, and the odds of a tornado forming in any given square mile in the heart of Tornado Alley or Dixie Alley each year are about 1 in 10,000.

» The Storm Prediction Center keeps a running tab of tornado reports as a function of time each year. While the average is approximately 1300, some years produce much more than the average, while others are much less active.

Timing of Tornadoes

» Tornadoes in the United States are most frequent in April, May, and June. What is it about spring and early summer that make the atmosphere so conducive to producing tornadic events?

» Severe thunderstorms require 4 ingredients. April through June in the central United States experiences frequent frontal passages due to active jet stream patterns that spawn low-pressure systems. These fronts trigger the storms; draw in warm, moist air; and produce ideal wind shear.

- But the real key for the high frequency of tornadoes during these months is the atmospheric destabilization that occurs each spring and early summer. Winter effectively cools the upper layers of the atmosphere, and they stay cool for some time after the spring warmth returns near the surface.

- Each time the ground warms up on south winds and strong solar heating, the thermodynamic profile of the atmosphere becomes very unstable. CAPE (convective available potential energy) values soar and lifted index values plummet under these conditions, and thunderstorms thrive on it.

- Later in the summer, fall, and winter, this instability lessens as the upper levels of the atmosphere warm and then surface temperatures drop late in the year.

- Atmospheric instability is also the reason why tornadoes are most frequent in the late afternoon and early evening. In the early morning hours, the temperature profile in the lower atmosphere often contains an inversion. This prevents convective clouds from forming by stabilizing the vertical motion in the lowest kilometer of the atmosphere.

- From 5 am to 6 am is typically the most stable time of day. This time therefore lacks one of the 4 ingredients needed to form severe storms. However, severe storms can persist overnight and even form early in the morning.

Tornadic Fatalities

- The National Weather Service has been keeping accurate records of tornado fatalities in the United States since 1940. The 1940s through the mid-1970s have many years with high fatality counts, but the numbers decline from 1975 through 2010.

- This drop-off in the number of fatalities is due to two significant scientific advancements that happened in the mid-1970s that revolutionized our ability to warn people of tornadic thunderstorms.

- In 1975, the first geostationary satellites were launched to monitor weather. These satellites provided the crucial imagery we needed to assess and forecast the weather. At the same time, significant advances in tornado research were happening. These advancements were aided by increases in radar technology.

- These scientific achievements allowed meteorologists to warn the public several minutes before a tornado impacted a community—something that was nearly impossible to do before these technological advances were in place in the United States.

- However, even with modern warning systems—such as news coverage, social media, a storm spotter network, and 160 Doppler radars—massive tornado outbreaks can still claim hundreds of lives.

- April 2011 shattered the record for the most tornadoes ever in one month as well as the record for most tornadoes in one day. Fueled by a very active jet stream, which produced multiple vigorous low-pressure systems, April 2011 had 747 confirmed tornadoes.

- From April 25 through 28, 2011, 355 tornadoes caused $11 billion in damage, killed 324 people, and injured more than 2000. Most of these tornadoes were in the heart of Dixie Alley. April 27, 2011, broke the record for the most tornadoes in a single day with 211 confirmed tornadoes.

» Tornadoes are most likely in the Tornado Alley states and Dixie Alley states, but fatality rates are not evenly distributed among these states. The top 5 states ranked by tornado fatality rate (number of deaths per year from tornadoes) is, from lowest to highest ranked: Indiana, Illinois, Alabama, Arkansas, and Mississippi.

SUGGESTED READING

Bluestein, *Tornado Alley.*

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes.*

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather,* chap. 19, p. 333–363.

Storm Prediction Center, "The Online Tornado FAQ."

QUESTIONS TO CONSIDER

1. Why does the United States have 2 tornado alleys?

2. Why is opening the windows to your home or apartment a very unsafe thing to do when a tornado is approaching?

LECTURE 14

Tornadogenesis and Storm Chasing

The study of tornadogenesis, which is the birth of a tornado, tells us that tornadoes are generated by storms and, moreover, by the unique structure of each storm. The science of tornadogenesis begins with an understanding of storms, in particular, and supercell dynamics. In this lecture, you will discover how tornadoes form. You will also learn about storm chasing. Just like with most things we fear, understanding the tornado and its parent storm is half the battle in staying safe and losing our fears.

The Science of Tornadogenesis

- In supercells, wind shear in the lowest mile of the atmosphere is responsible for creating horizontally aligned tubes of air. A strong, low-level jet races over the surface winds, creating a helical tube of spinning air.

- Developing thunderstorms can tilt a tube like this upward. The spin, which was once horizontally aligned, is now twisting vertically in the updraft. The updraft is now rotating, leading to the birth of the mesocyclone and the supercell.

- How this process leads to the formation of a tornado has long been a mystery. But continual research by the best meteorologists has discovered the storm-scale processes that occur within the supercell to create a tornado.

- A precursor to the formation of a tornado is the appearance of a wall cloud, which forms at the base of the updraft of the supercell. Its name is derived from how this cloud often appears to form a wall around the tornado.

- The wall cloud appears to lower itself from the base of the updraft as the supercell strengthens. However, this is just an illusion. In reality, the wall cloud builds itself at lower and lower altitudes as the supercell ingests its own juicy air.

- Once the mesocyclone forms, it spins its way upward through the depth of the troposphere at the heart of the supercell thunderstorm. Stronger winds aloft push the updraft downstream. These same winds create the forward-flank downdraft. This is the front side of the storm where the majority of the precipitation falls.

- Falling precipitation in the forward flank creates a powerful downdraft. As this downdraft hits the ground, it splashes radially outward. The air in the downdraft is cool and nearly saturated. As it collides with the warm, moist air that is flowing toward the storm, the warm air runs right over the top of the outflow.

- Strong but small-scale vertical wind shear results from this collision, and the result is a tightly spinning, horizontally aligned tube of air. The tail end of this tube runs just beneath the mesocyclone, where it is once again pulled upward by the updraft.

- The wall cloud emerges when this tube of air is ingested into the storm. It appears as a lowering of the cloud base because the storm is actually breathing in its own outflow. This air is very near saturation, and as a result, it needs only to be lifted a short distance to cool enough to begin condensation. The wall cloud spins faster than the mesocyclone, too.

- A cone-shaped cloud feature, the funnel cloud, appears in the wall cloud. In the same manner in which the wall cloud formed, the tornado is born out of the thunderstorm's other downdraft: the rear-flank downdraft.

- The mesocyclone, the updraft of the storm, is sandwiched between the forward-flank downdraft and the rear-flank downdraft. The rear-flank downdraft is much smaller.

- Descending air on the back side of the storm is pushed against the updraft by the environmental winds on the back side of the storm. This downdraft is often composed of heavy rain and occasionally hail. As this air descends, the rear-flank downdraft curls around the mesocyclone, producing the familiar hook shape, the hook echo, on radar.

- Just like the forward-flank downdraft, this descending air hits the ground and splashes outward radially. From the top down, both outflow boundaries spread and intersect near the updraft. The forward flank has already created the wall cloud. How does the rear flank create the tornado?

- The outflow in the rear flank creates yet another tube of spinning air that is horizontally aligned. Being so close to the updraft, this tube is pulled upward by the strong vertical winds within the wall cloud and mesocyclone.

- The tube of air bends and bows upward, creating two vertically aligned tubes of air. The one located nearest the updraft rotates counterclockwise, while the other rotates clockwise. Each tube is capable of producing a tornado; however, the clockwise-spinning tube often dissipates or is sheared apart, leaving only the counterclockwise-spinning tube.

- This tube of air is then stretched vertically as it is pulled upward by the mesocyclone. Stretching tightens the circulation, causing it to spin faster by the conservation of angular momentum. The tornado is born as this tube of air is stretched.

- Only about 30% of all supercells are able to produce tornadoes. Too often, the storm's outflow, both forward and rear, are not in an ideal configuration to produce a wall cloud or tornadic circulation.

Tornado Structure

- Small tornadoes, those that are at most a few hundred feet wide, have different internal structures than those that are much wider. The initial structure of a small tornado is such that the winds in the center of the tornado ascend rapidly, sucking debris upward into the storm.

- As a tornado strengthens, it often gets wider and undergoes a process called vortex breakdown. Strong centrifugal forces within the funnel create an opening in the center of the tornado where the air pressure drops off dramatically. Within this opening, air descends from above and creates a very small downdraft in the center of the tornado. This downdraft widens the tornado.

- Fundamental principles in physics tell us that as the radius of a rotating system increases, its velocity will decrease. This is exactly what happens in the tornado.

- As it widens, its rotational winds slow down. So, why does the tornado strengthen during this processes? Tornadoes that widen like this undergo a process called vortex breakdown. On the edge of the tornado, air is rapidly ascending. In the center, the air is descending. Where the rising air and sinking air meet, small-scale circulations called suction vortices form.

- A tornado that goes through vortex breakdown essentially breaks apart into several smaller tornadoes. The larger circulation still exists, but now embedded within its circulation are several smaller tornadoes.

- This is when the tornado is at its most dangerous. First, it is very wide. The large-scale winds are still spinning at triple-digit speeds and now cover a large area. Second, the suction vortices are spinning at triple-digit speeds themselves.

- Suction vortices are often hidden from view. They are masked by all of the dust, debris, and condensation in the tornado, so they are rarely seen. Each suction vortex may only be 50 to 100 feet wide. As it swirls around the inside of the larger tornado, it may take out one home entirely but leave the neighbor's house standing.

- This has caused many people to believe that tornadoes can hop around or slither back and forth like a snake, but they do not. Damage photos from nearly all tornadoes show their path to be quite straight.

Tornado Life Cycles

- Like all other parts of the supercell, the tornado has a life cycle. A telltale sign that a tornado is near the end of its life is if it takes on a rope shape. The reason it takes on this shape is because the rear flank of the storm has completely wrapped itself under the updraft and kicked out the base of the tornado from under the mesocyclone. It will not recover from this; it will shear apart and dissipate.

- The supercell, however, can recover and begin a new stage of development. As the rear flank undercuts the main updraft of the old tornado, a new updraft tends to form to the southeast of the old one. It forms here because this is where the warm, moist, unstable air is found.

- As the new mesocyclone forms, the supercell has the potential to form another tornado. Some supercells can go through many cycles and produce a family of tornadoes. Each new tornado track begins just a few miles after the old one ends and is offset to the southeast a few miles.

» Supercell cycles can often produce seemingly incredible tornadic events. But tornadoes can also form in non-supercell storms. Just like the waterspout, the landspout tornado forms from strong horizontal wind shear.

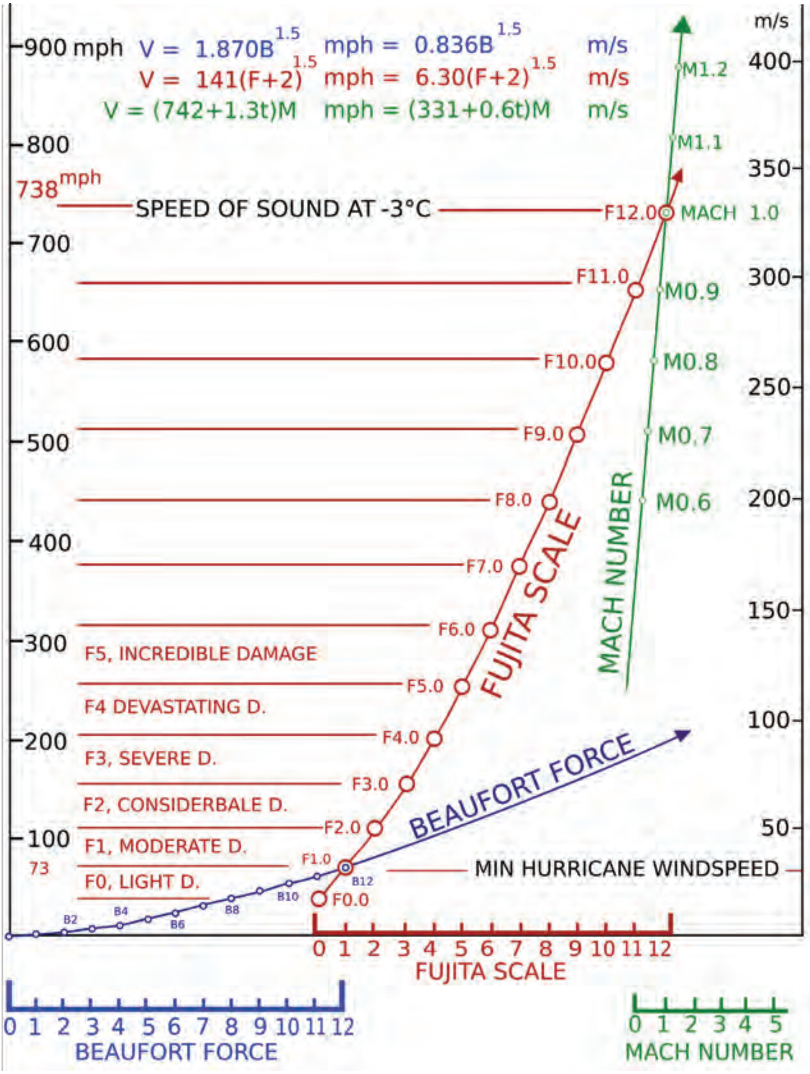
» When they do form, landspouts are typically found along the leading edge of squall lines. The winds ahead of a squall line, just like the supercell, often come from the southeast in the United States. Behind the leading edge of the squall line, the winds shift quickly and are often from a westerly direction.

» As these winds cross, small, vertically aligned circulations form that can be stretched into the updraft of the squall line. The landspouts that form along the leading edge of the squall line are often very weak and rarely produce damage greater than that of the squall line itself.

» Tornado-like vortices also form in fire. Just like the waterspout and landspout, horizontal wind shear can create small scale-eddies, such as a whirlwind. The heat from the fire causes the air to rapidly ascend. This stretches the fiery vortex vertically, causing it to spin faster. Sometime these fiery vortices move quickly as they are blown by the wind. They can easily spread forest fires with their incredibly intense heat.

Tornado Research

» Early tornado research was pioneered in the work of Dr. Theodore Fujita, who set out to measure the winds of a tornado by examining the damage they caused. His original scale had 13 levels, F0 to F12. In 2007, the Fujita scale was upgraded to the enhanced Fujita scale, which expanded on the original by adding 28 separate damage indicators that could be used by surveyors to more accurately estimate wind speeds.


900 mph
V = 1.870B^1.5 mph = 0.836B^1.5 m/s
V = 141(F+2)^1.5 mph = 6.30(F+2)^1.5 m/s
V = (742+1.3t)M mph = (331+0.6t)M m/s
800
738 mph
SPEED OF SOUND AT -3°C
700
600
500
400
300
200
100
73
m/s
400
350
300
250
200
150
100
50
M1.2
M1.1
MACH 1.0
M0.9
M0.8
M0.7
M0.6
F12.0
F11.0
F10.0
F9.0
F8.0
F7.0
F6.0
F5.0
F4.0
F3.0
F2.0
F1.0
F0.0
FUJITA SCALE
MACH NUMBER
F5, INCREDIBLE DAMAGE
F4 DEVASTATING D.
F3, SEVERE D.
F2, CONSIDERBALE D.
F1, MODERATE D.
F0, LIGHT D.
BEAUFORT FORCE
MIN HURRICANE WINDSPEED
B2
B4
B6
B8
B10
B12
0 1 2 3 4 5 6 7 8 9 10 11 12
FUJITA SCALE
0 1 2 3 4 5 6 7 8 9 10 11 12
BEAUFORT FORCE
0 1 2 3 4 5
MACH NUMBER

Fujita Scale

F0	40–72 mph winds
F1	73–112 mph
F2	113–157 mph
F3	158–206 mph
F4	207–260 mph
F5	261–318 mph

Enhanced Fujita Scale*

*In use since 2007

EF0	65–85 mph winds
EF1	86–110 mph
EF2	111–135 mph
EF3	136–165 mph
EF4	166–200 mph
EF5	> 200 mph

» A lot of tornado research has been conducted on the basis of increasing the tornado warning time. Since 2010, the average tornado warning time has exceeded 20 minutes and in some cases 30 minutes. Some research suggests extending this time beyond 30 minutes may not be a good thing; the concern is that extending the warning time may cause it to lose its immediacy.

» Seeing into the tornado is now done with high-resolution radar. Tornado research took a giant leap forward when Dr. Josh Wurman designed the first Doppler on Wheels. The idea was to strap a radar on the back of a truck, get it as close to the storm as possible, and scan it.

Storm Chasing

» Storm chasing has been a hobby for many people for decades. But the invention of mobile Doppler radar took storm-chasing research to a new level. Numerous federally funded field campaigns have used the Doppler on Wheels to safely scan tornadoes from a nearby location.

» The data collected by these radars has revolutionized our understanding of tornadoes and lengthened tornado warning times. These observations have helped us to better model these storms and forecast them.

- The following are some of the key precautions to stay safe if you, or anyone you know, decide to try storm chasing:
  - Always have a point of contact—someone who knows where you are.
  - Know your road network. Never chase on dirt roads or roads that go through forested areas. You can get stuck or find yourself in a position where you can't see the tornado.
  - Always bring a cell phone that has access to radar imagery. There are great radar apps that you can use that will show your position with respect to the storm.
  - Always have an out. Know exactly where you will go if things get too intense.
  - Never try to be a hero. Keep your distance, stay to the southeast of the storm, and enjoy the view.
- Whether you are storm chasing or simply caught out in your car when a tornado strikes, the following are some basic things you should know to stay as safe as possible:
  - If you are in an area where there is a nearby shelter or building, abandon your car and get to the shelter immediately.
  - If you are on the open road, never take shelter under an overpass. While it may look like a sturdy structure, do not get out of your car and hide under a bridge. Hiding in the supports under a bridge puts you in a very vulnerable situation.
  - It is no longer advised to abandon your car and seek shelter in a nearby ditch. Modern cars have many safety features that are designed to keep the passengers from injury, including air bags, seatbelts, safety glass, and crumple zones. Stay in your car if you can't find nearby shelter.

SUGGESTED READING

Markowski and Richardson, *Mesoscale Meteorology in Midlatitudes*.

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 19, p. 333–363.

Storm Prediction Center, "Forecast Products Guide."

QUESTIONS TO CONSIDER

1. Why is it impossible to rank a tornado using the Fujita scale (or enhanced Fujita scale) while a tornado is in progress?

2. When storm chasing, having access to mobile Internet along with live radar imagery is crucial to your success and safety. What features would you look for on a Doppler radar reflectivity and radial velocity image to identify the most severe parts of a tornadic supercell?

LECTURE 15

Mountain Windstorms and Avalanches

Earth's mountains host many of the planet's extreme weather records for cold and snow. The coldest temperatures are found on mountains, and snowfall records from the tallest mountains are far beyond the snowfall found in any inhabited part of Earth. But in addition to their ability to set such records, Earth's mountains also play a crucial role in the formation of many weather systems, including many extreme weather events—as you will learn in this lecture.

Mountain Winds

» Mountains serve as large physical barriers that shape the movements of air, water, and even soil along their slopes. From avalanches, to flooding, to high-speed winds, major mountains are like the directors of an extreme weather show that runs year-round.

» The most basic thing mountains do is force nearby airflow in the troposphere to change course. Mountains force air to speed up or slow down, to rise or sink.

» In general, weather is all about circulation, and mountain weather is all about how mountains intervene to change the circulation of air. Wind is the consequence of changing atmospheric pressure, but mountains alter any wind in their vicinity, sometimes producing extreme winds that can rival those of tornadoes.

» The first thing that air colliding with a mountain tends to do is drop its moisture on the mountain. This means that mountains control where precipitation falls on Earth. They also control the temperature, humidity, and speed of the wind.

- In Europe, the northern slopes of the Alps often see the formation of a hot wind from the south known as the foehn wind, which has come to more generally refer to any warm, dry wind that descends a mountain—such as mountain winds in Asia and the Americas.

- In the United States, strong mountain winds also go by at least two other another names: the chinook and the Santa Ana. The chinook wind of the Rocky Mountains was named after the Chinook Native American tribe of the Pacific Northwest. A strong chinook wind is feared by the residents living along the front slopes of the Rocky Mountains.

- A mild chinook wind can produce a beautiful and warm day in the middle of winter. West winds cross the north-south-oriented Rocky Mountains. On the windward slopes, which are those facing the west wind, the air rises due to the mountain forcing the air to ascend.

- Ascending air cools as it expands, and clouds and precipitation fall on the windward side. Once the air reaches the summit, it descends along the leeward side of the mountain. The air sinks along the leeward slopes and warms by compression. When this wind is gentle, it produces a warm, dry breeze that flows through cities like Boulder, Colorado.

- Air temperatures soar into the 60s or even higher in the middle of winter and provide a nice break from the bitter cold. The only side effect to a gentle chinook wind is the very low humidity of the air. The moisture was stripped from the air as it ascended the windward side. It was deposited as rain and snow on the westward-facing slopes.

- A second form of strong mountain wind is the Santa Ana wind of southern California. Just like the chinook wind, the Santa Ana wind is a dry, warm downslope wind. While not as fast as the chinook wind, the Santa Ana wind brings a different kind of threat to Los Angeles's enormous population.

- Santa Ana winds develop when a large high-pressure system builds over Nevada and Utah. While the chinook wind forms on a strong west wind, the Santa Ana forms on an east wind.

- To the east of heavily populated southern California are the vast Sonoran and Mojave Deserts. These are some of the driest locations on Earth. In fact, Death Valley is just on the other side of the mountains from Los Angeles.

- The consequence of having very dry air in this region is that an east wind will not carry much moisture as it rises over the San Gabriel Mountains. Just like with the chinook winds, the downslope flow of the air into the Los Angeles basin will dry, and compression will cause the air to become warmer.

- But this is an extremely dry wind that many locations never experience. Relative humidity levels fall to single digits. Vegetation is forced to evaporate the water in its leaves, stalks, and bark. The slopes of the San Gabriel Mountains turn into a tinder box. A single unattended campfire, a lit cigarette, or a lightning strike will set this dry vegetation ablaze.

- Wildfires in southern California put tens of millions of people at risk. The Santa Ana winds can spread the flames faster than firefighters can manage. Homes are burned to the ground in minutes, fueled by the oxygen-rich winds from the west. Hundreds of thousands of acres can burn before the fire can be contained and extinguished.

- Even if you live far from the fire, the Santa Ana winds will carry the smoke over the Los Angeles metropolitan area and quickly degrade the air quality.

Rain Shadows

- The polar regions on Earth are always dry. This is because the air is so cold that it simply cannot contain much water vapor. Tropical regions on Earth have the opposite problem. High temperatures combined with ample vegetation and warm ocean surfaces provide a continual source of evaporation.

- The reason some regions are so dry, even though they are in the tropics, is because of rain shadows, which form when a large mountain chain blocks the persistent flow of the atmosphere.

- The Atacama Desert is one of the oldest deserts on Earth. It is also the driest location on Earth, outside of the extremely cold polar regions. Even though it is very close to the Pacific Ocean and the Amazon Rainforest, some meteorological stations in this desert have never measured rainfall. Humidity levels in some parts of the desert rarely exceed 10%.

» The Atacama Desert is the result of a dual rain shadow. To the east of the desert are the Andes Mountains, with peaks climbing 10,000 to 20,000 feet. To the west is the Chilean Coastal Range. These two mountain ranges effectively block moist air from entering the desert except on the rarest of occasions.

» Mountains squeeze moisture from the air. When warm, moist air is forced to ascend over a mountain, it will cool as it rises. This process leads to the production of clouds and eventually precipitation. But all of this happens on the windward side only.

» By the time the air reaches the leeward side, more than 75% of the moisture is lost. The taller the mountain chain, the drier the air will be on the other side. What is left is not enough to produce clouds and precipitation.

» The Atacama is surrounded by mountains and is therefore in a geographical bowl that only faces leeward slopes. This is the same process that also makes Death Valley so dry in California.

Monsoons

» The wettest places on Earth are nestled into the windward side of large mountains. The Indian monsoon is one of the most important atmospheric circulations on Earth. Billions of people are dependent on its strength and timing. When it arrives late or when it is weak, hundreds of millions of people suffer. When it arrives early and is strong, hundreds of millions of people suffer.

» Monsoons are large-scale wind circulation patterns that are the direct result of contrasting land and ocean temperatures. Monsoonal circulations are called thermally direct circulations.

- Every summer, heat builds in central Asia. This large landmass benefits from long days and more direct sunlight and heats up quickly. In contrast, the waters in the Indian Ocean to the south are much cooler.

- The result is that atmospheric pressure lowers over the warmer continent while higher air pressure resides over the surrounding oceans. The temperature contrast produces a pressure gradient that results in a wind flow pattern that flows onshore.

- The Indian monsoon typically starts in June as the heat builds in Russia and Mongolia. Indians anxiously await the return of southerly winds. This air is full of water vapor that builds into clouds and rain over the subcontinent.

- The real show occurs along the foothills of the Himalayas, the tallest mountain chain in the world. When the warm, moist air is lifted over its slopes, tremendous amounts of rain fall. Floodwaters fill rivers and reservoirs, and snow builds on the peaks of the mountains. This rain is the lifeblood of the billions that live along the Ganges and Brahmaputra Rivers.

- On the other side of the Himalayas, a vast rain shadow forms the desert highlands of Tibet and the Gobi Desert in northern China.

- The United States also experiences a monsoon. It starts in late summer and persists through early fall. Driven by the same thermally direct circulation, frequent thunderstorm activity erupts during this time of year, increasing the risk for flooding and wildfires.

- Even though the monsoon is associated with so much adverse and destructive weather, without it, these regions could not support agriculture, ranching, and the large cities that dot the western United States.

Avalanches

- » The western United States has a distinct dry season, and April through December is normally very dry. By contrast, during the wet season of January through March, meteorologists in western states watch for the development of the Pineapple Express, a branch of the subtropical jet stream. It is an atmospheric river that connects Hawaii to the mainland.

- » Research has shown that during the rainy season, up to half of the total precipitation in the west comes from atmospheric rivers. They are called "rivers" because they carry lots of moisture, but also because their clouds appear on satellite as a narrow band that flows across the world's oceans.

- » When an atmospheric river sets its sights on the West Coast of North America, incredible amounts of rain and snow can fall.

- » Mount Rainier is often the first large obstacle that one of these atmospheric rivers encounters. Given its enormity and 14,400-foot elevation, this mountain can receive 10- to 15-foot snowfall events each time it finds itself the target of this persistent flow. When this occurs, there is a high risk for avalanche.

- » Avalanches occur when large masses of snow slide down a mountain. They can be triggered by winds, but avalanches can also be due merely to heavy snowfall, shifting snow, or a thaw-freeze cycle. Worldwide, there are an estimated 1 million avalanches each year.

- » The type of avalanche depends on snow conditions. At high elevations, the temperatures are often cold enough to support fine, powdery snowfall. As feet of snow pile up, the additional snow becomes unstable along the mountain slope and begins to slide—pulled toward the valley by gravity.

- Powder-snow avalanches race downhill at speeds that can exceed 100 miles per hour. The air is filled with what looks like white dust.

- Midwinter thaws can create a different type of avalanche event called the slab avalanche. The top few inches of snow may melt when warmer air spreads over the mountain during the thaw. When the temperatures fall again, the melted snow refreezes as a sheet of ice. New snow that falls has a difficult time bonding with this ice surface. Additional snow will pile up and suddenly slide all at once down the mountain as a huge slab.

- Avalanche fatalities have been increasing since records have been kept, rising to a little less than 30 deaths per year in the United States alone, and about 5 times that many worldwide. More than 2000 avalanches are recorded each year in Colorado alone.

DANGER AFTER AN AVALANCHE

Don't assume that once an avalanche happens, all is suddenly safe. The Colorado Avalanche Information Center reports that about 70% of avalanche fatalities happen within 4 days of a previous accident.

SUGGESTED READING

Avalanche.org, "Avalanche Safety."

Phillips, "The Coldest Place in the World."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 16, p. 273–288, and chap. 17, p. 289–303.

QUESTIONS TO CONSIDER

1. Why are chinook winds and Santa Ana winds so warm and dry?

2. Can you explain why the wind direction is pivotal in the location of a rain shadow?

LECTURE 16

Ice Storms: Freezing Rain Takes Over

The term "severe weather" typically conjures up images of tornadoes, lightning, hurricanes, and hail, but weather-related risk goes far beyond the chance of getting hit by a tornado. Wet pavement leads all weather categories for car accidents and deaths. But snow, sleet, ice, and slushy pavement cause more than a half million car accidents and claim nearly 1900 lives per year in the United States. With these numbers as a backdrop, it is clear why so much research has been put into understanding how ice storms form—the topic of this lecture.

Supercooled Water

» A freezing rain event requires supercooled water, which is water that has a temperature below its freezing point, 32°F or 0°C, but is still in its liquid phase.

» Why does supercooled water exist? For water to change phase and become ice, it must lose enough energy so that the molecular movements and vibrations become weak enough to not break a hydrogen bond. When water is in its liquid form, it is constantly making and breaking hydrogen bonds with neighboring water molecules.

» A hydrogen bond forms when the positively polarized hydrogen atom from one water molecule bonds with the negatively polarized oxygen atom of another. When the water is in liquid form, this bond does not last long, due to higher energy content of the molecules, which provides enough force to break the bond.

- A pure liquid water droplet will maintain enough energy to keep breaking these bonds until its internal temperature reaches −40°F. At that point, the molecules have lost so much energy that once a bond is created, it will remain, even in the absence of impurities. It is this point that pure water forms an ice crystal.

- Ice crystals are all 6-sided. This is due to the angle that hydrogen bonds with the oxygen. It takes 6 water molecules to complete one crystal.

- To get liquid water to freeze into ice at temperatures warmer than −40°F but colder than 32°F, impurities are needed to help the water molecules lock into their hydrogen bonds and form the lattice structure of ice.

- Just as impurities in the air serve as condensation points for water vapor to condense and form liquid water, liquid water needs impurities called ice nuclei to transform into ice. The role of an ice nucleus is to align a water molecule in such a way that the next hydrogen bond it creates is permanent.

- Once a few water molecules lock into this structure, others follow suit and ice crystals grow rapidly. This phase change leads to a cooling of the water through the release of latent heat to the surrounding environment.

- How does the atmosphere produce supercooled water, and how does this supercooled water lead to the formation of freezing rain?

- The structure of the temperature profile of the lower atmosphere is key in predicting a freezing rain event. There are 3 ingredients we are looking for in the temperature profile of the atmosphere just above the surface, in the lowest 3 kilometers of the troposphere. We need precipitation falling as snow in a subfreezing layer aloft. Beneath this layer, we need a deep layer of above-freezing air. Finally, we need a shallow surface layer of subfreezing air.

» Starting from the surface, temperatures are a few degrees below freezing, but a strong temperature inversion causes warming with height. A deep melting layer with temperatures above freezing forms before temperatures start to cool with height again. A cloud that forms above this temperature inversion will produce snow.

» Roads, trees, and power lines all have a temperature below freezing because they are in the shallow surface layer of subfreezing air. As the supercooled water hits these surfaces, it freezes on contact. The frozen surfaces serve as the nucleation point. Each drop builds a thicker and thicker icy glaze.

» Freezing rain can form without melting layers. Some clouds are shallow enough that the coldest parts of the cloud are warmer than –10°C to –15°C. This temperature range is important because ice nuclei—the impurities that help water freeze—are really only effective at temperatures below about –15°C.

» A shallow stratus cloud in winter can produce light freezing rain or freezing drizzle even though the entire temperature profile is below 0°C. This cloud is made of supercooled water, and as its precipitation falls, it freezes on contact with the ground.

» The difference between freezing rain and freezing drizzle is the size of the drops. Drizzle drops range in diameter from 0.1 millimeters to 0.5 millimeters. Drops larger than 0.5 millimeters are considered raindrops. While both situations produce ice accumulations, the melting process for freezing rain causes most large ice storms.

Low-Pressure Systems

» Winter storm systems in the midlatitude regions on Earth have a predictable precipitation type pattern. In the Northern Hemisphere, weather around a low-pressure system circulates in a counterclockwise direction due to the spin of the Earth. In the Southern Hemisphere, winter storms like this spin clockwise.

» In the winter, this circulation draws air from several different regions and forces it to gather in one place. Cold air is drawn south from Canada, where it meets warm, dry air that is drawn out of the southwestern United States. Warm, moist air is pulled into the mix from the Gulf of Mexico. It is this air that provides most of the moisture for the precipitation. Finally, cooler air is drawn in from the northeast.

» It is the overlapping of these air masses that creates such a wide variety of precipitation types.

» A mature winter storm has 4 primary sectors: a cold, dry sector; a warm, dry sector; a warm, humid sector; and a cool, humid sector. Different types of precipitation fall within each sector.

» Storms form in the south. Heavy rain falls to the east. This rain transitions to freezing rain and sleet as we progress north, and finally into snow. This transition from rain to freezing rain to sleet to snow happens near the warm front of the winter storm.

» The warm front of the winter storm is the result of warm, humid air that pushes north on the strong southerly winds in the warm sector. This air meets cooler air that flows from the east into the low-pressure center. When they meet, the warm front forms, and the warmer air, being less dense, rides over the top of the cooler air. The warm front is defined by advancing warm air, so the cooler air is actually retreating.

» This process is typically slower than the southward-advancing cold front because the warm air tends to slide over the top of the cooler air, rather than abruptly forcing it to move to the north. Meteorologists call this overrunning, and it is overrunning that gives us the variety of precipitation types. The determining factor in each type of precipitation near the warm front is the depth and presence of the melting layer.

» Warm-frontal freezing rain events are the most common weather pattern for freezing rain events in the Great Plains and Midwest. Occasionally, a very shallow cold front can also produce a band of freezing rain in this region. Cold Canadian air can slide south into the United States behind a cold front and quickly drop surface temperatures below freezing.

» Often, a band of precipitation forms on this front. The cold air will undercut and lift a band of warmer air. This warm pocket of air becomes sandwiched between the cold surface air and cold air aloft. A narrow band of freezing rain will form along the cold front.

» Living on or near mountains can also create the ideal temperature profile for freezing rain. Cold air can drain into the valleys, while warmer air resides above. If liquid precipitation falls into the cold air that has drained into the valley, it may supercool and freeze on contact.

» The Appalachian Mountains in the eastern United States are notorious for producing freezing rain events. In winter, cold air can dam itself up against the eastern slopes of the Appalachian Mountains. This air slides southward from the northeast but cannot spread west due to the mountain chain.

- When a developing low-pressure system forms west of these mountains, a plume of warm air is drawn from the east and southeast and ascends these mountains. The problem is that a pocket of subfreezing air is wedged between the warm air above and the mountains.

- Just like with the warm front, snow falls into the melting layer, completely melts, and then falls back into the cold air that is dammed up against the eastern edge of the mountains. These events are called cold-air damming events, and cities like Roanoke, Virginia, often find themselves at ground zero for a big ice event.

Ice Storm Safety

- Most ice storm safety involves either automobiles or preparing for power loss. But there are other dangers. Ice storms that hit large cities can present a serious threat to their residents. Ice will accumulate on the sides and roofs of tall builds and break off and fall to the ground. This is just as dangerous as boulders falling from steep cliff faces.

- Be extremely careful as you walk by buildings after an ice storm. Large chunks of ice can fall from the top of tall buildings and crush anything in their path.

ICE STORM WARNINGS

The National Weather Service will issue an ice storm warning for an area if the forecast calls for at least 1/2 an inch of ice accumulation. Just 1/10 of an inch of ice is enough to cause substantial issues with traffic. Even 1/10 of an inch is nearly impossible to drive on, because even the wheels of a large semitruck can't cut through that ice to get to the pavement. At 1/4 of an inch, the weight of the ice becomes so great that it causes damage to trees. If you were to spread just 1/4 of an inch of ice across a large tree branch, it can add hundreds of pounds to the weight of that branch.

- Ice can also shed off of wind turbines. The United States and other countries are rapidly building wind farms, and most turbines are at least 80 meters off the ground. At that height, a large chunk of ice that breaks off of a blade may reach speeds over 100 miles per hour as it falls.

- Ice can also accumulate on large radio antennas and cell phone towers. Ice will shed off these antennas in huge rods and fall several hundred feet. They achieve a speed that is double the speed of a bat swung by a Major League Baseball player.

- When one of the chunks of ice falls on a car, the damage is similar to hitting it with a large, heavy bat with twice the force of a Major League Baseball hitter.

- Although sleet is not as dangerous as freezing rain, because it refreezes before it makes contact with the ground, large accumulations of sleet can cause major problems. Unlike snow, you can't shovel sleet when it accumulates in large amounts because it freezes together.

SUGGESTED READING

Midwest Regional Climate Center, "Ice Storms."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 12, p. 207–222.

QUESTIONS TO CONSIDER

1. What is supercooled water, and why is it a crucial ingredient for an ice storm?

2. How are thermodynamic profiles used in determining precipitation type in a winter storm?

LECTURE 17

Epic Snowfall and the Lake Effect

Very snowy locations all seem to have a few things in common. The main thing is that there is access to plenty of moisture-laden air that is forced to rise over a large physical barrier. The moisture can come from a large lake, a bay, or an ocean, but the most common name for all of these is lake-effect snow. Being downwind from these large bodies of water is key. The physical barrier comes from topography, such as a mountain, ridge, or plateau—something that forces the air to rise. The rising air cools, condensation begins, clouds form, and snow falls. The fixed location of the mountain or plateau with respect to the moisture also focuses the snowfall more intensely into one location.

Lake-Effect Snow

» If there is one region in the United States where you could routinely experience epic snowfall events more than anywhere else, it is the region downwind of the Great Lakes. Arctic air passes over these lakes each winter, and each lake is able to create its own snowfall event.

» Some downwind locations receive over 200 inches (more than 16 feet) of snow each year from the process known as lake-effect snow. Big cities like Syracuse, Cleveland, and Buffalo are well known for their intense lake-effect snow events.

» The Great Lakes are enormous. They contain more than 20% of the world's surface freshwater. They formed at the end of the last glacial ice retreat around 15,000 years ago and are so large that standing on their shores feels as though you are looking across an ocean.

- Water has a very high heat capacity. It takes about 5 times more energy to change its temperature than the surrounding land. The large thermal inertia of the water means that each winter, the water cools at a much slower rate than the land that surrounds it. This physical property results in a much later freezing date for the water compared to the nearby land.

- Lake-effect snow occurs as arctic air flows over a long fetch of unfrozen water.

- Each lake is unique. Lake Ontario is practically ice-free, while Lake Erie is completely covered in ice. This is because of the depth of the lakes.

- Lake Ontario is deep. At its deepest, the waters extend below more than 800 feet, and its average depth is 283 feet. Lake Erie, on the other hand, is quite shallow. Its average depth is only about 62 feet.

- It is the shallowness of the lake that lets it freeze over first. When it freezes over in the winter, the lake-effect snow process shuts down. The ice blocks the transfer of heat and moisture into the atmosphere, acting like a lid on the lake. As a result, lake-effect snow can fall all season in Syracuse because of its proximity to Lake Ontario.

- Cleveland, being located near Lake Erie, usually experiences lake-effect snow early in the winter. By February in a cold winter, most of Lake Erie is frozen over.

- How do the lakes create their own snow? It all begins with a large ice-free lake and arctic air.

- Arctic air is a necessity. The temperature of this air must be cold enough that the contrast in temperature between the air and lake is large enough to destabilize the lower atmosphere. If the difference is not at least 18°F, lake-effect snow will likely not form.

» For most of the winter, the ice-free parts of the lake maintain an above-freezing temperature of 33°F to 40°F. Meanwhile the air temperature needs to be at most 15°F to 20°F—and, ideally, the air will be even colder.

» In North America, lake-effect snow is most common on the eastern and southern shores of the Great Lakes. This is simply due to the fact that getting air cold enough to create lake-effect snow will need to come from Canada, which is to the west and north of the lakes.

» The lake-effect clouds form several miles from the windward shore. Cold air blowing across land must deal with a lot of surface friction. Air that runs into trees, vegetation, houses, and buildings and changes in elevation is forced to move slower than it would if the surface were smooth.

- When the air hits the lake, everything smooths out, and the wind picks up speed. This forces the air to diverge and spread out near the windward side of the lake. Diverging air near the surface forces air to descend from above to fill in the void. Air must come down from above, and by doing so, it clears the skies.

- Clouds only form in rising air because sinking air warms by compression, which evaporates the clouds. The key in forming the lake-effect clouds is to destabilize the air just above the lake. Heat and moisture are transferred from the lake into the cold air. Pockets of warm air form and quickly become warmer than the air that surrounds them.

- Just like with thunderstorms, cumulus clouds form and rise because they are warmer than their surroundings. This is the destabilization process that must occur to get the lake-effect snow to start.

- The cumulus clouds are not very tall. At their highest, they are 3 to 4 kilometers in altitude. But, just like a thunderstorm, these clouds contain a lot of moisture.

- The best lake-effect snow events occur when the air gets to spend a lot of time over the lake, whether because the distance across the lake is long or because the winds are slow. Meteorologists carefully monitor the wind direction and speed because it will determine where and how much lake-effect snow can be produced.

- As the clouds build in depth and start to snow, the greatest snowfall amounts happen within 50 miles of the shoreline. The longer the air is able to spend over the lake, the greater the amount of heat and moisture it will pick up. This leads to greater amounts of snow that are able to push farther inland. It's all about the fetch, the distance traveled across water.

Types of Lake-Effect Snow

» Lake-effect snow organizes into 3 primary modes. Each mode is dependent on the orientation of the wind with respect to the shape of the lake.

» Wind-parallel bands form when the wind crosses the long axis of the lake in a perpendicular fashion. A west or northwest wind will blow perpendicular to the long axis of Lake Michigan and create several rows of lake-effect clouds.

» The clouds appear in rows because of the dynamics of rising air. When air rises in one location, it must sink in another to fill the void left by the rising air. Rows of lake-effect cumulus clouds form with clear air in between them.

» Meteorologists that forecast for cities downwind of Lake Michigan, such as South Haven or Kalamazoo, have a very difficult time predicting just how much snow will fall in each location. If one of the bands never moves over your location, you will get no snow. Just a few miles down the road, there can be more than a foot of snow that accumulates in just a few hours.

» The same winds that cross over the long axis of Lake Michigan blow parallel to the long axis of Lakes Erie and Ontario. Rather than numerous small bands of snow forming, this configuration produces a single intense shore-parallel band of snow. Cities like Buffalo, New York, are all too familiar with this type of lake-effect snow.

» The meteorology behind the shore-parallel band begins with the orientation of the wind. Blowing along the long axis of the lake produces one narrow band of rising air that forms in the center of the lake. As this air rises, a circulation develops that creates a land breeze along the shoreline.

- A land breeze forms when air flows from the land over water. In this case, the land breeze enhances the lake-effect snow band by causing convergence in the center of the lake. This converging air rises and fuels the lifting of the clouds, making them deeper.

- The eastern shores of Lakes Erie and Ontario have sharp rises in elevation. Lake-effect snow is greatly enhanced by this rise. The plateaus force the air to converge at the surface and rise faster into the lower atmosphere. The clouds grow deeper and produce more snow.

- Forecasting the exact position of a shore-parallel lake-effect snow band is extremely difficult because the narrow bands of snow can move throughout the day. Getting it right is vitally important for some of North America's largest cities.

- Lake-effect snow squalls can sometimes take on the shape of a small hurricane; these are called vortices. While they don't produce hurricane-force winds—not even close—they do share a few of the same characteristics.

- For example, cloud bands will feed into the center of the vortex, where low air pressure resides. An eye often forms near the center, too. Besides the much slower winds, these vortices are really small; most range in diameter from 10 to 50 miles.

- They typically form near the shoreline, where horizontal wind shear can produce small eddies, or circulation patterns, in the winds. The lake-effect clouds adopt this wind pattern and stretch it vertically as the clouds rise.

THE WIND FACTOR

While we often think of snow as being the most dangerous part of a winter snowstorm, there is one other facet of some winter storms that is far more perilous: the wind. If you ever get caught in a blizzard and can't find shelter, you should bury yourself in the snow. The snow can provide protection from the wind and offer a chance of survival.

» Most lake-effect vortices dissipate as they reach the shoreline, where the friction of the land weakens the vortex, and it fades into the background flow of the wind.

Large Winter Storms

» Large winter storms are capable of producing extremely heavy snow events. While they can match the snowfall rates of several inches per hour, they can't match the snowfall totals achieved by lake-effect snow events. The primary difference is that the snow bands that form in a winter storms are transient—they move with the system.

» Winter storms can, however, produce fine-scale bands of intense snowfall. This is accomplished through a process called deformation. In winter storms, the heaviest snow forms to the northwest of the low-pressure center. In this region, strong frontogenesis—the process by which a weather front is made—occurs, forcing the air to rise rapidly and produce copious amounts of snow.

» On the back side of a low-pressure system, strong northwest winds 1 to 2 miles above our heads flow into the low. They are met by warm, moist air in the wraparound region of the cyclone. Both sets of winds collide and diverge.

» At the axis of deformation, the temperature gradient is squeezed very tightly, and air is forced to rapidly rise on the warm side of the front. It is in this region that the most intense snow falls.

» There is another control in the amount of snow the atmosphere can produce. The total amount of moisture available to the winter storm is key in predicting just how much snow will fall, but snowfall rates are also a function of the air temperature.

» If we fix the amount of moisture in the air, we can see how temperature impacts snowfall amounts. The colder the air becomes, the more powdery the snow it will make. Snow that falls when the temperature is near freezing tends to be a "wetter" snow.

» The snowflakes aggregate together, forming large but wet and sticky flakes. When they hit the ground, they easily compress under their own weight. When snow falls in really cold air, the snowflakes resist aggregation and can fall as individual crystals.

» When they pile up on the ground, the snow is light and fluffy. This is because the ice crystals are small and completely frozen—unlike the wet flakes that fall when the temperature is closer to freezing.

» To predict the snow depth from a winter storm, meteorologists use a liquid-to-snow ratio. On average, 1 inch of rain will produce about 10 inches of snow. If it is really cold, and the snow is therefore especially light and fluffy, this ratio can expand to be 1 to 15 or even 1 to 20.

SUGGESTED READING

Laskin, *The Children's Blizzard*.

Niziol, Snyder, and Waldstreicher, "Winter Weather Forecasting throughout the Eastern United States."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 13, p. 223–235.

QUESTIONS TO CONSIDER

1. Why are locations that have the greatest annual snowfall amounts near a large body of water and also mountainous terrain?

2. Lake-effect snow rarely occurs on a southerly wind across the Great Lakes. Why is this?

Blizzards and Winter Cyclones

Blizzards can attack a region with overwhelming force. These large winter storms are the parent storm systems for a wide variety of severe winter weather—from freezing rain and ice, to whiteout conditions and blizzards, to severe thunderstorm outbreaks. These fierce winter storms are common all over the world in the midlatitudes, and even with advanced notice, their impact is inevitable and destructive. But why do blizzards form? What controls their strength? How predictable are they? This lecture will answer these questions.

Blizzards

» All blizzards share a few things in common. The following are the 4 criteria the National Weather Service uses to issue a blizzard warning.

1. There must be falling or blowing snow.
2. The winds must be at least 30 knots or 35 miles per hour.
3. Visibility must be reduced to 1/4 of a mile or less.
4. The first three criteria must be forecast to last for at least 3 hours.

» A brief, heavy snow squall that causes a temporary whiteout does not qualify as a blizzard because it does not last long enough. Snow doesn't have to be falling from the sky to make it a blizzard, either. Ground blizzards occur when freshly fallen snow is picked up by the wind, creating whiteout conditions. This type of blizzard can happen on a clear, sunny day.

HOW TO SURVIVE A BLIZZARD IF YOU ARE STRANDED IN YOUR CAR

If you live in a region that is occasionally impacted by blizzards, being prepared can save your life.

Keeping a blizzard survival kit in your car is very important. In the kit, keep a few bottles of water and some high-calorie food, such as granola bars or nuts, in a plastic bag in your trunk. Keep a few blankets and hand warmers in there, too, as well as a flashlight and a small shovel. Most importantly, have a fully charged cell phone with you at all times.

Always keep your gas tank above half a tank. Should you get stuck in a blizzard, you are going to want to use the engine to keep the heater running so that you don't freeze. Conserve gas by running your engine for a little while, warming up the inside of the car, and then shutting the engine down for a while.

If you become stranded on an open stretch of road and there is no nearby shelter, stay in your car and patiently wait for rescue. Call for help and let them know your location.

You are allowed to leave your car for one reason: to clear away the snow from around your tailpipe. When snow drifts over the back of your car, it can bury the exhaust pipe. The problem is that rather than blowing away with the wind, the exhaust becomes trapped under the car. When you turn on your heater, outside air is drawn into the car. If your car is buried in the snow, the exhaust can recirculate into the car, exposing you to dangerous levels of carbon monoxide. Too much of this can kill you, because it is poisonous to breathe. Check your tailpipe frequently to make sure that the exhaust gases are not getting trapped under your car.

» The National Science Foundation sponsored a research project called Profiling of Winter Storms (PLOWS). In this project, researchers measured in great detail how the most intense bands of snow were generated by thunderstorm-like clouds, with strong updrafts, embedded within the snowstorm. This research helped redefine how winter storms work.

Why Do Blizzards Exist?

» Before the first flake of snow falls, the atmosphere must get set up in such a way that a low-pressure system can form. The flow of the atmosphere must be monitored from top to bottom; it behaves as a 3-dimensional moving fluid.

» At middle latitudes, the jet stream is a key component of this moving fluid. The jet stream is a fast-moving river of air that forms in the upper troposphere, about 6 miles above our heads. It meanders north and south but has a continual flow to the east from the west.

» It is typically found between 30° N latitude and 80° N latitude. It exists here because of our global temperature patterns. It is warm in the tropics and cold in the polar regions. Where our atmosphere is warmer, such as near the equator, it is thicker, top to bottom. Where it is colder, such as near the poles, it is much more compact.

» There is always a sharp boundary where the warm air from the tropics meets the cold air from the poles. The atmosphere on the warm side of this boundary is tall and thick. On the cold side, it is compact. This contrast forces the air to flow from the tall side to the compact side—that is, from the warm side to the cold.

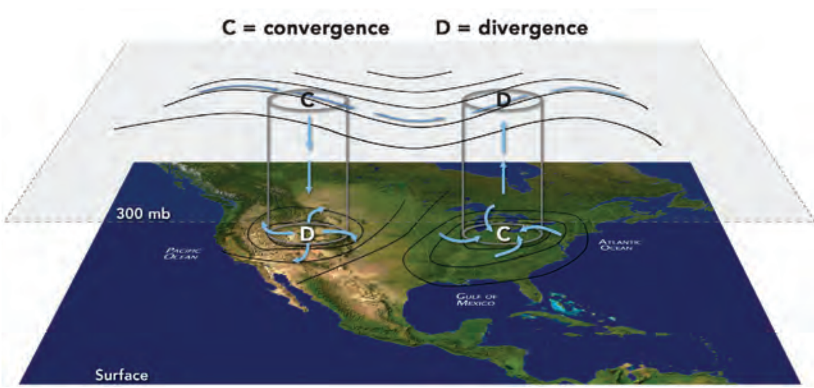
» This is a large, synoptic-scale movement, so as the air flows in this direction, the Coriolis effect, which is caused by the spin of the Earth, forces the air to turn to the right. The greater the contrast between the warm and cold, the faster the air flows above. Therefore, the jet stream, which is the fastest-flowing air in the atmosphere, can always be found above the strongest temperature contrast near the ground.

» Because the jet stream always sits above the strongest surface temperature gradient, the shape of the jet stream can be used to determine if your area will be warm or cold for a given time of year.

» Any time the flow of the jet stream bulges north, this feature is called a ridge. If you find that your location is south of a ridge, it will be warm. This is because the strong temperature gradient is to your north. You are in the warm sector.

» Another feature is called a trough. Troughs in the jet stream form when cold air surges south and pushes the strong temperature gradient toward the equator. If you find yourself in the trough, it will be cold.

» The jet stream has one more capability that is crucial in the formation of a deep low-pressure system. When the air in the jet stream flows between a trough and a ridge, the speed of the air changes. The air typically flows slowly through a trough and quickly through a ridge.



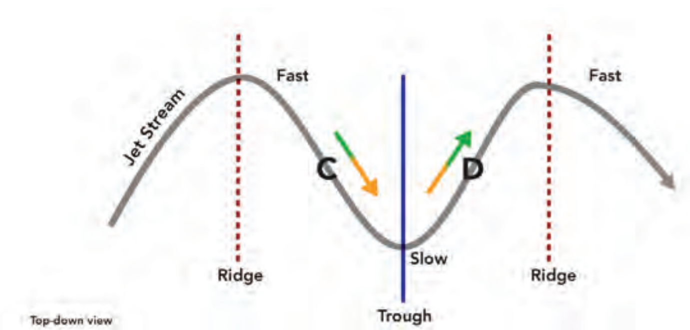
- This means that as the air enters a trough from a ridge, it slows, and as it exits the trough and heads toward the next ridge, it speeds up. Where the air slows down, there is mass convergence. Where the air speeds back up, there is mass divergence.

- If the air is forced to converge aloft in the jet stream, it has one place to go: down. It can't go into the stratosphere because the stratosphere is too stable to let the air rise—so it sinks. The converging of the air into this area leads to the buildup of mass. This in turn leads to the buildup of pressure.

- Underneath the region in the jet stream where the air converges, a surface-based high-pressure system forms. Convergence high in the jet stream forces air lower down in the column beneath it to fill with more air and sink downward.

- As the air pushes against the ground, the air must spread out horizontally. And because this is such a large-scale event, the rotation of the Earth causes the air to also turn to the right.

- This is why large high-pressure systems in the Northern Hemisphere are associated with clockwise-flowing air patterns. The skies are typically clear in the high-pressure column because the air is sinking. Clouds only form in rising air. All of this happens because the air slows as it flows from a ridge into a trough.



» After the air rides through the base of the trough, it accelerates and heads toward the next ridge. On the downstream side of the trough, there is net divergence where air is spreading out as it accelerates. This evacuates some of the air from this region. Air from below attempts to fill this void.

» That forces two things to happen. First, the air pressure falls under this region of jet stream divergence, and a low-pressure system forms. Second, the air rises, forming clouds and precipitation.

» At the surface, the air flows into the low-pressure center directly beneath the region of divergence aloft in the jet stream. This air spirals into the low-pressure center in a counterclockwise flow and converges. Then, it rises, forming clouds and precipitation.

» In the United States, it typically draws air southward from Canada, eastward from the desert Southwest, northward from the Gulf of Mexico, and westward from the North Atlantic Ocean. These air masses collide as they are spiraled into the low, giving rise to the midlatitude cyclone: the winter storm.

The Anatomy of a Blizzard

» Geography plays several important roles in the formation of a blizzard. The Rocky Mountains perform 3 necessary functions.

1 They block warm Pacific air from entering the central United States from the west.

2 They help channel cold air southward from the Canadian Prairies. This air is often bitterly cold due to the very short days in winter in Canada.

3 The Rocky Mountains are high enough to perturb the jet stream as it flows over their peaks. This actually helps to excite waves in the jet stream and enhances the development of low-pressure systems.

- Three of the most common locations for the birth of a low-pressure system—a process known as cyclogenesis—in the United States start just east of the mountains: the Alberta clipper, the Colorado low, and the Ark-La-Tex low. The other two preferred tracks start along land-ocean boundaries and are known as the Gulf low and the Hatteras low, also called the northeaster. The name of each low-pressure track is determined by where the midlatitude cyclone initially forms.

- There are some similarities in all midlatitude cyclone tracks. They start in the west and track toward the northeast, guided by the flow of the jet stream.

- Midlatitude cyclones produce a variety of precipitation: thunderstorms and rain to the south, freezing rain and sleet to the east and northeast, and snow to the north and northwest. The heaviest snow bands are typically found about 150 miles to the northwest of the track of the low-pressure center.

- This region of the midlatitude cyclone is called the wraparound region, which gets its name from how the warm air from the Gulf of Mexico flows north and then wraps itself into the low. This tongue of warm, humid air overrides the warm front and wraps around the back side of the low. It provides the moisture necessary to make the snow that falls in this region.

- Snow by itself is not enough to make a blizzard. The wind needs to reach speeds over 35 miles per hour, and reduced visibility needs to persist for at least 3 hours.

- The fierce winds of the blizzard are supplied by the contrast between the high- and low-pressure systems formed by the jet stream. A strong pressure gradient will develop on the northwest side of the low-pressure system.

- Contrasting air pressure produces a tight pressure gradient and powerful wind. It is because of this pattern that the states with the most frequent blizzards are those that are most often north of the typical low-pressure system tracks. North and South Dakota and Minnesota have the most frequent blizzard activity in the United States.

» East Coast blizzards that form from the Gulf low and Hatteras low have the added advantage of being very close to the warm, moist air of the Gulf of Mexico and Atlantic Ocean. The contrast between the cold Canadian air and the warmth of the ocean along the East Coast produces the perfect situation for the rapid intensification of these midlatitude cyclones known as a meteorological bomb, or explosive cyclogenesis, which is defined as a low-pressure system that strengthens at a rate great than or equal to 1 millibar per hour and continues changing at this fast rate for 24 hours or more.

SUGGESTED READING

Lackmann, *Midlatitude Synoptic Meteorology.*

National Weather Service, "A Retrospective View of the 2011 Blizzard."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather,* chap. 8, p. 137–154; chap. 9, p. 155–170; chap. 10, p. 171–188; chap. 11, p. 189–206; and chap. 15, p. 257–271.

QUESTIONS TO CONSIDER

1. Consider the position and movement of the air in the jet stream. Where is cold air typically found, and where do low-pressure systems form?

2. Blizzards require 4 ingredients. Why is snowfall depth not an ingredient?

Flash Floods and Deadly Moving Water

Water brings life to Earth, but it can also take it away. The often fast-moving waters of a flood are far more dangerous than you realize, until it's too late. Only about 6 inches of swiftly moving water can sweep you off your feet, and 2 feet of moving water can carry away a car. Our survival is determined on how we manage and coexist with Earth's hydrological cyclone. In this lecture, you will learn how too much water impacts our livelihood.

Earth's Water

» Earth is unique when compared to all other planets we have discovered in that it has an active water cycle with large reservoirs of surface liquid water. Globally, the rate at which water evaporates into the atmosphere matches the rate at which it condenses and falls back to the Earth as precipitation. However, the timing, location, and duration of this return varies greatly.

» The atmosphere can support enormous quantities of water. A single small thunderstorm, one that could fit in the corner of a small county, contains hundreds of millions of gallons of water. Flooding can happen when the sky is blue and the Sun is shining, as well. Dams can collapse, and rivers breach their levees.

» We have spent centuries taming and managing Earth's waterways because water is crucial to our survival. But water also has the power to quickly destroy property and claim lives. Our attempts to control the quantity and flow of this dense and powerful liquid are not always successful.

» There are numerous lists of the world's deadliest weather disasters. In the top 10, there are earthquakes and cyclones, but at the very top—claiming tens of millions of lives—are two flood events in China and a famine in India.

» Water is essential for life, but an excessive abundance of water has historically been a weather-related killer just as devastating as lack of sufficient water. And this is not merely in times past, or locations where people are poor.

» National Oceanic and Atmospheric Administration and National Weather Service statistics on the number of fatalities each year in the United States from specific weather events shows that over a recent 30-year period, the number of deaths from floods led this list, at more than 80 deaths per year.

» Since the early 2000s, additional records have been kept for heat, cold, wind, winter, and rip currents. That data shows extreme heat causing a larger total number of deaths during 2006 to 2015, but with flooding fatalities higher in some individual years.

» The number of deaths from floods is greater than lightning, tornadoes, and hurricanes. Additionally, global reinsurance companies provide financial tools to deal with risk associated with weather disasters. The number of global, catastrophic events that are associated with floods each year constitutes more than half of all insured losses.

Flood-Prone Regions in the United States

» The Gulf Coast and East Coast of the United States are subject to flooding events year-round. In fall, winter, and spring, powerful low-pressure systems called Gulf lows, Hatteras lows, and northeasters frequently track along the coastline.

» These systems tend to be the strongest low-pressure systems in the United States. As the central pressure falls, heavy rain and snow combine with fast winds to cause coastal beach erosion, flash flood events, and widespread flooding.

» During the summer and early fall, this same region must deal with landfalling hurricanes. Hurricanes can easily produce more than 20 inches of rain, but when combined with storm surge, floodwaters can inundate coastal communities.

» The Mississippi River and its tributaries drain more than 40% of the land area in the United States. This mighty river's floodplain is extensive, but it is also very fertile. Since the late 1800s, we have dredged and straightened this river and built earthen walls called levees to keep the river's waters from flooding the hundreds of towns and cities that have sprung up along its edge.

» When the Mississippi River floods, millions are at risk. Widespread flooding is slow, but inevitable. Once the river begins to rise, it is only a matter of time before disaster unfolds.

» The southwestern part of the United States is mostly desert. However, even here deadly flooding events are quite frequent. The southwestern United States experiences a monsoonal circulation each summer and fall. The warmth of the southwest and intermountain west drives a thermally direct circulation that brings warm, humid air from the Gulf of Mexico and Pacific Ocean.

» As this moist air rises over the mountains, it cools, and condensation begins building large thunderstorms. The rainfall often results in flash flooding because the desert soils are hard. The rainwater quickly runs off into dry riverbeds, which subsequently flood. People are often caught off guard because it may have been months since they last saw measurable rain.

» The Pacific Northwest, stretching from northern California to Washington State, watches the Pacific Ocean closely during the winter and spring. Atmospheric rivers of high-humidity air that stretch for thousands of miles aim at the Pacific Northwest during their rainy season. Large, persistent plumes of moisture stream off the Pacific Ocean, each capable of producing more than a foot of rain.

» In the coastal mountains, several feet of snow fall. Mount Rainier has been subjected to snowfall events in excess of 12 feet when one of these atmospheric rivers flows into the state of Washington. The most famous atmospheric river is called the Pineapple Express, which gets its name because the source of the moisture is near Hawaii.

» Wind patterns in midlevels of the atmosphere bring this tropical moisture to the Pacific Northwest. Research has shown that more than 50% of this region's total rainfall comes from events like this. Unfortunately, this much rain over such a short amount of time causes intense flooding events.

TURN AROUND DON'T DROWN®

Flood fatalities are frequently associated with people driving their cars through flooded roadways. The National Weather Service launched the Turn Around Don't Drown® slogan to remind people of the dangers of driving over flooded roads. Obeying this rule will save your life.

What you often cannot see when you drive on a flooded road is what has happened to the road's foundation. The water may not look too deep, but the excess water compromises the road structure. The result is that roads get washed out. As soon as you take a heavy vehicle across the road, it may collapse, creating even greater danger for you and your passengers.

» Even the main mountain chains in the United States—both the Rocky Mountains and the Appalachians—are subjected to topography-induced flash floods each year. Rain that falls in mountainous regions quickly flows into the valleys. As the water gathers there, it can pile up and quickly rush through canyons, carrying large boulders mixed with enormous quantities of mud and debris that sweep away vehicles and homes.

» Snowmelt in spring can flood valleys, streams, and rivers that flow through the mountains, making living along these beautiful slopes very dangerous.

Flash Flooding

» Coastal flooding events due to tropical cyclones are one of the most predictable types of flooding. Advanced satellite technology, combined with reconnaissance aircraft and dynamic computer modeling, allows meteorologists to forecast the track of a tropical cyclone with great certainty. Even though these flood events can be well predicted, they can still cause catastrophic damage and claim many lives.

- Major-river-system flooding events are often referred to as slow and leisurely disasters. They are inevitable but very predictable. These flooding events take weeks or months to unfold, but once they begin, there is usually nothing we can do to mitigate the ensuing disaster.

- The United States Geological Survey maintains a vast network of river gauges that are used to monitor flood stage in each river. As the water levels build, this gauge network is used to forecast the depth of the river.

- Warnings are issued if the river is forecast to crest above the height of the levees. These rivers rise slowly over hours or days, giving people that live in the floodplain plenty of time to evacuate. While lives can be saved, property cannot.

- But the good news is that coastal flooding and widespread flooding from large rivers are both predictable. Satellites and sophisticated modeling systems warn us of landfalling hurricanes days in advance. The river gauge network and radar coverage warn us of developing floods on our major river systems. In sharp contrast, flash floods, by their nature, are challenging to forecast.

- Mountainous regions produce the most spectacular flash floods. When flash flooding hits in mountainous areas, climb to safety—never try to outrun the water.

- Thunderstorms are the most common source of flash flooding events. Their ability to support billions of gallons of water in focused, narrow, tall clouds allows them to deposit their rain over a small area.

- Meteorologically, a thunderstorm on a stationary front provides the ideal situation for flash flooding. After all, stationary fronts don't move. These fronts are frequent across the United States and form when cooler, drier air from the north meets warm, humid air from the south. If strength and direction of the airflow on either side of the front produce opposing but equal-strength winds, the front does not move.

» Fronts are focal points for severe weather. They serve as boundaries by which moist, unstable surface air can rise into the atmosphere to create thunderstorms. Along a stationary front, storms often form in succession, where one storm follows the storm in front of it. This is called training.

» Individual storm cells form as the warm, moist, unstable air is lifted over the front. The storms ride along the front. However, the front doesn't move, so they repeatedly form and ride over the same location.

» Large cities carry great risk for flash flooding. Water must be properly managed by drainage and sewer systems. Often, these systems can be overwhelmed. Vegetation and porous soil provide an excellent catchment to manage rapid rainfall events and prevent flooding. Cities have covered that soil with concrete and asphalt and buildings, which are objects that have no water permeability.

» Rainwater collects in the city streets and overwhelms or blocks drainage systems, causing a rapid rise in floodwaters. Floodwater levels can quickly rise, because water has no place to run off or be absorbed. Storefronts on city streets are then inundated with filthy water full of street residue, trash, and waste, causing millions of dollars in damage.

» Some cities have developed clever strategies to manage storm water by planting rooftop gardens and green spaces. Rainwater is prevented from gathering in the streets below because it is soaked into the soil and grass and greenery in place on the roofs of large buildings. These roofs not only manage storm water, but also insulate the building from extreme heat and cold.

- Just like in the city, flash flooding in the desert is often the result of water falling on an impermeable surface. Desert soil becomes hard throughout the dry season. Rainwater cannot absorb into the hardened soil quickly enough and therefore runs off, creating a flash flood.

- Residents in desert regions are frequently caught off guard by these flash floods. Water flowing over the hard ground picks up mud and debris. Together, they flow with incredible force that can easily sweep away anything in their path.

- Desert landscapes are vulnerable because a small amount of rainfall can cause major flooding. Mudslides and landslides can occur on sloped surfaces, where a lack of vegetation has compromised the stability of soil. Trees and plants put down deep roots that act to anchor the soil in place. If the vegetation is destroyed by a fire or drought, the soil is now vulnerable to a heavy rain event. The ground will liquefy and slide at great speed down the sloped surface. In moments, valley communities become encased in mud and debris.

SUGGESTED READING

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 25, p. 475–498.

Scott, "Historic Rainfall and Floods in Colorado."

QUESTIONS TO CONSIDER

1. What makes the desert such a vulnerable place for a flash flood?

2. What weather observation tools would you use to monitor the position and strength of an atmospheric river?

LECTURE 20

Drought, Heat Waves, and Dust Storms

No weather phenomenon has influenced human existence more than drought. From famine to mass migration and war, drought can disrupt human livelihood in ways that other weather events cannot. Drought develops slowly and often goes unnoticed until it has a nation or region so firmly in its grip that there is no escape. In this lecture, you will learn about drought, as well as the related phenomena of heat waves and dust storms.

Drought

- Drought is region-specific and therefore difficult to universally define. What we do know about drought is that it is globally the top weather-related killer. It is also the largest and longest-lasting weather disaster.

- While drought is difficult to define, we can categorize it. Plants are an excellent indicator of drought. Their drought stress signals are easily recognized as changes in their physical appearance and color. Just a few days without adequate water and the plant will show signs of distress.

» Agricultural drought, which is a reduction in topsoil moisture, is often the first type of drought to set in for a region and can be relatively short in duration. Satellites have been designed to monitor for agricultural drought using an imaging technique know as the normalized difference vegetation index.

» From space, satellite imagery of a field is captured using both red and near-infrared satellite channels. The difference in the brightness of these plants between these two channels is an indicator of their health. Normal, healthy plants are very bright in the near infrared. Agricultural drought is detected when there are changes in the plants' reflectance of near-infrared light.

» Meteorological drought is defined as an extended period of time of below-normal precipitation. Precipitation is monitored very closely on Earth using rain gauges, Doppler radar, and satellites. These data can be graphed to see when meteorological drought has formed.

» If the groundwater levels drop or stream and river flow are reduced, then a region is said to have experienced hydrological drought. This kind of drought is often categorized as long term, because it often lasts several months and also takes longer to recover from.

» The worst form of drought is socioeconomic drought, which occurs when water supply is reduced for human consumption.

» The United States Department of Agriculture is constantly monitoring for drought conditions across the United States. Each week, they update the U.S. Drought Monitor, which is a map that uses color shading to determine the severity of a drought.

» The values on the map are calculated regionally using the Palmer Drought Severity Index (PDSI), which is based on a balance of groundwater, surface water, and water supplied by precipitation against evaporation, water use, and runoff. The PDSI was designed to be region-specific and cumulative with respect to time.

» Precipitation patterns along the West Coast of the United States are heavily dependent on the behavior of the ocean temperatures and jet stream across the Pacific Ocean during the winter. Meteorologists constantly monitor satellite animations of water vapor to forecast the transport of moisture into the West Coast of the United States.

» Atmospheric rivers—defined as long stretches of moisture-laden air—stream out of the tropics toward the West Coast of the United States. Nearly half of all precipitation during the wet season along the West Coast is provided by these atmospheric rivers.

» When these atmospheric rivers are diverted north or south of the West Coast, the rainy season is abnormally dry, mountain snowpack is reduced, and reservoir levels drop.

» To end a drought in the West, persistent onshore flow of the jet stream is the key. During an El Niño, it is common to have an active jet stream that routinely flows onshore out West.

» Unlike the West Coast, the eastern 2/3 of the country has its rainy season in the spring and summer. Repeated thunderstorm activity during these months replenishes the water levels in the soil as well as lakes and rivers. If these thunderstorms do not routinely migrate across the Great Plains, Midwest, and East Coast, drought will settle in.

» A drought in the central United States starts when the jet stream, which usually meanders north and south through the spring and early summer, gets stuck in a particular configuration. A common cause for the stagnation in the weather patterns is the development of strong high air pressure in the central-north

Atlantic Ocean, where the semipermanent subtropical high migrates west and strengthens.

» The jet stream responds by producing a large unmoving ridge in the central United States. Ridges in the jet stream generate high air pressure in the lower atmosphere through a process called convergence.

» As air flows through the ridge in the jet stream, it is forced to slow as it enters the downstream trough. As the air slows, it converges and builds the air pressure in this region. The consequence of the convergence forces the air to slowly descend in the atmosphere at this point.

» Descending air warms and clears the skies. The clear skies associated with this high-pressure system permit strong insolation, which heats the surface and dries out the ground. The clockwise surface airflow around the high-pressure system blocks the return of high-humidity air from the Gulf of Mexico. This all leads to hot and dry conditions in the central states. The buildup of heat reinforces the ridge in the jet stream aloft.

» A positive feedback cycle forms, where the outcome of this series of events reinforces what caused them to happen in the first place. A ridge that does not move will continually build higher air pressure. High air pressure leads to clear skies. The airflow around the high-pressure system blocks Gulf moisture. Clear skies allow the Sun's energy to be used to evaporate what little moisture is left in the soil. This dries out the ground.

» Now, all of the Sun's energy is used to heat the soil. The hotter the surface air temperature, the stronger the ridge is aloft. The stronger the ridge, the stronger the high-pressure system. The stronger the high, the greater the heating of the soil. All of this positively feeds back on the development of the drought by sustaining the ridge.

Heat Waves

» Extreme heat often accompanies extreme drought. Although records of deaths due to extreme heat do not go back as far as records from other severe weather events, the deadliest form of weather in the United States over the last 10 years is extreme heat.

» Extreme heat is an elusive killer. It targets people with heat-related illnesses, such as asthma and other respiratory diseases. It targets the very young, who need adults to care for them, and it targets the very old. Older people cannot easily change the rate at which their bodies metabolize food. As a result, heat stress can easily impact their energy levels and dehydrate them.

» Heat waves are often embedded within long droughts. But how long do droughts typically last? There is no real answer to that question. Some droughts can be very short-lived, only lasting a few weeks. Other droughts have no end. Desertification—the extreme deterioration of land in arid or dry subhumid areas due to a loss of vegetation in soil moisture—can change the climate of a location permanently.

The Dust Bowl

» As the United States pushed westward and populated western states, there were several governmental plans that aided in the settlement. One of the most historically impactful plans was the Homestead Act of 1862.

» Essentially, the government was giving away land to settlers in return for farming and taxes. The problem was that farming practices during this time period were rudimentary, and conservation was practically absent.

- Settlers transformed the land west of the Mississippi River into farmland and unwittingly altered the climate of the Great Plains. Deforestation, drainage of swampland, and clearing of grassland took place to farm this region, and settlers were eager to transform the land.

- Following on the Homestead Act, the U.S. government enacted the Timber Culture Act of 1873. The main purpose was to encourage the planting of trees, but part of this act stated, in effect, that all farmers needed to do to guarantee rainfall was to plant a row of trees near their farms.

- From the late 1800s through the 1920s, spells of drought did occur, but for the most part, rain was abundant and farming was profitable in Great Plains.

- With almost uncanny timing, when the stock market crashed in 1929, the rain in the Great Plains stopped, too. The drought was exacerbated by human activity. Decades of poor land management contributed to what became the worst drought in U.S. history. Long-lasting heat waves came through in 1934, 1936, and 1939, setting many records that still stand into the 21st century.

- Advice to farmers during times of little rain and extreme heat was another source of problems. Farmers were told that every time that it did rain during the off-season, they should immediately till their fields. The thought was that by doing this, one could turn over the saturated topsoil and store the water a few inches down.

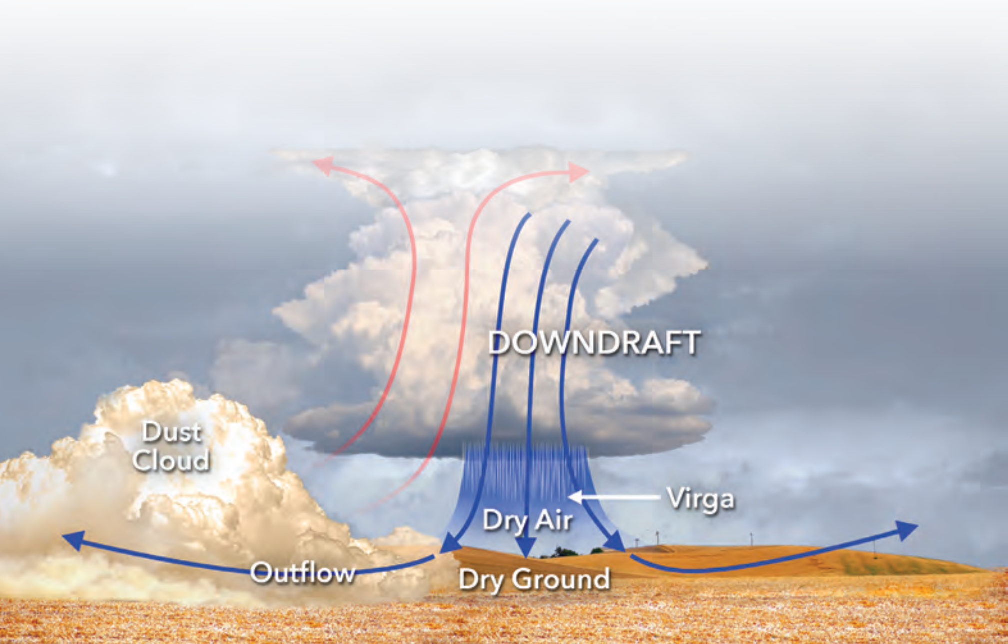
- The problem was that each time the soil was tilled, it broke the soil down into smaller and smaller chunks. After a while, the soil granules were so small that each field looked as though it was covered in a fine dust.

- When the strong winds of the Plains swept over the fields of dry and granulated soil, large dust storms were born. About 2/3 of the nation was in severe drought. Repeated dust storms swept across the land, fueled by the exposed topsoil. They were nicknamed "black blizzards"

- Ironically, most dust storms are caused by thunderstorm downdrafts. During the Dust Bowl, "dry" thunderstorms attempted to bring rain. But the air underneath the thunderstorms was so dry that most of the rain evaporated before it hit the ground. Meteorologists call this virga.

- So, even the thunderstorms of this time were "dry." The downdrafts from "dry" thunderstorms can hit the ground with great force and spread out horizontally, picking up dust as they go.

- Other dust storms formed as large pressure gradients increased the winds across the Plains and formed huge black blizzards. These blizzards of dirt could block out the Sun for hours. Many people died from black pneumonia due to inhaling so much dust.



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National Drought Mitigation Center, "The Dust Bowl."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 26, p. 499–522, and chap. 27, p. 523–549.

QUESTIONS TO CONSIDER

1. Why is there no universal definition for drought?
2. What is the urban heat island effect?

LECTURE 21

Where Hurricanes Hit

Where they strike, tropical cyclones pose one of the greatest of all natural threats to life and property. However, despite their enormous destructive force, on a global scale, they are also an integral part of the Earth's energy balance. They play an important role in the redistribution of heat into the upper atmosphere and into the polar regions. In fact, without tropical cyclones, many regions outside of the tropics would be considerably drier. Tropical cyclones provide the rain necessary to keep these parts of Earth fertile. In this lecture, you will learn how tropical cyclones form and where they are most common on Earth.

Tropical Cyclones

» Tropical cyclones are the general name given to deep low-pressure systems that form over warm tropical waters. In the Atlantic and eastern Pacific, tropical cyclones that achieve sustained winds of at least 74 miles per hour are called hurricanes. Worldwide, about half of the named tropical storms reach hurricane strength.

» For centuries, tropical cyclones in China, Japan, and much of Asia have commonly been referred to as typhoons, a word that originally meant "big wind." Regardless of the name, tropical cyclones have played a large role in human history and, to this day, have an enormous impact on human livelihood.

» Herbert Saffir, an engineer, and Bob Simpson, the director of the National Hurricane Center, developed a scale, called the Saffir-Simpson scale, that used maximum sustained wind speed to measure the intensity of a hurricane.

- In the development of their scale, they used 1-minute average wind speeds as the metric by which hurricane intensity would be categorized. Average sustained wind speed was used instead of wind gusts because the damage caused by the wind is proportional to the square of the sustained wind.

- On their scale, a category 1 strength hurricane will produce sustained winds over 74 miles per hour, while a category 2 strength hurricane will produce sustained winds over 96 miles per hour. A category 3 hurricane will have sustained winds over 111 miles per hour; a category 4 will be over 130 miles per hour. To achieve a category 5 rating, the hurricane must produce sustained winds in excess of 157 miles per hour.

NAMING TROPICAL STORMS AND HURRICANES

The National Hurricane Center first developed a name list for each hurricane basin. These name lists are now maintained and updated by the World Meteorological Organization. The name list adheres to the following rules.

- *Names must reflect the primary languages spoken in the region where the hurricanes occur. So, for the Atlantic basin, those languages are French, Spanish, and English.*
- *The names must alternate male and female, and each year must alternate the sex of the first name.*
- *Names must also be relatively short and easy to pronounce.*
- *The list of names is only 21 names long, because it leaves out Q, U, X, Y, and Z.*
- *Should we exhaust all the names on the list, the contingency plan is to use the Greek alphabet to name hurricanes.*
- *The name list is repeated every sixth year.*
- *New names can be added to the list if a name is retired. Retiring hurricane names is typically only done if the storm was particularly devastating, such that the continued use of its name would be insensitive.*

- Many people assume that only after a tropical cyclone reaches hurricane strength it receives a name, but in fact, tropical cyclones are given their names when they reach tropical storm status, with sustained wind speeds anywhere in excess of 38 miles per hour.

- Even though a large percentage of the global population lives in the tropics along the coastline, many people have never experienced what it is like to live through a landfalling tropical cyclone. As a result, there is a lot of confusion over the size and appearance of tropical weather systems.

- People often confuse them for tornadoes. While both tornadoes and hurricanes spin violently, they do so by entirely different mechanisms and on completely different scales. For perspective, you could put hundreds of tornadoes into the eye of one hurricane, and the eye is just a small fraction, typically about 5%, of an overall storm system whose diameter stretches hundreds of miles.

- Many people who have not experienced a hurricane often think that the amazing cloud structure we see from space using satellite imagery means that these storms produce brilliant and intricate cloud formations when viewed from below.

- Far from displaying intricate or sharply defined cloud features like a supercell might have, hurricanes on the ground are extremely windy, wet, and gray. They are beautiful to see from space, but there is nothing picturesque to witness when a hurricane makes landfall. This is because the cloud structure of a hurricane is wrapped into a large low-pressure system. By contrast, a supercell is a standalone storm system that has easily definable and viewable edges.

- Hurricanes and tornadoes are different in fundamental ways. Tornado structure is easy to see because tornados are small structures that form on land in the presence of sharp temperature and pressure differences in highly sheared environments. By contrast, hurricane structure is difficult to see from the ground because hurricanes are vast structures (far too big to see the whole thing) that form over water in the presence of uniform conditions that lack sharp temperature boundaries.

Where Tropical Cyclones Exist

» On average, there are 80 tropical cyclones that form each year, more than half of which reach hurricane strength, with a sustained wind speed that exceeds 73 miles per hour.

» Tropical cyclones that form in the North Atlantic, Caribbean, Gulf of Mexico, and eastern Pacific are called hurricanes. In the western North Pacific, they are called typhoons, while in the South Pacific and Indian Ocean they are commonly called cyclones.

» The most active ocean basin for tropical cyclone activity is the western Pacific. The Northern Hemisphere has roughly 2/3 of the world's tropical cyclones.

» It is impossible for a tropical cyclone to cross the equator. Tropical cyclones rely on the rotation of the Earth to spin up themselves, and the direction of spin depends on whether it's in the Northern or Southern Hemisphere. As a consequence, it is impossible for one to cross the equator.

» Most tropical cyclones form between 5° and 35° north or south of the equator. It is rare for them to form and survive for much time outside of this region. Less than 5° latitude from the equator and the hurricane cannot spin due to the weak impact the Coriolis force has on air movement here.

» Hurricanes—like all large low- and high-pressure systems—spin because of the rotation of the Earth. This impact is negligible near the equator.

- This is also the reason why a tropical cyclone cannot cross the equator. For a hurricane to cross the equator, it would have to stop spinning, migrate across the equator, and then start spinning in the other direction. As soon as it stops spinning, it collapses on its self; this is why they can't cross the equator.

- Outside of the tropics, the issue is that the cooler sea surface temperatures and stronger winds aloft in the subtropical and polar regions on Earth are not supportive of tropical cyclones. These weather systems thrive on the heat transfer from warm surface water and prefer to exist where the winds surrounding the system are relatively calm.

- It is for these reasons that tropical cyclone development is exceptionally rare in the eastern South Pacific and South Atlantic. These ocean basins have cool surface water and higher wind shear.

Tropical Cyclone Tracks

- In general, these weather systems tend to start in the low latitudes, move to the west, and then curve to the north in the Northern Hemisphere. In the Southern Hemisphere, tropical cyclones take similar tracks, but the curve is now to the south.

- The surface winds on either side of the equator, the so-called trade winds, blow from the northeast on the northern side of the equator and from the southeast on the southern side of the equator. As clusters of tropical thunderstorms erupt in the summer and fall, the northeast trade winds initially steer these storms to the west.

- Near the Lesser Antilles, these winds tend to curve a bit to the north. This occurs due to the clockwise flow of the wind around the large subtropical high-pressure system that is a near-permanent feature in the central Atlantic. This clockwise flow helps to turn the tropical cyclone to the north. As the system shifts north, it is eventually picked up by the westerly wind belt in the midlatitudes and steered back to the east.

» During the heart of the hurricane season, this is the typical configuration of the wind patterns in the North Atlantic Ocean. Tropical cyclones develop in the open Atlantic, Caribbean, or Gulf of Mexico. Then, they migrate to the west and finally make a turn to the north.

» Many times, this curved path causes the tropical cyclone to hit land in the Caribbean, Central America, the Gulf Coast, and the East Coast of the United States. However, occasionally these steering winds are very weak, allowing the hurricane to follow its own path.

» The 2005 hurricane season broke the record for the most named tropical cyclones in the Atlantic in one season with 28 named systems. During this season, records were also set for the number of hurricanes, at 15, and the number of major hurricanes, at 7. Hurricane Wilma set the all-time record for the most intense hurricane in the Atlantic, and Hurricane Katrina became the costliest natural disaster ever in the United States.

Hurricane Seasons

» The start of the hurricane season in the Atlantic Ocean is June 1. On this date, we typically find, for the first time of the year, a large enough area of warm sea surface temperatures to support tropical cyclone formation.

» As August approaches, the number of hurricanes climbs significantly before reaching a peak around September 10. The season slows down through October and ends at the beginning of December.

- Because hurricane strength and timing are directly tied to sea surface temperature, the peak in the season corresponds to the time of year when the Atlantic Ocean has its largest extent of warm surface water.

- Even though summer heat is greatest in June and July, the fact that water takes a longer amount of time to heat up compared to land delays the peak in the sea surface temperatures by about 6 weeks.

- The Pacific Ocean is a bigger breeding ground for tropical cyclones, so although the peak months are roughly the same as for the Atlantic, there are more of them spread across the season. In fact, some parts of the tropical Pacific Ocean can have typhoons at any time of year. So, there is no "off-season" in the western Pacific; typhoons regularly appear there throughout the year, though with far fewer in the winter months in the Northern Hemisphere.

- Of course, the season is reversed in the Southern Hemisphere. For Australia and the southwest Pacific, the season begins by early November, peaks in late February or early March, and ends by early May.

- In the United States, it is exceptionally rare for tropical cyclones to impact the West Coast. The remnants of hurricanes in the eastern Pacific can push northward and impact states in the southwest United States. But cold sea surface temperatures and wind shear prohibit the survival of well-developed storms from impacting the California coast.

- By contrast, the Gulf Coast and the East Coast experience landfalling tropical cyclones that pose a threat to life and property from Texas to Florida to Maine every year.

» The most vulnerable spots in the United States are the Mississippi Delta in Louisiana, the southern tip of Florida, and Cape Hatteras in North Carolina. These three regions jut out into the oncoming path of a typical hurricane track. The broad sweeping bays and coves on each side of these regions are largely protected from a direct hit.

SUGGESTED READING

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Larson, *Isaac's Storm*.

National Climactic Data Center, "Hurricane Katrina."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 24.

QUESTIONS TO CONSIDER

1 What is the typical track of a hurricane, and what forces shape its path?

2 Why do tropical cyclones thrive in some ocean basins and never form in others?

LECTURE 22

The Enormous Structure of a Hurricane

Hurricanes have captivated our attention for hundreds of years. How are such storms even possible? Hurricanes, at their simplest, are deep low-pressure systems. The key to understanding a hurricane is to determine why the air pressure can fall to such incredibly low values so quickly. In this lecture, you will learn about how hurricanes form—in particular, why hurricanes have an eye and what ingredients are necessary to create a hurricane.

Hurricanes as Intense Low-Pressure Systems

» When low-pressure systems form, the air surrounding them tries to fill in the void where the pressure is falling fastest. The air then gathers near the center of the low-pressure area, and as it piles up there, it is forced to rise into the atmosphere. The rising air then expands in size, which causes the air to cool. The cooling of the air leads to the condensation of the water vapor in the air, which gives birth to a cloud.

» The faster the air pressure decreases near the surface, the faster this whole process happens. This is important because at its core, a tropical cyclone is a specific kind of intense low-pressure system.

» When searching for a trigger that will start the development of a tropical cyclone, we need to watch for regions of surface air convergence in the trade winds. Converging air is forced to rise in the atmosphere. Rising air, especially violently rising air, gives birth to tropical thunderstorms.

- The main hurricane development region is in the North Atlantic Ocean. African thunderstorms that form between the Saharan Desert and tropical rainforest can excite waves in the trade winds. These are not waves of water on the ocean, but rather waves in the airflow.

- As the trade winds emerge from the west coast of Africa, they often meander to the north and south. Northward turns in the wind result in a measurable slowing of wind speeds, causing the air to converge. Converging air near the surface leads to rising air, which builds into clouds and thunderstorms.

- The meandering airflow is called easterly waves. Clusters of tropical thunderstorms that form in the airflow of the easterly waves give rise to the conditions necessary to build a tropical cyclone.

- An enormous amount of latent heat is released when these thunderstorms build. Heated air in the atmosphere expands, so the release of latent heat into the atmosphere causes the air pressure to decrease. Changes in pressure are part of the reason why these large clusters of tropical thunderstorms organize themselves into a large circulation.

Why Hurricanes Rotate: The Coriolis Effect

- When objects move on a rotating surface, they will experience forces that they would not experience if the surface were still. Over small distances at low speeds, the effect of a rotating planet is negligible on the path of the object that is moving.

- If the rotation of the planet were not negligible, you would always feel this force, just like you feel gravity. In other words, as you walk around, you would always have to be compensating for the right or left tug of this force just to walk in a straight line. But this doesn't happen.

- However, as the speed of the object increases, the Coriolis effect does play a role in its direction. For example, if a pitcher throws a baseball at 100 miles per hour from the pitcher's mound to home plate, the path of the ball will be deflected almost 1 millimeter during its flight—not much, but it is measurable.

- Increase the speed of the object or the distance it travels through the air even more, and the Coriolis effect is a dominant force in governing the object's path. A hurricane covers a large area and has wind speeds that are very fast. Therefore, the rotation of the planet does have an impact on how and why they spin.

- In the midst of these tropical storms, a great amount of heat is released, and this lowers the air pressure in the center of these storms. The air flows from all around into the area where the pressure is decreasing the fastest.

- However, because this air is covering a great distance as it travels in toward the low-pressure center, the Coriolis effect influences its path. In the Northern Hemisphere, this influence is to turn its path to right. In the Southern Hemisphere, it is turned to the left.

- In a hurricane, air will flow from higher air pressure toward lower air pressure, and its speed will be governed by the difference in the air pressure. Without the Coriolis effect, the air would flow straight into the low without turning. Therefore, the hurricane would never spin.

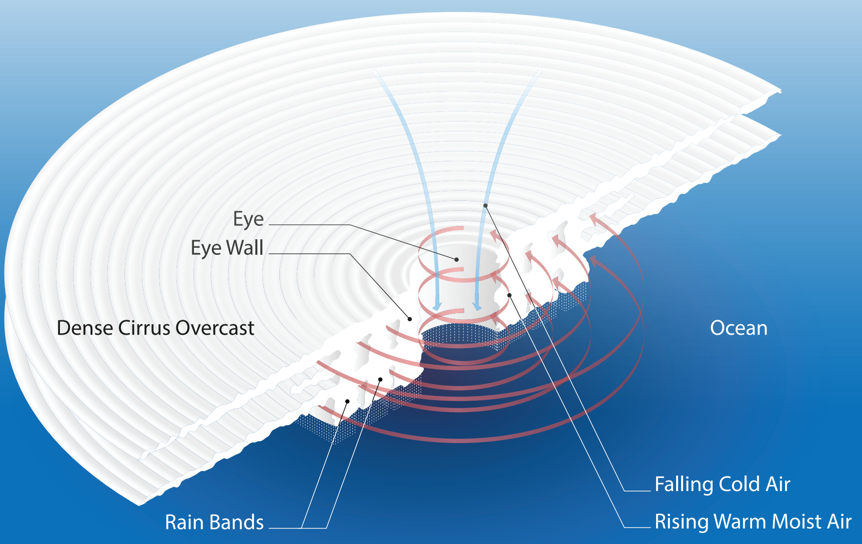
- The Coriolis effect turns the wind to the right in the Northern Hemisphere, making the wind orbit the low-pressure center in a counterclockwise direction. In the Southern Hemisphere, the wind orbits the low-pressure center in a clockwise direction.

The Large-Scale Structure of a Hurricane

» There are 3 components in the large-scale structure of a hurricane. Starting in the middle, a well-developed hurricane will have a relatively clear and calm eye. Surrounding this eye is the eyewall, which is the most violent and powerful part of the hurricane. Feeding into the eyewall are spiral rain bands, which are also called feeder bands.

» Why is the eye of the hurricane clear? To make the clouds of a hurricane, air must ascend and cool. This leads to condensation of water vapor, which forms the basis of a cloud. By this reasoning, the opposite must be happening in the eye of the hurricane.

» In the eye, where the pressure is the lowest and the winds are the calmest, air slowly descends. The vertical change in air pressure has been significantly reduced here, allowing gravity to slowly pull the air down.



» The surrounding eyewall has violently rising air. But in the eye, air is slowly sinking and also warming as it sinks. Warming the air decreases the relative humidity and evaporates the clouds and clears out the eye.

» The most intense part of the hurricane is the eyewall, which contains the hurricane's fiercest winds, torrential rains, and greatest storm surge. This part of the hurricane rarely extends more than 100 miles from its center.

» Identifying exactly where this part of the hurricane makes landfall is crucial for evacuation orders and survival.

» Feeding into the eyewall are bands of rain that are often hundreds of miles long. They are difficult to see from above because the top of the hurricane is often covered with a large shield of cirrus clouds. However, as these rain bands wrap themselves into the eyewall, they too can contain incredibly heavy rain and hurricane-force winds.

FORECASTING HURRICANES

The National Hurricane Center (NHC) in Miami, Florida, is responsible for forecasting the track and intensity of hurricanes in the western Atlantic basin and eastern Pacific. Aiding in this forecast are numerous dynamical forecast models. Each model predicts a slightly different path and intensity. The NHC looks at all of these plots at once and uses the spread in the model, along with the historical forecast error, to produce a forecast track cone.

A hurricane watch is issued when tropical storm or hurricane conditions are possible within 48 hours for a coastal location. A hurricane warning is issued when those conditions are expected within 36 hours.

It is very challenging to accurately forecast the track and intensity of a hurricane. However, forecast track error has decreased significantly since the 1970s, when records began. With increased observations and computing power, forecast accuracy will continue to improve and save more lives in the future.

From a Cluster of Tropical Thunderstorms to a Hurricane

- For a cluster of tropical thunderstorms to evolve into a massive hurricane, it all starts with the sea surface temperature. Hurricanes thrive on heat transfer from the ocean surface. If the temperatures are not warm enough, the hurricane will not form.

- Research has shown that if the skin temperature of the ocean is not above about 81°F to 82°F, hurricanes cannot form. This is why meteorologists seek to measure the sea surface temperature at all times to know exactly when and where hurricane formation is possible.

- Sea surface temperatures are monitored closely using infrared satellite technology along with buoy networks. As sea surface temperature rises, so does the potential strength of a tropical cyclone. Knowing this, many have proposed tactics to try to reduce sea surface temperatures to weaken or even prevent tropical cyclones.

- Although these tactics have been unsuccessful, it's good that people are thinking scientifically about a solution. However, modifying the weather on the scale of a hurricane is nearly impossible.

- Hurricanes thrive on warm water. They extract energy from the ocean surface at an incredible rate, which acts to quickly cool the sea surface as they pass over. If the water just below the sea surface to a depth of about 200 feet is not warm too, the developing hurricane will weaken quickly.

- Hurricanes not only extract a lot of heat from the sea surface, but they also churn up a lot of water from below. They do this with huge waves of water. Some hurricanes can easily produce waves that are more than 50 feet tall. These waves can be very destructive, contributing to what is called storm surge.

- Hurricanes can also be undone by wind shear, which is defined as the change of wind speed and direction with height. Thunderstorms over land thrive on wind shear, but for a developing tropical cyclone, wind shear can easily cause it to dissipate.

- Tropical cyclones must concentrate their latent heat release over a small region to maintain their low air pressure. Wind shear spreads this heat out, which weakens the tropical cyclone. Additionally, wind shear can disrupt the cyclonic flow of the winds, which causes asymmetries in the structure. Essentially, for a tropical cyclone to reach its true potential, the environment around it must be almost calm.

- Wind shear in the Atlantic hurricane basin increases substantially during El Niño events. Hurricane activity in the Caribbean and Gulf of Mexico shows a negative correlation with El Niño. Even though El Niño events form in the Pacific Ocean, a side effect of their formation is to produce higher than average wind shear across the Caribbean and Gulf of Mexico.

- Tropical cyclones spin as a consequence of the rotation of our planet. Cyclones simply do not form without the Coriolis effect. Consequently, if a cluster of tropical thunderstorms stays within 5° of the equator, it has no chance of taking on rotation and thus never evolves into a tropical cyclone.

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Emanuel, *Divine Wind*.

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 24, p. 437–473.

Snodgrass, "Coriolis Force."

QUESTIONS TO CONSIDER

1. Why do hurricanes have eyes?

2. Why do hurricanes spin, and why can they never cross the equator?

LECTURE 23

Storm Surge and Hurricane Intensification

Hurricanes have 4 weapons at their disposal to destroy life and property: storm surge, inland flooding, high winds, and embedded tornadoes. Accurate statistics have been collected in the United States since 1968 and reveal that water—not wind—is responsible for the most fatalities from hurricanes. Historically, wind is responsible for less than 10% of all hurricane fatalities while water is responsible for 80%. And nearly half of all hurricane-caused fatalities can be attributed to storm surge, which you will learn about in this lecture.

Storm Surge

» People who have never experienced storm surge equate the disaster with a tidal wave or tsunami. Tsunamis and tidal waves are caused by non-meteorological events, such as earthquakes and underwater volcanic eruptions. The events materialize as single large waves that crash against the shoreline and push water miles inland.

» Storm surge, by contrast, is the result of persistent windblown water. Storm surge forms as repeated wave action inundates a shoreline slowly over several hours. It does not arrive all at once like a tsunami.

» The wind field of the hurricane is asymmetrical in strength. Northern Hemisphere hurricanes have the strongest winds and therefore greatest storm surge on their right side, where the forward speed of the hurricane adds to the rotational speed of the hurricane winds, producing the fastest winds in the system.

- The hurricane can spend several days moving over open ocean. Sea level rises on the right side of the hurricane as the winds relentlessly push the water forward. With time, the water piles up to heights as much as 35 feet above normal sea level.

- A barometric effect of reducing the air pressure by 10% to 20% in the eye allows the ocean surface to swell up under the lighter weight of the atmosphere compared to the ocean that surrounds the hurricane. The combined effect of reduced air pressure leads to a gradual increase of the water level as measured from the outside of the hurricane into the right side of the eyewall.

- Tsunamis can travel across the ocean at speeds greater than 500 miles per hour, with waves that easily crest over 100 feet. Storm surge moves at the speed of the hurricane, which is typically less than 30 miles per hour. The height of the storm surge is typically less than 30 feet. But it lasts much longer.

- Storm surge occurs over hours or days as wind-driven waves slowly inundate a coastal area. Instead of just a few large and powerful waves, storm surge is the result of a succession of much smaller waves. Each wave is a little bit higher than the one before it.

- The water never has a chance to retreat back to the ocean. The hurricane's persistent and powerful winds prevent the water from sloshing back to the ocean. With time, the water piles up and is pushed farther and farther inland. Storm surge takes hours (or more) to reach its full potential.

- Coastal locations that are impacted by the right side of the hurricane will feel the greatest impact from the storm surge. Timing is everything. The National Hurricane Center (NHC) strives to provide the most accurate landfall time because the natural tidal forces enhance storm surge.

» Coastline geography matters, too. Dozens of the world's deadliest hurricanes have struck the Bay of Bengal, to the east of India, which is the largest bay in the world. This bay also has very warm sea surface temperatures, which are ideal for tropical cyclone development. The worst combination for any coastline is to have the right side of the hurricane make landfall in a bay or inlet at high tide.

Predicting Storm Surge

» Nearly half of all hurricane-caused fatalities can be attributed to storm surge. The NHC has developed two modeling systems to better display and predict storm surge.

» One is the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, which uses the hurricane's size, pressure, track forward speed, and winds to predict the timing, depth, and extent of its storm surge. The SLOSH model accounts for tidal fluctuations and coastline shapes, including barrier systems levees and roads.

» However, its predictions often represent the lower end of storm surge damage, because it is not designed to handle wind-driven waves on top of the surge, additional water from rainfall, or river flow in coastal waterways.

» The second modeling system indirectly addresses those weaknesses by using numerous SLOSH model runs to model a probability distribution of possible storm surge heights along the coastline. This is known as the Probabilistic Hurricane Storm Surge (P-Surge) model.

» The use of these modeling techniques aids officials in creating evacuation orders. They are also used by the NHC to issue advisories, watches, and warnings for coastal residents.

Inland Flooding

» The second deadliest aspect of hurricanes in the United States is from inland flooding due to excessive rain. In fact, even though the windblown waves of storm surge cause more fatalities, the true power of a hurricane lies in its clouds.

» Hurricanes efficiently draw evaporated water into the lower atmosphere. As this air rises, it cools to the point where the atmosphere is saturated. Condensation begins and clouds form.

» The amount of energy required to vaporize a single gram of water is approximately 2500 joules. A typical hurricane is made of about 2 quadrillion grams of vaporized water. This means that the energy content in the cloud field alone of a strong, large hurricane is the equivalent of a 1000-megaton nuclear bomb. But this energy is dissipated much more slowly, which is why clouds don't explode, and most of the water returns to the ground as rain.

» Rain forms in the clouds as the cloud droplets collide and coalesce. Some of the rain forms in upper, frozen levels of the hurricane as ice crystals fall and melt. A typical raindrop is about 1 millimeter in diameter. Large raindrops can grow to 4 or 5 millimeters in diameter.

» Large raindrops have a difficult time surviving as they fall, because they deform and shear apart into smaller drops. Sometimes large drops collide and shatter into dozens of small drops. Regardless of how they fall, hurricanes have the ability to produce a lot of rainfall.

Hurricane Intensification

» Hurricanes require constant monitoring. The rapid intensification of a hurricane can happen in just a few hours, taking a weak hurricane or tropical storm to its severe limits. Rapid intensification occurs when the hurricane's central pressure drops quickly, at a rate of a millibar per hour or faster. This increases the pressure gradient and hurricane winds, causing the hurricane to strengthen and rise on the Saffir-Simpson scale.

» Rapid intensification is often accompanied by a process known as eye-wall replacement, where a new eyewall forms just outside of the original eyewall. As the inner eyewall collapses, the outer eyewall contracts inward. This contraction leads to a strengthening of the winds by the conservation of angular momentum. The contracting eyewall is forced to spin faster as its radius of rotation is reduced.

» Rapid intensification can also occur if the environment surrounding the hurricane becomes ideal for hurricane development.

Embedded Tornadoes

» Some hurricanes are capable of spawning numerous tornadoes. This may sound confusing, but remember that tornadoes and hurricanes form differently—and are vastly different in size. A typical tornado is only a hundred feet wide while a hurricane is several hundred miles wide. Tornadoes can form in the storms that orbit the hurricane.

» It is very difficult to forecast the formation of tornadoes within hurricanes, but statistically, most embedded tornadoes are found in the right-front quadrant of the hurricane as it makes landfall in the United States. This region of the storm favors tornado development due to its wind shear profile at landfall.

» Land has a much higher surface roughness compared with the smoother ocean surface. The result is that winds slow down once part of the hurricane makes landfall. These winds also turn and have a new direction that points more toward the center of the hurricane. Winds just above the surface are not impacted by the surface friction and therefore continue spiraling around the eye in a more circular fashion.

» Vertical wind shear, which is the change in wind speed and direction with height, is formed in this situation. This small-scale wind shear causes the air to form smaller mesoscale vortices. When an updraft in one of the hurricane's storm cells picks up this rotation and tilts it vertically and stretches the rotation, a tornado can quickly spin up.

Seasonal Hurricane Forecasting

» Seasonal hurricane forecasting pushes the boundaries of meteorology. A single landfalling hurricane can cost tens of billions of dollars to insurance and reinsurance companies. Financially preparing for these disasters is a top priority for this industry and many others.

» How predictable is an entire hurricane season? Is it possible to know how many hurricanes there will be months before the season starts? Meteorologists use many forecasting methods to forecast an upcoming hurricane season, but nearly all of them rely heavily on a few key ingredients.

AFTERMATH OF HURRICANE IKE

- Hurricane strength is controlled by the warmth of sea surface temperature. The warmer the sea surface, the greater the heat transfer into the atmosphere, and the more powerful the hurricane can be. Sea surface temperatures are monitored closely using infrared satellites, as well as a network of buoys.

- For years when ocean temperatures are anomalously high, any potential hurricane can extract more energy from the ocean and strengthen. However, sea surface temperatures far from the hurricane—even on the other side of the world—can have a huge impact on hurricane development.

- El Niño events occur when the equatorial Pacific Ocean anomalously warms. When this occurs, global weather patterns shift. Within the Pacific Ocean, near the El Niño warming, the frequency of tropical storms rises in the eastern Pacific.

- But another, more distant, consequence of El Niño is that wind shear in the western Atlantic, Caribbean, and Gulf of Mexico increases above its base state. Hurricanes are weakened by wind shear, so the number and intensity of Atlantic hurricanes declines. Therefore, a change in the sea surface temperatures in the Pacific Ocean, thousands of miles away, alters hurricane development in the Atlantic Ocean.

SUGGESTED READING

Emanuel, *Divine Wind*.

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QUESTIONS TO CONSIDER

1. Why does the right side of a tropical cyclone in the Northern Hemisphere have the greatest storm surge and fastest winds?

2. Why is land management so important for human safety when a hurricane makes landfall?

LECTURE 24

El Niño and Cycles of Extreme Weather

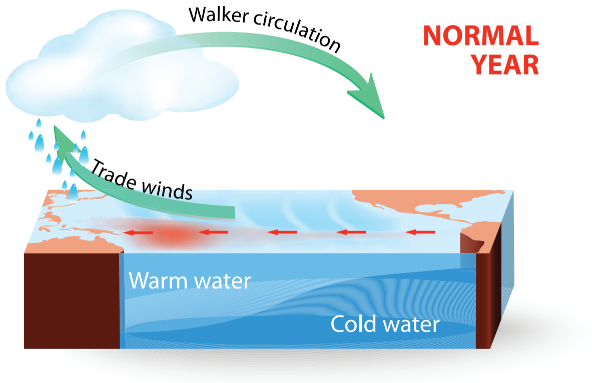
Earth's weather systems are connected. Changes in one part of the world can alter the weather half a world away. The largest weather system on Earth is El Niño. It is sneaky. To an untrained eye, a reduction in Pacific trade winds from east to west and a small bit of warming in the Pacific Ocean don't look like much, but because of this one change in Earth's largest ocean, global weather is disrupted. And new patterns of severe weather appear all over the globe. In this lecture, you will learn about El Niño and cycles of extreme weather.

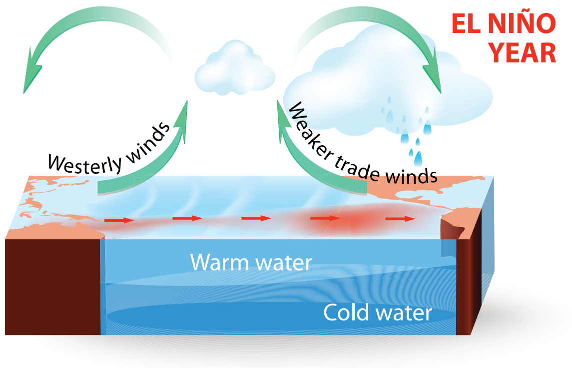
El Niño

» El Niño events are a great example of what are known as teleconnections in the atmosphere. The term "El Niño" dates back to the late 1800s, when Peruvian fishermen began using it to describe the strange warming of the ocean. The fish and birds would leave when the waters warm because the base of their food chain—the cold, nutrient-rich water—was gone.

» The term *el niño* translates from Spanish to English as "little boy." But the El Niño event being discussed refers to a very specific little boy. The periodic Pacific Ocean warming events often peak in intensity during the Northern Hemisphere winter—usually in December. El Niño refers to Jesus Christ, the messiah of the Christian faith, because of its timing with the Christian holiday of Christmas, when the birth of Christ is celebrated.

» When a strong El Niño forms, Peru is not the only place on Earth that is impacted. This event impacts weather conditions globally.





- Meteorologists have studied El Niño events for decades and have discovered that the accuracy of seasonal weather prediction for most places on Earth increases when information about an El Niño event is included in the forecast.

- The winter of 2009 to 2010, which was marked by several major snowstorms in Washington DC, experienced a moderately strong El Niño event. As the warm ocean water appeared in the eastern Pacific Ocean, the probability of major winter storms along the Mid-Atlantic increased.

The Meteorology behind El Niño

» If Earth did not spin, the global wind patterns would be much simpler. As heat builds in the tropics, air would rise and the air pressure would be reduced. This rising air would then spread toward the north in the Northern Hemisphere and to the south in the Southern Hemisphere.

» The flow of the air begins to descend as it reaches the North and South Poles. It will then begin to flow back toward the equator, completing two large loops, one in the Southern Hemisphere and one in the Northern Hemisphere. These large looping circulations are the Hadley cells.

» Earth's spin breaks these cells up into 2 or 3 belts of winds. Each wind belt is defined by a direction and is sandwiched between centers of high and low air pressure. These pressure belts alternate such that low pressure is near the equator, high pressure is in the subtropics, low pressure is again at midlatitudes, and then high pressure is in the poles.

» As a direct consequence of this pressure pattern, winds in the high-pressure tropics flow from the east. Winds in the midlatitudes flow from the west, and winds in the polar regions flow from the east again. This is why weather for people who live in the United States comes from the west; the general circulation pattern is dominated by westerly wind flow, the so-called trade winds.

» Sir Gilbert Walker was a British physicist who, among many other things, applied his field of study to understanding global wind patterns. One of his greatest achievements was in understanding fluctuations in monsoonal airflow over India. While there, he discovered that the strength of the trade winds would fluctuate periodically, especially in the Pacific Ocean.

- Wind is a direct consequence of pressure differences, so Walker paid very close attention to global pressure patterns. His observations lead to the discovery of the Southern Oscillation—a crucial aspect of an El Niño event. This is also why El Niño events are also referred to as El Niño/Southern Oscillation (ENSO) events.

- Earth's atmosphere and ocean operate as a coupled system. Changes in one lead to changes in the other.

- On average, the pressure patterns across the Pacific Ocean are arranged such that two large semipermanent high-pressure systems form off the West Coast of the United States and South America. Across the Pacific, lower air pressure resides over Australia and Indonesia.

- An east-to-west wind will flow along the equator as a result of this pressure pattern. These are the trade winds of the Pacific Ocean. Near Australia, the trade winds converge and rise above the surface low-pressure system. Rising air expands and cools, which leads to condensation and the development of clouds and rain.

- The rising air eventually hits the tropopause and is forced to spread horizontally in the upper parts of the troposphere. Some of this air flows back to the east, over 10,000 miles of open Pacific Ocean. The air begins to sink toward the surface as it nears the high-pressure centers in the eastern Pacific.

- Sinking air compresses and warms, which lowers the relative humidity of the air, and as a result, skies are clear above a high-pressure center. This circulation pattern is called the Walker cell, named after Sir Gilbert Walker. The ocean responds to this atmospheric circulation by flowing in a similar manner.

- The trade winds blow the surface waters to the west. The Sun beats down on this water, and it warms considerably. As the trade winds pile this warm water up in the western Pacific, sea level rises between 10 and 50 centimeters due to the thermal expansion of the water.

- Downwelling of the warm surface waters occurs as the current meets the Australian continent. The current then begins to flow back to the east far below the ocean surface. At these depths, the water is quite cold, but as it reaches South America, the water returns to the surface.

- Upwelling occurs when this ocean circulation brings cold, nutrient-rich water to the surface off the coast of Peru. The gradient in the thermocline, which is the rate of change of the temperature of the water as a function of its depth, is much different in the western Pacific than in the eastern. The warm water extends much deeper in the west compared to the east.

- Much warmer water resides at a greater depth in the western Pacific when the Walker cell is in its normal phase. During an El Niño event, this circulation weakens or is reversed, and the thermocline evens out as the warm water sloshes back to the east. This occurs as the low air pressure that resides over Australia and Indonesia becomes anomalously high, while the high pressure in the eastern Pacific becomes anomalously low.

- Without strong easterly trade winds, the buildup of warm water is allowed to slosh back across the equatorial Pacific Ocean. Long, deep waves of warm water propagate back to the east. These waves are identified as Kelvin waves.

- As an El Niño develops, the trade winds can weaken, stop, and even reverse. Global wind maps show averages, but an El Niño can affect the existence or direction of the trade wind.

IT'S NOT ALL ABOUT EL NIÑO

Using only El Niño and La Niña to forecast the severity of weather is not wise. Earth's atmosphere has many circulation patterns. While El Niño is often the most dominant, other large-scale ocean-atmosphere circulations include the Pacific Decadal Oscillation, the Arctic Oscillation, the North Atlantic Oscillation, the Antarctic Oscillation, and the Madden-Julian Oscillation. All of these circulations work together on a global scale to modulate Earth's weather and determine where extreme weather takes place. Meteorologists are constantly monitoring for changes in each circulation, each of which contributes predictable influences on the weather.

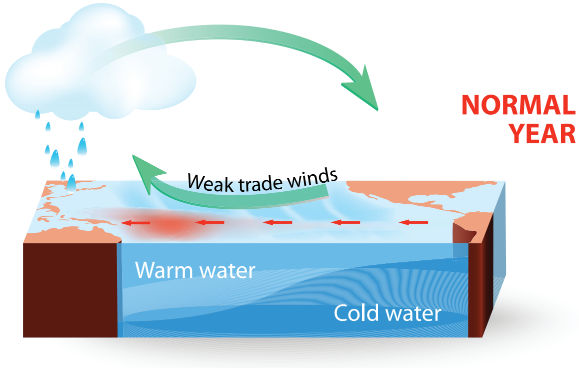
» Strong El Niños have repeated westerly wind bursts, where pulses of winds race from west to east across the Pacific. Monitoring westerly wind burst strength and frequency is a key in determining the strength of the El Niño event.

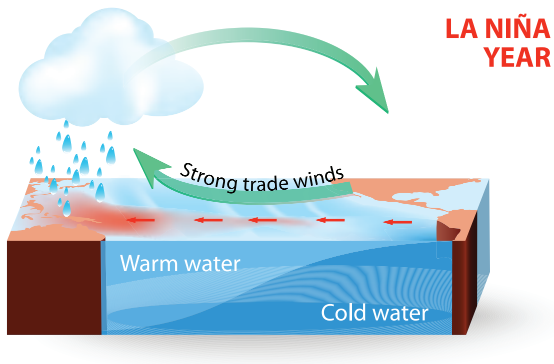
» A telltale sign that an El Niño is occurring is to watch for warm sea surface temperature anomalies. Meteorologists monitor sea surface temperatures across 4 separate regions in Pacific. These regions are called Niño regions 1 and 2, which are near the west coast of Peru; Niño region 3, which encompasses the eastern equatorial Pacific; Niño region 4, which covers the western equatorial Pacific; and Niño region 3.4, which covers the central equatorial Pacific.

» When these waters warm and the trade winds change, the weather changes across 10,000 miles of open ocean. Global weather patterns are connected, and a large perturbation in the Pacific leads to significant weather changes downstream.

La Niña

» El Niño events end when both the atmospheric and oceanic circulations return to their normal patterns. High air pressure builds in the east, and lower air pressure forms in the west, and the trade winds resume their normal westward flow.





» La Niña events occur when the circulation attempts to return to normal but overshoots a bit in the other direction. The trade winds blow anomalously strong, sea surface temperatures in the equatorial Pacific cool rapidly, and upwelling along the South American coastline goes into high gear.

» While El Niño was named by Peruvian fishermen and refers to Jesus Christ, La Niña was named by scientists studying this phenomenon and refers to no one. La Niña events are just as powerful as El Niño events in terms of disrupting global weather patterns.

Global Impacts

- How do El Niño and La Niña impact the weather globally? What changes in the weather should we expect if meteorologists are forecasting the development of an EL Niño? Thousands of peer-reviewed publications have attempted to answer these questions, and the summation of their work reveals wintertime patterns. Regional variability is high, but in general, weather patterns change December through January. Weather patterns can also be affected at other times of the year.

- The two most directly impacted locations are Peru and Australia/Indonesia. El Niño events are notorious for causing major flooding in Peru. The return of warm water to the eastern Pacific lowers the air pressure, and frequent showers and storms build over the region.

- Normally, coastal Peru is quite dry, with most regions receiving less than 30 inches of rain per year. Some locations—such as the capital of Peru, Lima—receive less than 10 inches. The atmosphere is very stable here due to the presence of semipermanent high air pressure.

- During an El Niño, Lima can receive an entire year's worth of rainfall in a single afternoon. Flooding, landslides, and mudslides occur frequently during EL Niño. Agricultural production is severely impacted, as well. Historically, El Niño has had a large and negative impact on the Peruvian economy.

- But El Niño does not have the same effects everywhere. Far across the Pacific Ocean, 10,000 miles away, the opposite weather patterns unfold. El Niño conditions typically bring higher air pressure and clear skies to Indonesia and Australia. Drought often develops on that side of the Pacific. Not all El Niño events create drought in Australia, but historically, there is a high probability of drought when El Niño conditions develop.

SUGGESTED READING

Climate.gov, "El Niño & La Niña."

Rauber, Walsh, and Charlevoix, *Severe and Hazardous Weather*, chap. 23, p. 421–436.

QUESTIONS TO CONSIDER

1 How does an El Niño event impact temperature and precipitation across the United States in the winter?

2 What atmospheric and oceanic features are the best indicators that an El Niño is forming the Pacific Ocean?

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Internet Resources

The following web page, which is housed on the University of Illinois servers, contains recommended links for weather information:
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