Investigations in Weather and Climate

Neel Desai and Alicia Mullens

De Anza College

Geosciences

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Investigations in Weather and Climate

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Neel Desai and Alicia Mullens

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Program Page

De Anza College sits in the heart of Silicon Valley, where innovation and opportunity are part of daily life, and also has one of the highest costs of living in the country. For our students, that makes every dollar count, and the price of a textbook can be the difference between staying enrolled or dropping a class. Our Zero Textbook Cost (ZTC) program closes that gap by giving students full access to high-quality, faculty-created course materials at no cost from the first day of class.

De Anza is proud of its diverse student community, and we hold our ZTC materials to the same standard of excellence that defines the college. Faculty across departments write, adapt, and review these resources themselves, keeping them accurate, current, and grounded in the perspectives of the students who use them, with accessibility and inclusive design built in from the start.

This program reflects the time and care our faculty invest in their students. If you have questions, feedback, or come across any issues with a ZTC resource, contact De Anza College's ZTC Grants Coordinator, Shagun Kaur.

Learn more about De Anza ZTC Program [www.deanza.edu/academic-services/oer/]

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Accessibility Statement

Accessibility

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We selected LibreTexts as our preferred platform because of its commitment to accessibility. In addition to the platform's inherent accessibility, we collaborated with the LibreTexts team to fix any accessibility issues we found.

Our Accessibility Review Process

Accessibility was built into the resource as it was written. This resource went through the following stages of review:

1. **Template check.** The project coordinator and instructional designers checked the first chapter for accessibility as a model to ensure later chapters meet accessibility standards.
2. **Progress checks.** The manuscript was checked at approximately 40%, 60%, and 80% completion to catch and correct accessibility issues in production.
3. **Specialist review.** Once the manuscript was complete, an accessibility expert conducted an accessibility check.
4. **Remediation.** The author and the project manager who conducted the earlier progress checks worked together to remediate the issues identified by the accessibility expert.
5. **Final check.** The resource underwent another full check by the accessibility expert before the book was deemed ready for publication.

This process combines ongoing checks during writing with a final specialist review, so issues are caught early and confirmed fixed before publication.

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- A description of the problem you encountered
- The device, browser, and any assistive technology you were using (e.g., Windows 11, Google Chrome, JAWS screen reader)

Contact us: De Anza ZTC team

This statement was last updated August 2026

This resource was project-managed by **Shagun Kaur**, overseeing scope, budget, and schedule; stakeholder coordination via monthly meetings; training and platform support (LibreTexts, troubleshooting, technical support); QA/accessibility check scheduling; and licensing and copyright governance.

A Note on Known Limitations

No accessibility check is perfect. We've made a genuine, sustained effort to catch and fix issues throughout the writing and review process described above, but some barriers may remain, especially in complex or interactive content. We'd rather be upfront about that than claim a standard of perfection we can't guarantee.

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About the Lab Manual

This **Meteorology Laboratory Manual** is part of the **De Anza College Zero Textbook Cost (ZTC) Pathways** initiative, supporting both students and instructors with free, adaptable Open Educational Resources (OER).

Welcome to the wonderful world of weather! This lab manual provides a brief introduction to some of the applications of material typically covered in an introductory weather and climate course. The authors of this textbook realized during their college days that learning is easier and more fun when it is hands-on rather than just in a classroom. Thus, this manual was designed to provide students with hands-on experience with meteorological diagrams, datasets, and weather maps. This lab manual, along with all the included activities, is designed to be completely stand-alone and can be completed remotely, even outside of a traditional classroom setting. In this manual, you will examine a variety of weather data sources, both provided for you and retrieved independently. The goal is to provide you with an overview of the various tools available to investigate the weather around you.

How to Use This Book

Each Investigation should take about 2-3 hours to complete, which is common for a traditional one-unit introductory Meteorology laboratory course. While we attempt to explain every concept and procedure in depth, we strongly recommend supplementing this material with small demonstrations and mini-lectures. Questions are presented in multiple-choice and short-answer formats to allow maximum flexibility in modality.

Each investigation consists of a combination of multiple-choice and brief problem-solving/plotting/analysis questions. We've designed each component to equate to 25 points, but please feel free to adjust the scale to meet the needs of your course.

Acknowledgments

The authors would like to thank their respective spouses for their infinite patience and support during the writing of this manual. A special thanks also to the ZTC coordinators and the OER team at De Anza College for their guidance during the publication process.

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About the Authors

Information about the authors

Author Images	Author Bios
	**Alicia Mullens** is a Meteorology instructor at De Anza College in Cupertino, CA, and at San Jose State University, in San Jose, CA, where she has lived and worked since 2017. Growing up, Alicia always showed a deep interest in weather, oftentimes dropping anything she was doing to watch the local weather report, or running outside anytime stormy weather was in the area. Parallel to that passion about weather was her passion to tell everyone she knew about it, which led many people to tell her that she should become a teacher someday. During graduate school, she had opportunities to apply her knowledge of the atmosphere to many activities, but she found teaching about it to be her favorite activity. After graduation, she found numerous opportunities to teach various earth sciences, but was thrilled in 2017 to join De Anza as their new Meteorology professor. She holds a Master's degree in Meteorology from San Jose State University, along with a Bachelor of Science in Mathematics and a Bachelor of Arts in Geography from California State University, Long Beach. In her spare time, Alicia loves participating in LGBTQ+ activism, train travel, homebrewing, and spending time with her lovely partner, Jamie.
	**Neel Desai** is a Meteorology instructor at De Anza College in Cupertino, CA, and at San Jose State University in San Jose, CA. He is passionate about Meteorology and Climate Science, and strives to provide an enjoyable in-class learning experience for his students. He believes in a visual and hands-on approach to learning, incorporating multiple videos/in-class activities to keep students engaged. He has experience teaching students at multiple levels, including high school to university bridge programs at the University of Michigan, community college at De Anza, and at the university level, including graduate students at SJSU. Neel received his Bachelor's degree in Mechanical Engineering from the University of Mumbai, India, a Master's degree in Aerospace Engineering from the University of Michigan, Ann Arbor, and a doctorate in Atmospheric Sciences from Michigan Technological University in Houghton, MI. His research interests include cloud physics, turbulence, and remote sensing. Outside of teaching and research, Neel enjoys traveling, hiking, and reading sci-fi novels.

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Licensing

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1: SURFACE AND UPPER-AIR WEATHER

Introduction

The weather is a constant force that shapes our daily lives in numerous ways. Every morning, you check your phone's weather app to decide what to wear today. Do you need a jacket, or is it too warm for it? What about your plans for the day? Do you need a rain check? A sudden downpour may ruin a beautifully planned outdoor wedding or throw a wrench into your estimated commute time. It's no surprise, then, that it remains one of the most common topics for small talk. Have you ever found yourself in an elevator with someone you don't know? You probably smiled and then said something like... "It's hot today, isn't it?" and got a reply saying, "Yeah, it's unbearable! I hear it'll cool down in a couple of days." Discussing the weather is a universal icebreaker—a neutral subject that fosters casual conversation between strangers, colleagues, and friends alike. Some people like particular kinds of weather, like thunderstorms or snow, while others swear they hate all types of weather (Figure 1.1). So, which one are you?



Figure 1.1: Complaining at the weather. (CC BY-NC 4.0; Jono Hey via sketchplanations)

In this investigation, we will explore the fundamentals of weather. We will learn about various weather variables and how to read and interpret weather maps. We will explore the differences between the weather we experience at Earth's surface and what is happening at higher altitudes in the atmosphere. Here are the learning objectives for this Investigation.

Learning Objectives

By the end of this investigation, you should be able to:

1. Explain how weather conditions vary depending on location and time of day.
2. Identify surface weather conditions on a weather map using station models.
3. Analyze upper-air weather data, and compare data collected from a weather balloon launch to the U.S. Standard Atmosphere.

Navigational Note

Investigation 1 has 23 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

1.1: What is Weather?
1.2: Weather Maps and the Station Model
1.3: Precipitation on a map
1.4: The Vertical Atmosphere
1.5: Vertical Atmosphere data charts
1.6: Accessible Descriptions

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1.1: What is Weather?

Geographical Location

The condition of the atmosphere at a given time and place defines weather. It is important to note that weather conditions can vary greatly depending on geographical location and time of day. The weather at the location where you are currently reading this can be vastly different from that at a location a few miles away. Figure 1.1.1 shows temperatures across the San Francisco Bay Area on Thursday, May 1, 2025. The term "Weather" is often used interchangeably with "Climate" during casual conversations. But the two aren't the same. In future investigations, we'll cover Climate in greater depth, but Climate is defined as the "average" conditions of the atmosphere at a location. For now, let us focus on the weather and address the following question.

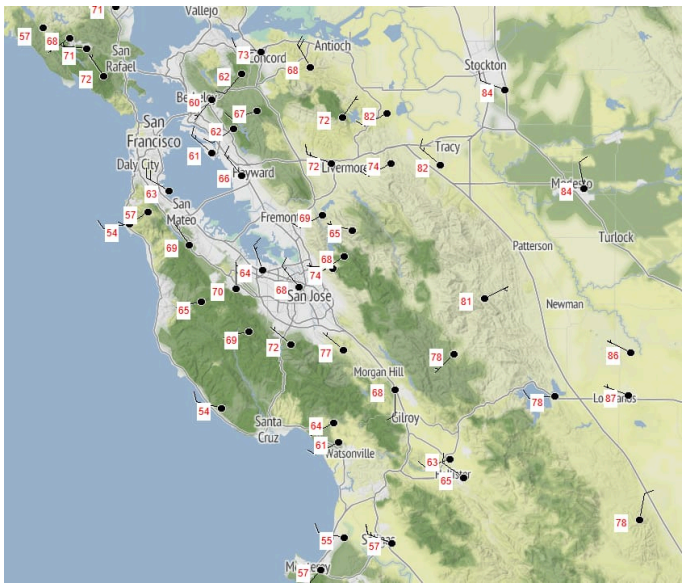


Figure 1.1.1: Weather Conditions for the San Francisco Bay Area at 5:50 pm on Thursday, May 1, 2025. (CC BY-NC 4.0; John Horel via University of Utah. Permission obtained from the University of Utah.) Alternative description of the image.

1. In Figure 1.1.1, we notice that the temperatures across the San Francisco Bay Area at this time:
   a. were very similar everywhere.
   b. varied greatly from location to location, with areas further inland being colder than areas near the coast.
   c. varied greatly from location to location, with areas further inland being warmer than areas near the coast.

Time of day

In addition to varying from place to place, weather conditions vary greatly with the time of day. Open a weather app on your phone. It will not only report the ambient air temperature at that time but also other weather variables, such as Relative Humidity and Dew Point Temperature. These quantities indicate the amount of moisture or water vapor in the air, indicating whether the air is dry or humid. We'll learn more about these terms in Investigation 4, but for now, let's understand how these quantities can vary during the day. Figure 1.1.2 shows weather conditions at San Jose International Airport from July 21 to July 23, 2025.

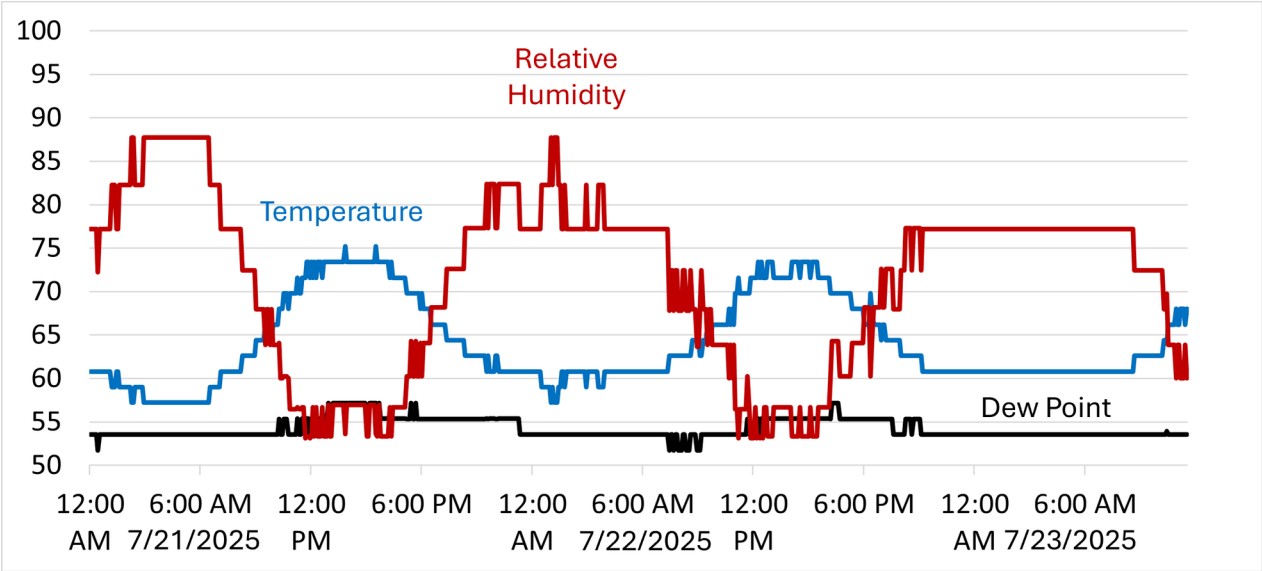


Figure 1.1.2: Surface Weather Observations for San Jose International Airport between 7/21/2025 and 7/23/2025 noon. A simplified version of the data is tabulated in Table 1.1.1 (CC BY 4.0; Neel Desai via NWS/NOAA)

Table 1.1.1: Temperature, relative humidity, and dew point from Figure 1.1.2 at 6-hour intervals.

Date	Time	Temperature (°F)	Dew Point (°F)	Relative Humidity (%)
July 21	12:00 AM	60	54	75
July 21	6:00 AM	58	54	85
July 21	12:00 PM	72	55	55
July 21	6:00 PM	68	55	65
July 22	12:00 AM	61	54	80
July 22	6:00 AM	58	54	88
July 22	12:00 PM	70	55	62
July 22	6:00 PM	67	55	70
July 23	12:00 AM	60	54	78
July 23	6:00 AM	61	54	78

Let us address the following questions based on the information provided earlier.

2. According to the observations in Figure 1.1.2 and Table 1.1.1, all three weather conditions _____ over the 3 days.
   a. did not change much
   b. changed quite a bit

3. In general, air temperature and relative humidity:
   a. were directly related (when one went up, the other went up as well)
   b. were inversely related (when one went up, the other went down)
   c. had no relationship with one another

You may have already noticed that, as you go about your daily life, the ambient air temperature is often cool in the morning and at night, whereas it is warmer in the afternoon. Figure 1.1.2 confirms your suspicions. It shows that weather conditions vary with the time of day.

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1.2: Weather Maps and the Station Model

Weather Maps

While the previous questions focused primarily on changes in temperature over time/place, there are numerous weather conditions that Meteorologists are concerned with. There is more to weather than just temperature! In fact, here are some of the other weather conditions commonly measured at weather stations:

- Humidity (Relative Humidity, Dew Point Temperature, etc)
- Cloud Cover
- Precipitation (Type and Amount)
- Wind (Direction/Speed)
- Barometric Pressure
- Other weather events (such as Fog, Smoke, Thunder, Tornadoes, etc).

Most weather stations measure most, if not all, of these conditions. The data is then distributed and presented in many ways to Meteorologists and to the public. One of the key ways weather data is presented is through weather maps. Meteorologists want to gain as big a picture of the weather (both locally and nationally) as possible. Thus, they need to view as much data as possible. There are many ways to do this, including using multiple weather maps, each showing a single weather variable (temperature, wind direction, wind speed, etc.). However, that would quickly become very cumbersome. Imagine having to toggle between six or seven weather maps to get a decent picture of the region's overall weather. Trying to view ALL weather data on a single map can also cause problems due to data cluttering. Weather maps provide a happy medium between too many maps and too much data on a single map. At first, a new reader may feel overwhelmed by the amount of information on a weather map. Meteorologists use these maps daily and have years of experience interpreting the data they display. So make sure to take it slow, since we're just starting our journey.

Figure 1.2.1 is a weather map displaying data collected across the United States at 2200 UTC (3 pm Pacific Time, 6 pm Eastern Time) on June 26, 2020. Before moving on, take a moment to consider the different weather parameters from the previously mentioned list and how they can be represented on the map.

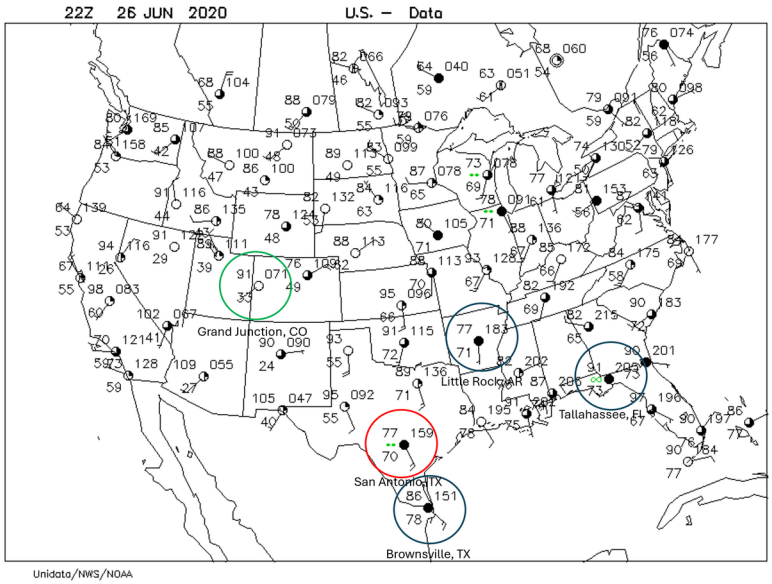


Figure 1.2.1: Weather Data for Continental United States at 2200 UTC on June 26, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of the image.

The Station Model

In Figure 1.2.1, you'll notice that the map is filled with many small circles, with some degree of shading, numbers on both sides of them, and barbs or flag poles sticking out of them. These symbols, called “Station Models,” provide a convenient way to display large amounts of weather data in a straightforward, user-friendly manner. It’s better than flipping between numerous weather maps or listing all the data from each weather station next to it in tiny font. It may take you a few minutes to get used to the station model data, but using the guide in Figure 1.2.2, you’ll quickly become comfortable with decoding it.

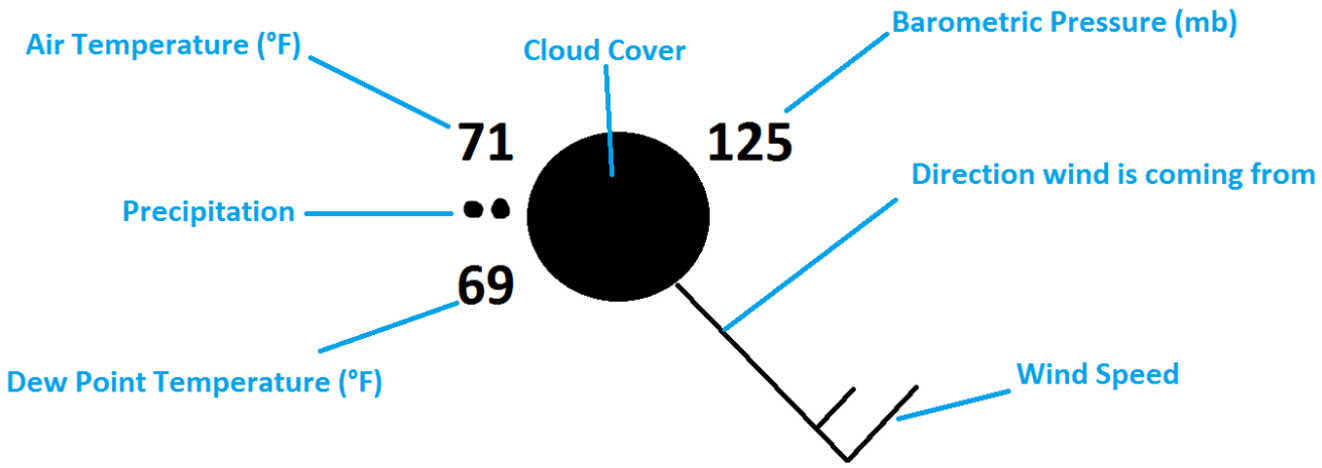


Figure 1.2.2: The Station Model Guide showing air temperature (°F), dew point temperature (°F), symbols for precipitation, barometric pressure (mb), wind direction, wind speed, and cloud cover. (CC BY 4.0; Alicia Mullens) Alternative description of image.

Let’s take these one at a time: Figure 1.2.2 shows the different components of a station model.
The left side: Air Temperature is shown in the upper left, and Dew Point Temperature is shown in the lower left.

4. Go back to Figure 1.2.1. The observed air temperature at San Antonio in central Texas is:
   a. 77°F
   b. 159°F
   c. 70°F

5. The observed Dew Point temperature at San Antonio is:
   a. 77°F
   b. 159°F
   c. 70°F

Notice that the two numbers on the left side are separated by a series of dots representing precipitation. An excellent guide to precipitation symbols can be found in Figure 1.2.3 and Table 1.2.1.



Figure 1.2.3: The NOAA convention showing precipitation type and intensity on a station model. Table 1.2.1 presents a condensed version of the salient features from Figure 1.2.3 in tabular form. (Public Domain; Station Model via NOAA/NWS)

Table 1.2.1: Precipitation symbols on a station model and their meaning.

Symbols	Meaning
One, two, or three solid dots in a column	Rain (light, moderate, heavy)
One, two, or three asterisks in a column	Snow (light, moderate, heavy)
A lightning bolt with a dot or asterisk	Thunderstorm (with rain, snow, or no precipitation)
An inverted triangle with a dot or asterisk	Shower (rain or snow)
Two short apostrophe-like marks	Drizzle
Curved lines resembling the number 2	Freezing rain or freezing drizzle
Triangle with a dot	Ice pellets or sleet
Two or three stacked horizontal bars	Fog (thin or thick)
Infinity symbol	Haze

6. Going back to San Antonio in Figure 1.2.1, the two dots along the station model indicate that _____ is occurring at this time.
   a. snow
   b. rain
   c. hail
   d. fire and frogs

The Middle: The circle in the middle of the station model represents cloud cover. The circle is shaded according to the amount of cloud cover currently over the station. The more shaded-in the circle is, the cloudier the sky is. A guide to cloud cover shading can be found in Figure 1.2.4 and Table 1.2.2.

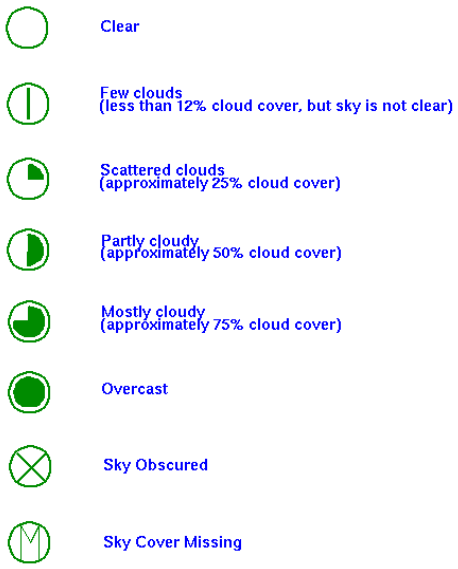


Figure 1.2.4: The NOAA convention showing cloud cover on a station model. Table 1.2.2 presents a condensed version of the salient features from Figure 1.2.4 in tabular form. (Public Domain; Station Model via NOAA/NWS)

Table 1.2.2: Cloud cover symbols on a station model and their meaning.

Symbol	Sky Condition Description
Open circle	Clear sky
Circle with thin vertical line	Few clouds (less than 12% cloud cover)
Circle one-quarter filled	Scattered clouds (approximately 25% cloud cover)
Circle half-filled	Partly cloudy (approximately 50% cloud cover)
Circle three-quarters filled	Mostly cloudy (approximately 75% cloud cover)
Completely filled circle	Overcast (100% cloud cover)
Circle with an "X" inside	Sky obscured (e.g., fog, smoke, or heavy precipitation blocking visibility)
Empty circle with question mark	Sky cover missing (data unavailable)

Based on this information, let's try to answer the following questions.

7. At the time of Figure 1.2.1, the cloud cover over Brownsville in southern Texas is approximately:
   a. clear
   b. partly cloudy
   c. mostly cloudy
   d. overcast

8. Along the Gulf Coast and in the southeastern United States, most stations _____ experiencing varying amounts of cloud cover.
   a. are
   b. are not

9. For example, Brownsville in southern Texas, Little Rock in Central Arkansas, and Tallahassee on the Florida Panhandle are all experiencing _____ skies.
   a. clear
   b. partly cloudy
   c. mostly cloudy
   d. overcast

The long pole with feathers sticking out of the center circle represents Wind Direction (the pole) and Wind Speed (the feathers at

the end of the pole). Wind direction refers to where the wind is coming *from*. This is different from typical convention, where the direction of movement is often determined by where something is *headed* instead. Thus, the long pole points toward the direction of the oncoming wind (similar to a needle on a compass). For example, at Bownsville, TX, the wind is blowing *from* East-Southeast since the long pole is pointing right and slightly down.

10. The wind at San Antonio, TX in Figure 1.2.1 is coming *from* the:
    a. north-northeast
    b. south-southeast
    c. west-northwest

The feathers at the end of the pole have nothing to do with wind direction. Instead, they indicate wind speed. One long feather represents a speed of 10 kts (knots, or nautical miles per hour... 1 kt = 1.15 mph... knots are commonly used in Aviation, Sailing, and other travel/trade related industries), while a short feather represents 5 kts. The short feather is always placed slightly away from the end of the pole to make it easier to differentiate from the long feathers. The total number of feathers represents the wind speed. For example, in Figure 3, Brownsville's station model had one long feather and one short feather, representing a speed of 15 kts. In contrast, in Amarillo, TX, the furthest-north station in the Texas Panhandle, had two long feathers, representing a speed of 20 kts.

11. The wind at San Antonio in Figure 1.2.1 has a speed of:
    a. 5 kts
    b. 10 kts
    c. 15 kts
    d. 20 kts

Sometimes, the wind is calm (meaning there is no wind blowing), and when that occurs, it will be denoted by a circle surrounding the station's circle. In general, the winds over the continental United States (excluding Alaska and Hawaii) can be represented using the long and short feathers mentioned previously. However, sometimes the winds may be so strong that an additional symbol, a triangular pennant (representing 50 kts), may be necessary and is placed at the end of the pole.

The Right Side: While some station model guides may include various information (such as pressure trends and accumulated precipitation), we will focus only on the three-digit number in the Upper-Right side, which represents Sea Level Air Pressure. This is the air pressure the location would have at Sea Level, accounting for its altitude. Air Pressure is another standard weather variable that your phone's weather app will show. Air pressure is the force exerted by the weight of the air above a given area of the Earth's surface. Think of our atmosphere as a giant ocean. But instead of water, it is filled with air. If you've ever tried to swim along the bottom of a swimming pool, you may have felt the higher water pressure near the bottom. That's the weight of the water above pressing down on you. Similarly, as we live on the floor of the great ocean of air that is our atmosphere, the weight of the atmosphere presses down on us each day, and we call it air pressure. We'll learn more about air pressure in Investigation 6.

Like other weather quantities, such as temperature and relative humidity, air pressure varies with location and time of day. Thus, to identify locations of high/low pressure and other weather systems (such as fronts), every surface map is calibrated to sea level (to remove the influence of elevation on air pressure). At sea level, average pressures typically range between 950 millibars (mb) and 1050 mb. However, this number can become large and cumbersome, considering how complex the map already appears. So Meteorologists often abbreviate it in a station model by removing the first digit (or the first two digits). To convert the three-digit number to an actual sea level pressure, a two-step procedure is needed:

Step 1: Focus on the 3-digit number:

- If the 3-digit number is LESS than 500, place a 10 in front of it.
- If the 3-digit number is EQUAL to or Greater than 500, place a 9 in front of it.

Example: The number 149 on the right side would be converted to 10149 by placing a 10 in front, and 549 would be converted to 9549 by placing a 9 in front.

Step 2: Place a decimal (".") between the last two digits: Air pressure doesn't vary much at sea level, so Meteorologists want to notice the slight differences to identify variations. As a result, they commonly round air pressure numbers to one decimal place. Example: 10149 would be converted to 1014.9 mb, and 9549 would be converted to 954.9 mb. It is important not drop any of the digits. Keep and work with all three of them, including 0. So 071 is not the same as 71.

12. Returning to San Antonio, the sea-level pressure at San Antonio at the time of Figure 1.2.1 is:

a. 159 mb
b. 915.9 mb
c. 1015.9 mb
d. 115.9 mb

13. On the other hand, Grand Junction, in Western Colorado, has a “071” in the upper-right corner of its station model, indicating a pressure of:
    a. 71 mb
    b. 907.1 mb
    c. 1071 mb
    d. 1007.1 mb

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1.3: Precipitation on a map

Doppler Radar

Precipitation (rain, sleet, snow, hail, etc.) is an important part of weather and is often considered by people as they go about their daily lives. As such, it's very important to identify where precipitation is located on a weather map, so that you can figure out if there is any in your area. As indicated in Figure 1.2.1, the only station in Texas reporting precipitation is San Antonio, TX. This could lead to a potentially misleading interpretation that precipitation is isolated to the region. Thus, we need to rely on more than just station reports to identify where precipitation is occurring.

While we'll cover the details of precipitation in greater depth in a separate investigation, weather stations can detect precipitation over a larger area using Doppler radar data. Many weather stations have a Doppler radar that emits a pulse of energy into the air, which is reflected off precipitation and returned to the station. The properties of the "reflected" energy (called an echo) tell us about the location, movement, and intensity of precipitation. The data is then plotted on a map, like Figure 1.3.1, where irregular shadings of blue/green/yellow/red represent precipitation. Blue and green indicate light precipitation; yellow indicates moderate; orange and red typically indicate heavy precipitation, including thunderstorms.

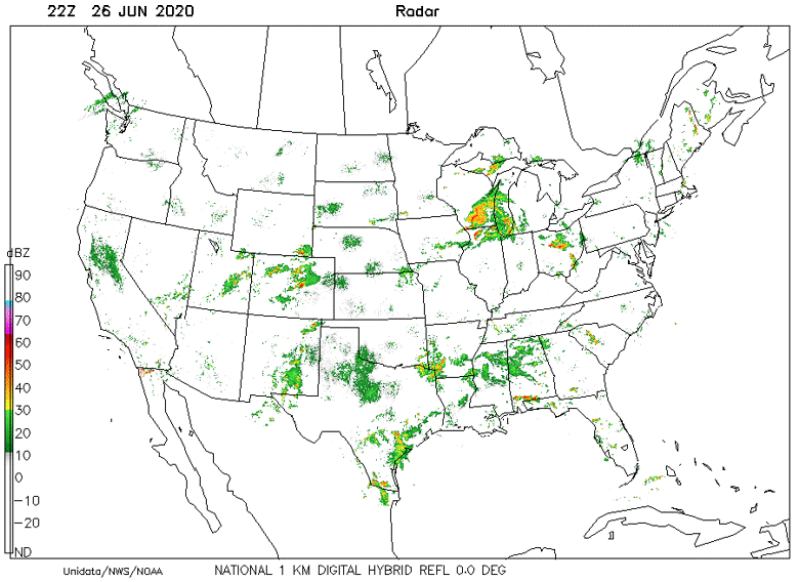


Figure 1.3.1: Doppler Radar detected precipitation for 2200 UTC on June 26, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

14. Based on Figure 1.3.1, Doppler radar echoes indicate that precipitation ____ present over/near San Antonio, in central Texas.
    a. is
    b. is not

15. Additionally, widespread precipitation is also occurring in:
    a. The Texas Gulf Coast
    b. Southern California
    c. Northern Illinois and Southern Wisconsin
    d. All of these locations
    e. All but b

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1.4: The Vertical Atmosphere

Upper-Air Data

The previous section demonstrated the variation in weather conditions, such as air temperature and precipitation, near Earth's surface. However, as we continue this course, you will also learn that surface weather conditions depend greatly on upper-air conditions. As a result, Meteorologists need to observe changes in weather conditions as we move upward through the atmosphere. To gain context of this upper-air data, let's first understand the basic structure of the atmosphere, as shown in Figure 1.4.1 and Figure 1.4.2. Table 1.4.1 provides a summary of the salient features of Figure 1.4.1 and Figure 1.4.2.

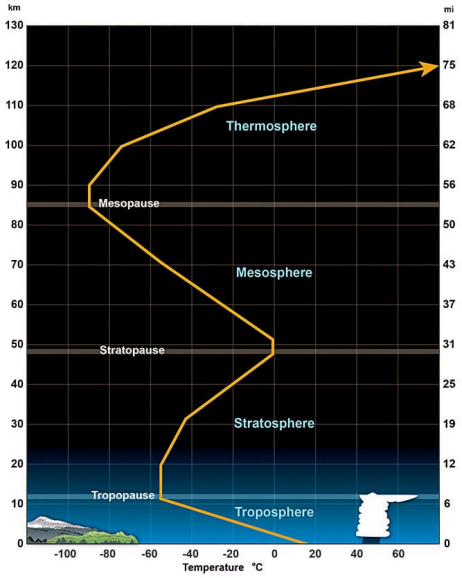


Figure 1.4.1: Vertical profile of temperature in the atmosphere and atmospheric layers. (Public Domain; Layers of the Atmosphere via NOAA).

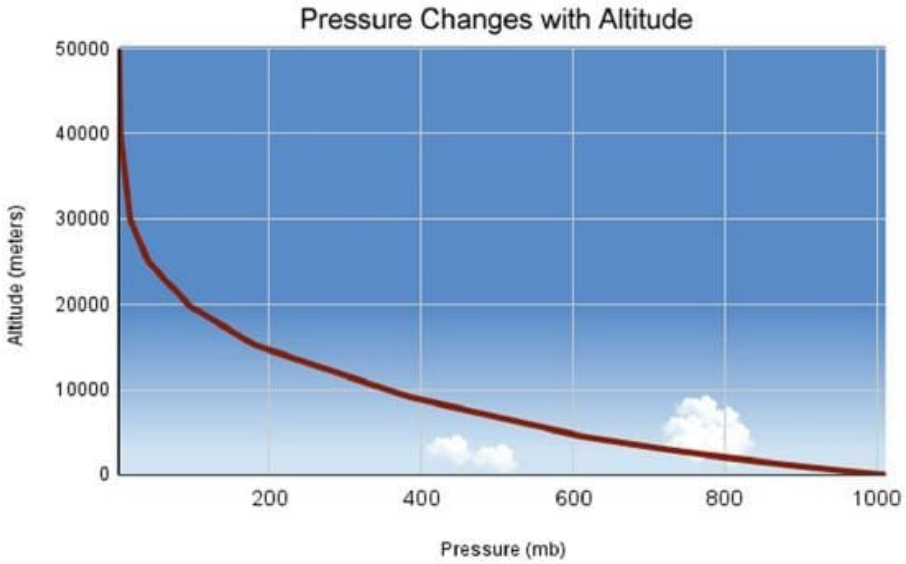


Figure 1.4.2: Vertical profile of pressure in the atmosphere. (Public Domain; Pressure change with Altitude via UCAR)

Table 1.4.1: Variation in air temperature and pressure with altitude in the atmosphere.

Altitude (km)	Pressure (mb)	Temperature (°C)	Atmospheric Layer
0	1013	15	Troposphere
5	540	-17	
10	365	-56	Tropopause
15	160	-56	Stratosphere
20	55	-44	
25	27	-33	
30	12	-15	
35	7	-6	
40	4	-2	Stratopause
50	1	-2	Mesosphere
60	0.2	-25	
70	0.04	-50	
80	0.007	-90	Mesopause
90	0.002	-90	Thermosphere
100	0.0005	-75	
110	0.00005	-30	
120	0.00001	65	

Using this information, investigate how the temperature and pressure change with height in our atmosphere, as you answer the following questions.

16. Air Pressure ____ with height in the atmosphere:
    a. increases
    b. decreases
    c. does not change

17. However, the relationship between air temperature and height _____ as you move from one layer to the next.
    a. does not change
    b. changes

18. The top of each layer is called a “pause.” For example, the top of the troposphere is called the Tropopause. As suggested in Figure 1.4.1 and Table 1.4.1, what happens when you reach any of the “pauses” in the atmosphere?
    a. The temperature "levels off" (it stops decreasing or increasing).
    b. The temperature suddenly increases.
    c. The temperature suddenly decreases.

19. As a result, an excellent way to identify the tropopause would be to identify:
    a. Where the temperature stops decreasing.
    b. Where the temperature stops increasing.
    c. A sudden, sharp decrease in temperature.

While the previous figures and the table provide a basic representation of the “average” atmosphere, the vertical structure of the atmosphere varies greatly from place to place. Therefore, we cannot rely on the “average” atmosphere to determine real-time conditions in the upper atmosphere. Instead, we must make direct observations. We do this by collecting Upper-Air Data through weather balloon launches.

Weather Balloons

Every day at 0000 UTC and 1200 UTC, observers across the United States—and, in fact, around the world—launch weather balloons into the atmosphere at the same time. Attached to each of these weather balloons is an instrument pack called a Radiosonde (Figure 1.4.3). As the balloon rises, the radiosonde collects data on numerous weather variables that we measure at the surface, such as temperature, dew point, air pressure, wind direction, and wind speed, and relays them to a computer on the ground. These weather balloons can rise as high as 100,000 feet (about 30 km).



Figure 1.4.3: A LMS6 Radiosonde instrument. (CC by-SA 4.0; Famartin via Wikimedia Commons)

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1.5: Vertical Atmosphere data charts

Stüve Diagrams

As the weather balloon ascends, the radiosonde continuously collects weather data. This data is then plotted on numerous diagrams for Meteorologists to interpret. Throughout this course, we will examine additional weather data and many diagrams that help analyze it. For this investigation, we will focus on upper air temperature profiles. One of the most effective diagrams for plotting upper air temperature data is the Stüve Diagram, which plots temperature as a function of pressure or altitude. In Investigation 5, we will learn more about other features of the Stüve Diagram, but for now, Figure 1.5.1 shows a blank Stüve Diagram.

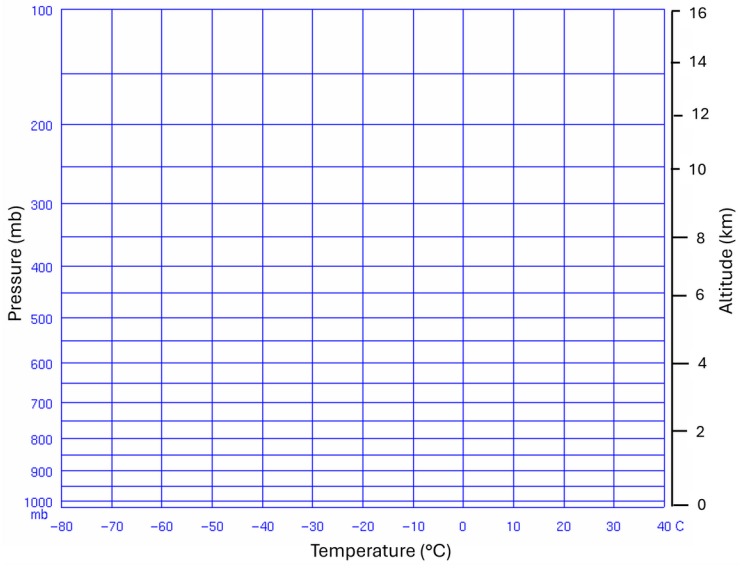


Figure 1.5.1: A blank Stüve Diagram with Temperature on the horizontal axis and Pressure and altitude in the vertical. Temperature ranges from -80°C to +40°C in 10°C increments; Pressure (mb) ranges from 1000 mb at the bottom to 100 mb near the top; Altitude (km) ranges from 0 km to 16 km, aligned with the pressure levels. (CC BY-NC 4.0; Steve Ackerman via University of Wisconsin)

Data collected from a weather balloon launch with a radiosonde is called a "sounding". Table 1.5.1 shows radiosonde data collected over Tampa Bay, FL, on January 10, 2025. Sounding data in a tabular form typically consists of two columns: atmospheric pressure and the corresponding temperature measured by the instrument at that pressure. We use pressure rather than elevation because Meteorologists look for certain features at particular pressure levels. Higher pressure values correspond to lower altitudes, and lower pressure values correspond to higher altitudes. The data obtained from a sounding can be plotted on a Stüve diagram, just as you'd plot data on a simple X-Y graph. Temperature would be your "X" coordinate, while Pressure would be your "Y" coordinate. On a blank Stüve diagram, find where the first Pressure value (Y-axis) and the corresponding Temperature value (X-axis) intersect, and add a dot or an X there. Repeat this procedure for each Pressure and Temperature point in your table, then connect the dots with a straight line. This will give you the upper-air temperature profile at the sounding location.

20. Let's analyze the data collected from Tampa Bay, FL, sounding in Table 1.5.1. Plot the data on a blank Stüve diagram.

Table 1.5.1: Data from a Radiosonde launch over Tampa Bay, FL, at 1200 UTC on January 10, 2025. (CC BY-NC 4.0; Larry Oolman via University of Wyoming).

Pressure (mb)	Temperature (°C)
1017	06.2
1000	11.0
970	12.2

Pressure (mb)	Temperature (°C)
930	10.2
925	10.0
894	09.9
850	11.8
800	12.3
746	10.2
700	07.0
598	00.7
500	-07.3
400	-20.5
300	-32.9
250	-43.9
200	-52.3
140	-66.5
100	-75.5

The U.S. Standard Atmosphere

Congratulations! You created a Stüve diagram plot of the temperature profile over Tampa Bay, FL. But how do we know whether the upper-air temperature over Tampa Bay is warmer or cooler than that of the rest of the U.S.? To compare radiosonde observations with the “average” atmospheric conditions, the U.S. Standard Atmosphere was developed. The U.S. Standard Atmosphere is a simple model of how the pressure, temperature, density, and viscosity of Earth's atmosphere vary over a wide range of altitudes or elevations. The lower portion of the US Standard Atmosphere has only three points: a surface temperature of +16 °C, -56.5 °C at 11 km, and -56.5 °C at 16 km. This data is shown in Figure 1.5.2 with the data recreated in Table 1.5.2.

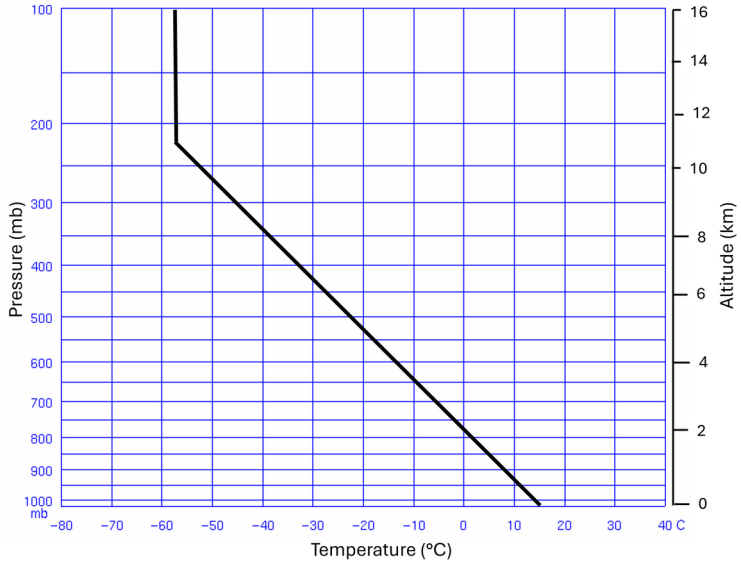


Figure 1.5.2: A Stüve Diagram with U.S. Standard Atmosphere plotted using a line. (CC BY-NC 4.0; Steve Ackerman via University of Wisconsin)

Table 1.5.2: The temperature profile as a function of pressure and altitude as modeled by the U.S. Standard Atmosphere.

Pressure (mb)	Altitude (km)	Temperature (°C)
1000	0	15
900	1	8
800	2	1
700	3	-6
600	4	-13
500	6	-22
400	7	-33
300	9	-45
250	10	-52
200	11	-56.5
175	12	-56.5
150	13	-56.5
125	14	-56.5
100	16	-56.5

Remember, the U.S. Standard Atmosphere profile isn't a measured temperature profile, but an idealized model of the atmosphere. Let's now combine our knowledge of what we learned about our vertical atmosphere in Section 1.4 with the upper air data over Tampa Bay (question 20) and the U.S. Standard Atmosphere (Figure 1.5.2 and Table 1.5.2) to answer the following questions:

21. The tropopause _____ present between the surface and 100 mb over Tampa Bay.
    a. is
    b. is not

22. The tropopause over Tampa Bay is at a _____ pressure level than the U.S. Standard Atmosphere (NOTE: lower pressure level = higher elevation).
    a. lower
    b. about the same elevation as
    c. higher

23. The atmosphere over Tampa Bay is warmer than the U.S. Standard Atmosphere from approximately 970 mb to a pressure level of approximately _____.
    a. 500 mb
    b. 200 mb
    c. 150 mb
    d. 100 mb

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1.6: Accessible Descriptions

Figure 1.1.1: Weather Conditions for the San Francisco Bay Area

This map displays real-time weather data for the San Francisco Bay Area and Central California as provided by MesoWest. Each dot represents a weather station. Numeric values next to each dot indicate the temperature in degrees Fahrenheit. Short arrows point in the direction of the wind at each station.

- Coastal cities such as San Francisco, Half Moon Bay, and Santa Cruz report cooler temperatures between 54°F and 63°F.
- San Francisco reports 61°F, while San Mateo is at 63°F.
- Inland areas are warmer:
  - San Jose area ranges from 64°F to 74°F, with some parts like east San Jose reaching 74°F.
  - Fremont reports 69°F, and Hayward shows 72°F.
  - Gilroy and Morgan Hill show values of 68°F and 68°F, respectively.
  - East Bay cities like Livermore and Concord show temperatures around 74°F and 73°F, with surrounding areas in the mid-70s to low 80s.
  - Further inland:
- Tracy: 82°F
- Stockton: 84°F
- Modesto: 84°F
- Manteca: 86°F
- Los Banos: 87°F (the warmest reading on the map)
- Wind directions vary, indicated by short arrows pointing in various directions, suggesting a mix of local wind patterns.

Figure 1.2.1: Weather Data for Continental United States

This is a synoptic surface weather map of the contiguous United States showing meteorological observations at various reporting stations, dated 22Z on June 26, 2020. Each station is represented by a standard station model symbol showing multiple weather variables.

Each station plot typically includes:

- Temperature (upper left number)
- Dew point (lower left number)
- Sea-level pressure (upper right number, usually in millibars)
- Wind barb indicating wind direction and speed
- Cloud cover (black or white circle)
- Pressure trend symbols (if present)

Several areas are highlighted with circles:

- Circle around Grand Junction, CO:
  - Temperature: 91°F
  - Dew point: 33°F
  - Pressure: 071
  - Light winds from the west
  - Mostly clear sky
- Circle around Little Rock, AR:
  - Temperature: 77°F
  - Dew point: 71°F
  - Pressure: 183
  - Moderate winds from the south
  - Partly cloudy

- Circle over San Antonio, Texas:
  - Temperature: 77°F
  - Dew point: 70°F
  - Pressure: 159
  - Wind from the southeast
  - High humidity
- Circle over Brownsville, TX shows:
  - Temperature: 86°F
  - Dew point: 78°F
  - Pressure: 151
  - Wind from the southeast
  - High humidity
- Circle around Tallahassee, FL:
  - Temperature: 81°F
  - Dew point: 79°F
  - Pressure: 203
  - High relative humidity
  - Winds from the south-southwest

Across the map:

- The western U.S. shows generally hot and dry conditions, especially in Nevada, Utah, and Arizona, with dew points often below 40°F and temperatures in the 90s to 100s.
- The eastern U.S. shows much higher humidity with dew points in the 70s and overcast or partly cloudy skies.
- Wind barbs indicate southerly to southeasterly flow in the central and eastern U.S., likely feeding moisture into the region.

Figure 1.2.2: The Station Model

This diagram is an annotated illustration of a standard station model, used by meteorologists to summarize weather observations at a particular location visually. The model consists of a central circle surrounded by several numbers and symbols, each representing a different weather parameter.

The annotations and data values shown in the diagram are as follows:

- Air Temperature (°F): Displayed in the top left corner as "71".
- Dew Point Temperature (°F): Displayed in the bottom left corner as "69".
- Barometric Pressure (in millibars): Displayed in the top right corner as "125".
- Cloud Cover: Indicated by the fill level of the central circle. A fully filled black circle represents overcast conditions (100% cloud cover).
- Precipitation: Shown as two small dots to the left of the central circle, indicating light rain or drizzle.
- Wind Direction: Represented by a line extending from the circle, pointing in the direction from which the wind is blowing. In this example, the wind is coming from the southeast.
- Wind Speed: Shown by barbs on the end of the wind direction line. Each full barb represents 10 knots, and each half barb represents 5 knots. This model shows two full barbs and one half barb, indicating a wind speed of 25 knots.

Figure 1.3.1: Precipitation

This is a national composite radar map showing areas of precipitation across the contiguous United States, valid at 22Z (6:00 PM UTC) on June 26, 2020. The radar data represents reflectivity, a measure of the intensity of precipitation, collected from a 1-kilometer hybrid digital scan.

Key Information:

- The map covers all 48 contiguous U.S. states, as well as portions of southern Canada and northern Mexico.
- Reflectivity values are measured in dBZ (decibels of reflectivity), with values ranging from below 20 dBZ (very light rain or drizzle) to over 70 dBZ (indicative of very heavy rainfall or hail).

- The radar data is displayed as reflectivity with no base map features such as cities or terrain. Only state outlines are visible.

Areas of Notable Precipitation Activity:

- Upper Midwest (especially Wisconsin and Michigan):
  - Contains the most intense precipitation on the map, with reflectivity values exceeding 50 dBZ, indicating strong thunderstorms or heavy rain.
- Southern Plains (including Oklahoma and Texas):
  - Scattered clusters of moderate to heavy precipitation, possibly thunderstorms.
- Central Rockies and Four Corners region:
  - Numerous small to moderate radar returns suggest widely scattered showers and embedded storms.
- Southeast U.S.:
  - Radar echoes indicate light to moderate rainfall, especially across Alabama, Georgia, and parts of Florida.
- Pacific Northwest and West Coast:
  - Light precipitation detected in isolated areas, primarily in western Oregon and northern California.

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2: HEATING THE EARTH

Introduction

Have you ever wondered why the weather can vary significantly from one place to another? Why does rain fall in some places and not in others? Why are some days very windy while other days are very calm? All of these phenomena originate from one source: the Sun (Figure 2.1). Heat from the sun fuels temperature differences across the planet, which then drive many of the weather patterns we often take for granted. In this investigation, we'll explore the different types of heat transfer, their mechanisms, and then focus on electromagnetic radiation and its role in heating the Earth.

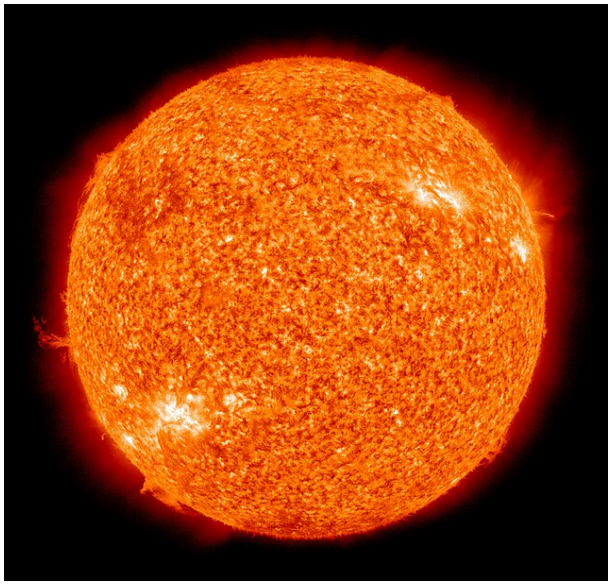


Figure 2.1: The sun is the source of over 99% of Earth's surface energy. (Public Domain; NASA via Wikimedia Commons)

Learning Objectives

- To discern one type of heat transfer from another.
- To identify the relationship between the temperature of an object and the type and amount of radiation the object emits.
- Distinguish the roles of angle of insolation and length of day in determining seasonal temperature changes.

Navigational Note

Investigation 2 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

2.1: Types of Heat Transfer

2.2: Radiation

2.3: Selective Absorbers and Greenhouse Gasses

2.4: Reflection, Albedo, and Land Cover

2.5: Seasons and Latitude

2.6: Length of Day and Insolation vs. Latitude

2.7: Accessible Descriptions

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2.1: Types of Heat Transfer

Heat transfer

Heat is energy that flows between two objects due to a temperature difference. Imagine you're cooking a pizza in the oven: you put a cold pizza in a warm oven, and heat from the air inside transfers to your pizza, cooking it. This example demonstrates the fundamental facts of heat transfer:

- Heat travels from a warm object to a cold object.
- Once the two objects have the same temperature (i.e., thermal equilibrium), heat transfer ceases.

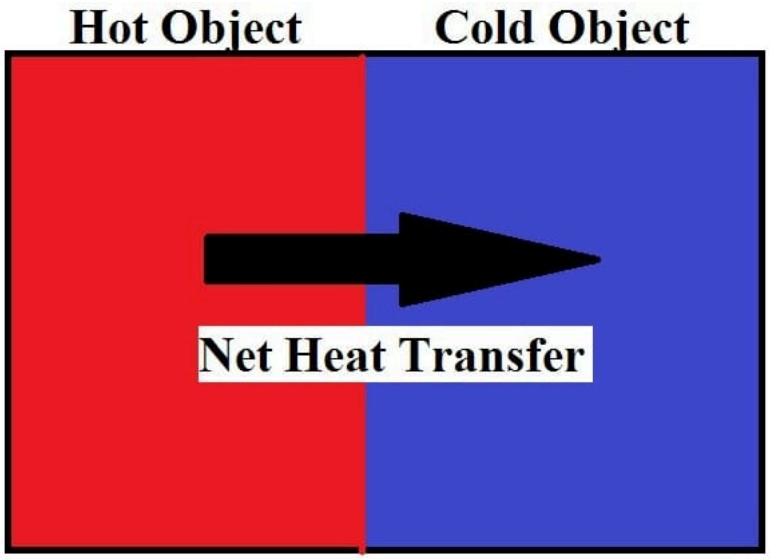


Figure 2.1.1: The net direction heat travels is from warm object to cold object. The figure indicates heat transfer from a "Hot Object" in red to a "Cold Object" in blue, and this process is shown via a black arrow with the words "Net Heat Transfer" (CC BY 4.0; Alicia Mullens)

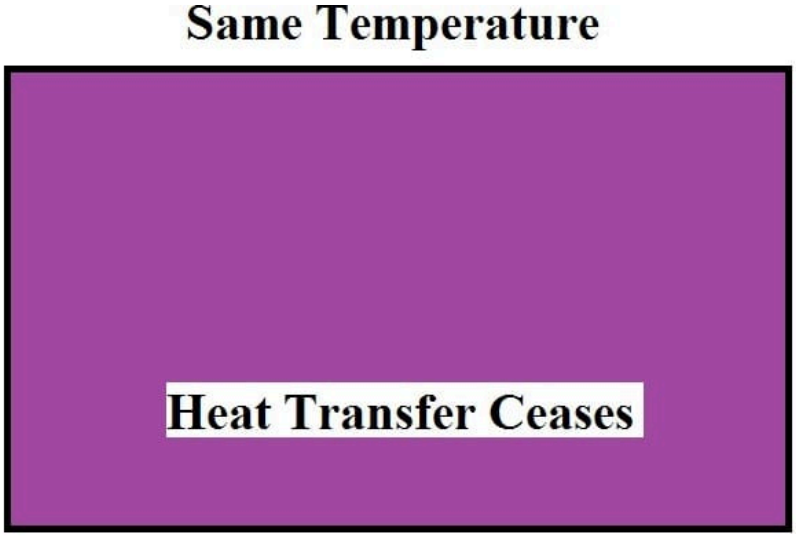


Figure 2.1.2: Once everything has the same temperature, net heat transfer ceases. (CC BY 4.0; Alicia Mullens)

Figures 2.1.1 and 2.1.2 illustrate the general nature of heat transfer. When two objects of different temperatures are next to one another in Figure 2.1.1, heat travels from the hot object to the cold object until the two objects have the same temperature (in Figure 2.1.2). There are three ways that heat can travel between the warm object and the cold object.

- Conduction: The transfer of heat through direct contact/via an intermediate object.
- Convection: The vertical transfer of heat through a fluid.
- Radiation: The transfer of heat through waves of electromagnetic energy called photons.

An example of the three types of heat transfer is provided in Figure 2.1.3. When roasting a marshmallow at a bonfire, heat can travel from the flame through the skewer to the person holding it. This is conduction, where the metal skewer acts as an intermediate object that allows heat from the flame to transfer to the person's hand. Wearing a thick glove or having a wooden handle on the skewer can insulate the hand from the heat transfer. Air itself is a poor conductor. However, when air comes into direct contact with the flame, it heats up, becomes less dense than the surrounding air, and rises. This, in turn, forces the cooler air surrounding the warm air to sink toward the flame, where it is heated. This transfer of heat via warm air rising and cold air sinking is called Convection. This distributes heat throughout the atmosphere and is key to warming our atmosphere. Finally, the heat radiated by the flame is called radiation. If you've ever been near a warm object, such as a flame or a heater, and felt heat without touching it or being directly above it, the heat you experienced is radiation. Radiation is the transfer of heat through electromagnetic particles, known as photons. The benefit of radiation is that, unlike conduction, which requires either direct contact or an intermediate object, and convection, which requires a fluid, it can travel through a vacuum. Radiation can travel through various media, such as water, air, and glass, as well as through space, known as a vacuum.

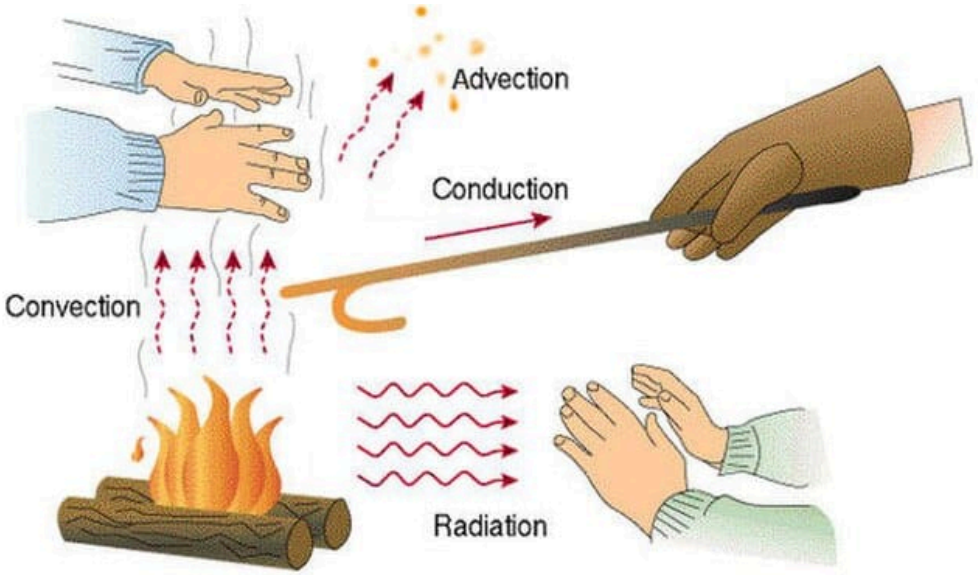


Figure 2.1.2: Different Types of Heat Transfers. (CC BY 4.0; Cmglee Kmecfiunit via WikiMedia Commons) Alternative description of image

Reflect and Respond Question

1. Consider the following processes. Are they conduction, convection, or radiation, and why?
   a. Steam rising off a cup of coffee
   b. Touching your computer and feeling warmth as you touch it
   c. Burning your feet when walking on a hot concrete surface
   d. A hot air balloon
   e. Being warmed by standing out in the sun.

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2.2: Radiation

What is radiation?

Radiation is how the Sun heats the Earth. The sun, being a large and hot object, radiates a massive amount of energy that makes an 8-minute, 92,000,000-mile journey to Earth. Meteorologists must have a keen understanding of radiation. You would be surprised how much radiation is surrounding you right now. As a society, we often equate radiation with nuclear disasters, gamma rays, Homer Simpson, and so on. However, the light that brightens your home at night, the Wi-Fi signal you receive on your phone, and the radio signal that brings your favorite radio station to you are all examples of radiation. However, they are all very different types of radiation. Therefore, we need to understand what determines the type of radiation a photon contains. There is one key property that defines this: The radiation's wavelength (the Greek symbol λ, or lambda, is often used to denote wavelength). If you visualize a beam of radiation as a wave, the wavelength is the distance between successive peaks (as shown in Figure 2.2.1). The wavelength determines two other key properties of radiation: Energy and Frequency. Both are inversely proportional to the wavelength. This means that as the wavelength of a beam of radiation increases, both its frequency (f) and its energy (E) decrease. Therefore, longer-wavelength radiation is low-energy and typically harmless.

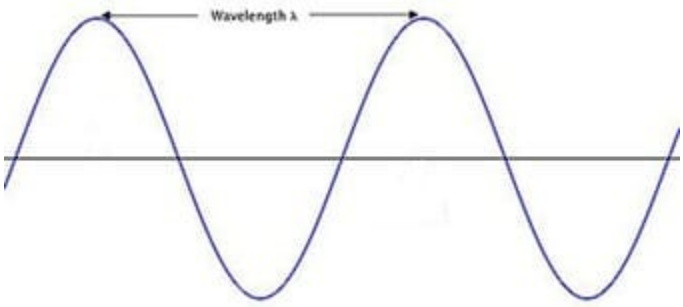


Figure 2.2.1: The wavelength is the distance between two consecutive peaks of an Electromagnetic Wave. (CC BY 4.0; Alicia Mullens)

The Electromagnetic Spectrum

The Electromagnetic Spectrum (Figure 2.2.2) shows the relationship between the wavelength, frequency, and energy of a category of radiation. AM Radio Waves have wavelengths of tens or even hundreds of meters, are extremely low-energy, and thus pass through things harmlessly. On the other hand, as the wavelength shortens, the type of radiation changes to FM Radio Waves, TV Waves, Microwaves, Infrared Waves, and so on, with each type becoming more energetic as the wavelength decreases.

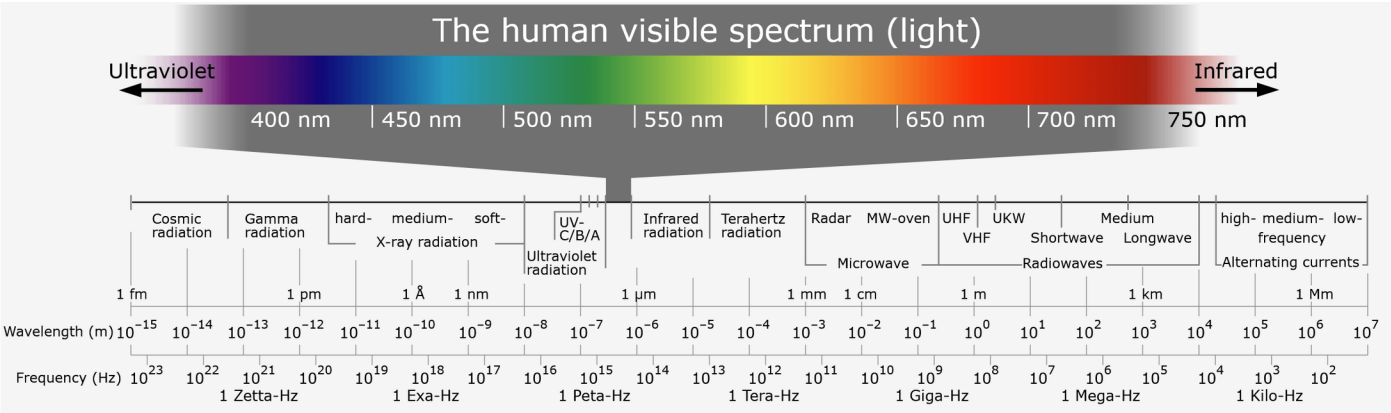


Figure 2.2.2: The Electromagnetic Spectrum. (CC BY 4.0; Horst Frank via Wikimedia Commons). Alternative description of image

Table 2.2.1 provides a more detailed description of the types of radiation, their wavelength ranges, and the corresponding types.

Table 2.2.1 Electromagnetic Spectrum Explained

Region	Wavelength Range (m)	Frequency Range (Hz)	Explanation
Cosmic Radiation	≈ 10^{-15}	≈ 10^{23}	Extremely high-energy radiation originating from space; the shortest wavelength and the highest frequency.
Gamma Radiation	10^{-14} – 10^{-12}	10^{22} – 10^{20}	High-frequency radiation from radioactive decay and cosmic events; used in medical treatments.
Hard X-ray	10^{-12} – 10^{-11}	10^{20} – 10^{19}	Shorter wavelength X-rays with higher energy, used in imaging and materials analysis.
Medium X-ray	10^{-11} – 10^{-10}	10^{19} – 10^{18}	Intermediate energy X-rays used in diagnostics and research.
Soft X-ray	10^{-10} – 10^{-9}	10^{18} – 10^{17}	Lower-energy X-rays have greater penetration depth.
Ultraviolet (UV-C/B/A)	10^{-9} – 4×10^{-7}	10^{17} – 10^{15}	Non-visible light just shorter than visible; UV-C is germicidal, UV-B causes sunburns, UV-A penetrates deeper into skin.
Visible Light	4×10^{-7} – 7.5×10^{-7}	10^{15} – 10^{14}	The portion of the spectrum visible to the human eye; used in vision and illumination.
Infrared Radiation	7.5×10^{-7} – 10^{-4}	10^{14} – 10^{12}	Emitted by warm objects; used in night-vision, heating, and communication.

Region	Wavelength Range (m)	Frequency Range (Hz)	Explanation
Terahertz Radiation	10^{-4} – 10^{-3}	10^{12} – 10^{11}	Bridges microwave and infrared; used in spectroscopy and imaging.
Radar	10^{-3} – 10^{-2}	10^{11} – 10^{10}	Used in detection systems for aircraft, ships, weather.
Microwave (MW Oven)	10^{-2} – 10^{-1}	10^{10} – 10^{9}	Used for cooking, telecommunications, and radar.
Radio – UHF	10^{-1} – 1	10^{9} – 10^{8}	Ultra High Frequency; used in TV, cellphones, GPS.
Radio – VHF	1 – 10	10^{8} – 10^{7}	Very High Frequency; used in FM radio, aviation.
Radio – UKW	10 – 100	10^{7} – 10^{6}	Ultra-shortwave radio; overlaps with VHF/shortwave.
Radio – Shortwave	100 – 1000	10^{6} – 10^{5}	Used for long-distance radio transmissions.
Radio – Medium Wave	1 km	10^{5} – 10^{4}	AM radio broadcast frequencies.
Radio – Longwave	10 km	10^{4} – 10^{3}	Long-distance, low-frequency communication.
Low-Frequency (AC)	10^{3} – 10^{7}	10^{3} – 10^{-3}	Alternating current; used in power transmission.

2. Based on the visible light portion of the EM spectrum, _____ light has the shortest wavelength while _____ light has the longest wavelength.
   a. Red;Violet
   b. Yellow;Violet
   c. Violet;Red
   d. Blue;Green

Because radiation waves can become so short, we must introduce two new units into our toolbox: The nanometer (1nm =

0.000000001m) and the micrometer (1μm = 0.000001m). 1000nm = 1μm.

There are a few key facts and laws of the electromagnetic spectrum that you need to know before we can thoroughly investigate how radiation affects our weather:

Fact and Law

Fact: Every object with a temperature above Absolute Zero (0 K) emits radiation! Yes, that includes everything around you, and you as well! We jokingly call this "Oprah's Law" (EVERYBODY EMITS RADIATION!!!), but it's important to note that it's a fact, not a law.

Law: The Warmer and object is, the more radiation the object emits. This is called the Stefan-Boltzmann law, and the equation for it is given as:

$$E = \sigma T^4 \tag{2.2.1}$$

Where E is the total amount of energy, T is the object's temperature, in Kelvin, and σ is called the Stefan-Boltzmann Constant, and σ = 5.670373 x 10-8 Wm-2K-4. Don't worry about the equation; focus on the idea that Warmer Objects Emit More Radiation.

3. Based on the Stefan-Boltzmann Law, the Sun (T = 6000K) emits _____ radiation than the Earth (T = 290 K).
   a. more
   b. less

Law: The warmer an object is, the shorter the wavelength it emits. This is called Wein's Law (Pronounced Vein's Law), and the equation for it is:

$$\lambda_m = \frac{2898(\mu m K^{-1})}{T(K)}$$

Where λ_m is the wavelength (in micrometers) most emitted by an object, and T is the temperature in Kelvin. To convert a wavelength from micrometers to nanometers, multiply by 1000.
Thus, not only is the amount of radiation emitted by an object dependent on the temperature of the object, but so is the type of radiation.

4. Using this equation for Wein's Law, the wavelength most emitted by the Sun (T = 6000K) is approximately:
   a. 48.3 μm
   b. 483 μm
   c. 0.483 μm
5. According to the Electromagnetic Spectrum, the radiation most emitted by the Sun is in the form of: (to convert your answer from question 4 to nanometers [nm], multiply it by 1000)
   a. Infrared rays (741nm-1mm)
   b. Visible Light (400-740nm)
   c. Ultraviolet Rays (10nm-399nm).
6. On the other hand, Earth, with a temperature of approximately 290K emits radiation primarily as _____.
   a. Infrared Rays
   b. Microwaves
   c. Gamma Rays
7. Thus, the _____ emits Shorter-Wave radiation (we'll call this Shortwave Radiation from now on). In contrast, the _____ emits Longer-Wave radiation (we'll call this Longwave Radiation from now on).
   a. Earth; Sun
   b. Sun; Earth

Now that we have a baseline understanding of the types of radiation emitted by the Earth and the Sun, we can discuss how they affect our atmosphere. Once Solar radiation, which extends beyond the wavelength calculated above, reaches the top of the atmosphere, several processes can occur. Radiation that enters the top of the atmosphere can either be:

- Reflected by clouds
- Reflected/Scattered by the Atmosphere

- Reflected by Earth's Surface (Land and Ocean)
- Absorbed by the Atmosphere
- Absorbed by the Earth's surface (Land and Ocean)

All of these factors significantly affect the amount of heat the Earth receives and, thus, its temperature.

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2.3: Selective Absorbers and Greenhouse Gasses

Absorption by the atmosphere

Most of the key gases in the atmosphere are called Selective Absorbers, meaning they are entirely transparent to some wavelengths of radiation while completely absorbent (i.e., opaque) to others. This is particularly crucial when considering Greenhouse Gases, which are widely regarded as the primary drivers of global warming.

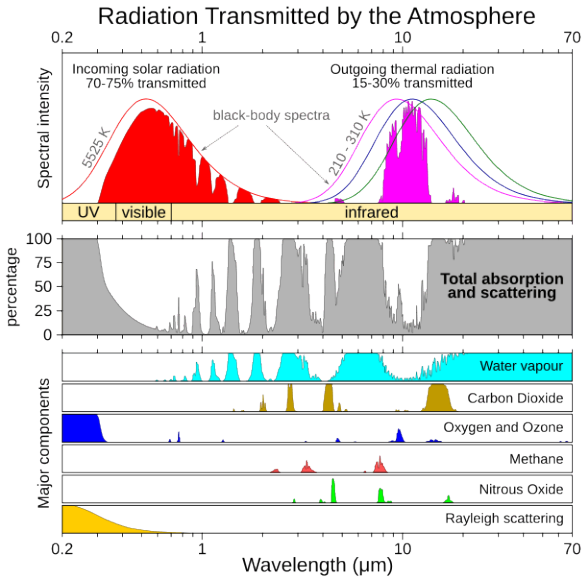


Figure 2.3.1: The Absorption Spectrum of the Atmosphere. (Public domain; Wikkiwonkk via Wikimedia Commons). Alternative description of the image.

To understand which gases absorb which wavelengths of radiation, we must examine the absorption spectrum in Figure 2.3.1 . Here's how to read this figure: There are eight panels, each with the same “x” axis (wavelength) and “y” axis (% of radiation absorbed or scattered by gases). Wherever you see a grey area in the second panel, it represents absorption happening at that wavelength. Meanwhile, for panels 3-7, the amount of colored area represents the percentage absorbed. For example, Oxygen and Ozone absorb almost 100% of radiation between 0.2-0.3μm (200-300nm). These wavelengths fall within the ultraviolet range. This is reasonable because the ozone layer absorbs ultraviolet radiation, thereby protecting us from its effects. It can also be assumed that radiation not absorbed by these gases passes right through them. The bottom panel represents Rayleigh Scattering, which we won't cover here.

Gases that are mostly transparent to shortwave radiation (visible Light and shorter wavelengths... 0.7 μm and less) but absorb longwave radiation (Infrared radiation, mostly above 0.7 μm) are called Greenhouse Gases. These gases play a crucial role in keeping Earth warm by allowing shortwave radiation to heat the Earth while preventing longwave radiation from escaping to space.

8. According to the second panel in Figure 2.3.1 (Total absorption and scattering, which represents the total absoprtion from all of the gases of the atmosphere) most visible light is _____ by the atmosphere.
   a. Absorbed
   b. Not Absorbed
9. According to the Absorption Spectrum, which of these gases are greenhouse gases?
   a. Water Vapor (H_2O)
   b. Methane (CH_4)
   c. Carbon Dioxide (CO_2)
   d. Nitrous Oxide (NO_2)
   e. All of these
10. Except for a massive spike in absorption of radiation near 10 μm, the atmosphere is mainly transparent to wavelengths between _____. This is called the Atmospheric Window.

a. 1 and 100 μm
b. 5 and 20 μm
c. 7 and 12 μm

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2.4: Reflection, Albedo, and Land Cover

Albedo

Radiation that isn't absorbed by the atmosphere is either absorbed by the surface of the earth, reflected by the surface of the earth, or reflected by clouds. With the exception of some surface covers, which we will cover below, the Earth's surface absorbs almost 100% of the radiation that reaches it. However, many objects both in the atmosphere and on Earth's surface are good reflectors of sunlight. Every object has a property called Albedo that represents the percentage of sunlight it reflects. While you can measure albedo by calculating the ratio of sunlight reflecting off an object to sunlight hitting the object, you can actually estimate the albedo simply by looking at how dark/light colored the object is. If you've ever worn a dark-colored t-shirt, or driven in a car with dark interiors, you probably know that dark objects don't reflect much of the sunlight that hits them... and thus have a low albedo. Objects with a low albedo absorb the radiation instead, causing them to heat up. On the other hand, if you've ever gone skiing and been snow-blinded, or had a bad sunburn, you probably know that light-colored objects have higher albedos, thus reflecting sunlight and keeping them cool. A simple guide to albedo is found in Figure 2.4.1.

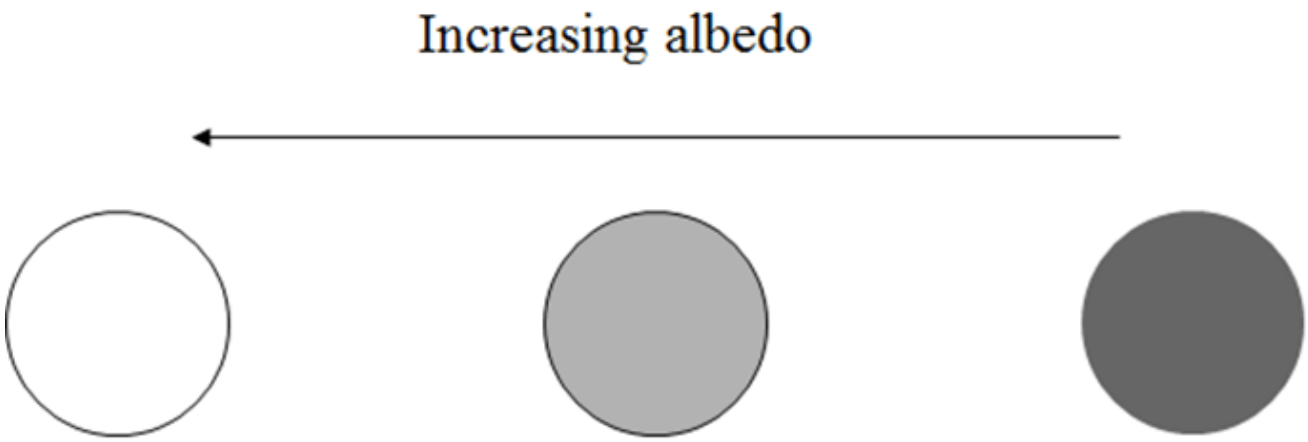


Figure 2.4.1: Relationship between Albedo and Darkness. Lighter colors have a high albedo while darker colors have a low albedo (CC BY 4.0; Alicia Mullens)

Simply put, the lighter an object's color is, the higher the albedo. Let's put this to the test. Figure 2.4.2 is a typical snow-covered mountainside and Figure 2.4.3 is a typical building in an urban area.



Figure 2.4.2: A snow capped mountain (Public Domain; Wikimedia Commons)



Figure 2.4.3: Dark buildings and street typical of an urban area. (CC-BY-SA 2.0; Wikimedia Commons)

We know that objects that reflect sunlight are cooler, while objects that absorb sunlight are warmer. The phenomenon covered above is called the **Urban Heat Island Effect.**

11. Ice and Snow, as shown in Figure 2.4.2, would likely have a _____ albedo.
    a. high
    b. middle
    c. low
12. On the other hand, urban areas, as shown in Figure 2.4.3, most likely have a _____ albedo.
    a. high
    b. low
13. Therefore, urban areas are likely to be _____ than ice-covered locations.
    a. warmer
    b. colder

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2.5: Seasons and Latitude

Latitude

One of the most significant factors affecting a location's climate is the location's latitude – the distance from the equator (the equator represents a latitude of 0° and the poles are 90°N for the North Pole, and 90°S for the South Pole). Figure 2.5.1 displays lines of latitude on Earth for the Northern Hemisphere.

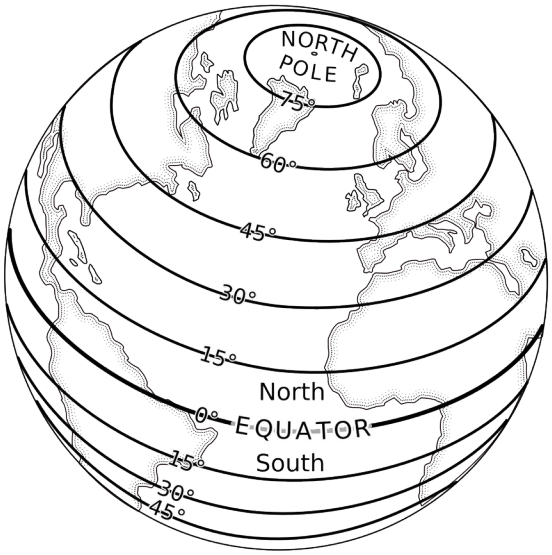


Figure 2.5.1: Lines of Latitude. (Public Domain; Gregors via Wikimedia Commons). Alternative description of the image.

We'll cover latitude more in depth when we investigate the Earth's coordinate system in a future investigation. For now, just know that the further away you get from the equator, the larger your latitude is. The key impact that latitude has on climate is its effect on the angle of incoming sunlight, or the Angle of Insolation. A higher angle (closer to 90° or directly overhead) concentrates solar energy into a smaller area, resulting in higher, hotter temperatures, while a lower, oblique angle spreads energy over a larger area, resulting in lower temperatures. To demonstrate the importance of the angle of insolation, do the following experiment: Using a flashlight and in a dark room, hold the flashlight so that the light is directly over the ground, as shown in Figure 2.5.2. Then, tilt the flashlight so it is low on the horizon, as shown in Figure (2.5.3).



Figure 2.5.2: Flashlight directly over the surface. (CC BY 4.0; Alicia Mullens)

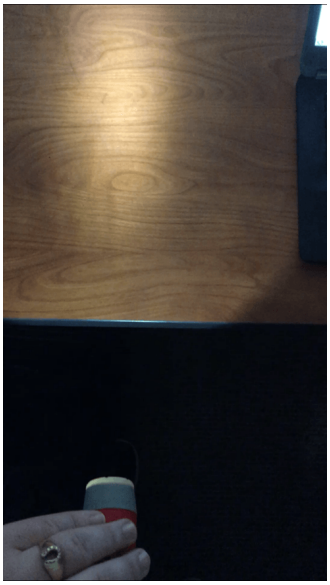


Figure 2.5.3: Flashlight lower on the horizon. (CC BY 4.0; Alicia Mullens)

14. When the flashlight is shining directly above the surface (Figure 2.5.2), the area illuminated on the surface is:
    a. a small, bright circle
    b. a large, dim area
15. When you lower the flashlight on the horizon (Figure 2.5.3). The area illuminated on the surface becomes:
    a. smaller and brighter
    b. larger and dimmer
    c. it doesn't change

We can apply these conclusions to sunlight and how its intensity changes throughout the day. Specifically, when the sun is high in the sky, the incoming sunlight is more intense, whereas when the sun is low on the horizon, it is less intense. Now, let's examine how this would relate to latitude. There are a few things to note here. If the Earth were *not* tilted, the sun would be directly overhead year-round, and the overall set-up of incoming sunlight would appear as shown in Figure 2.5.4.

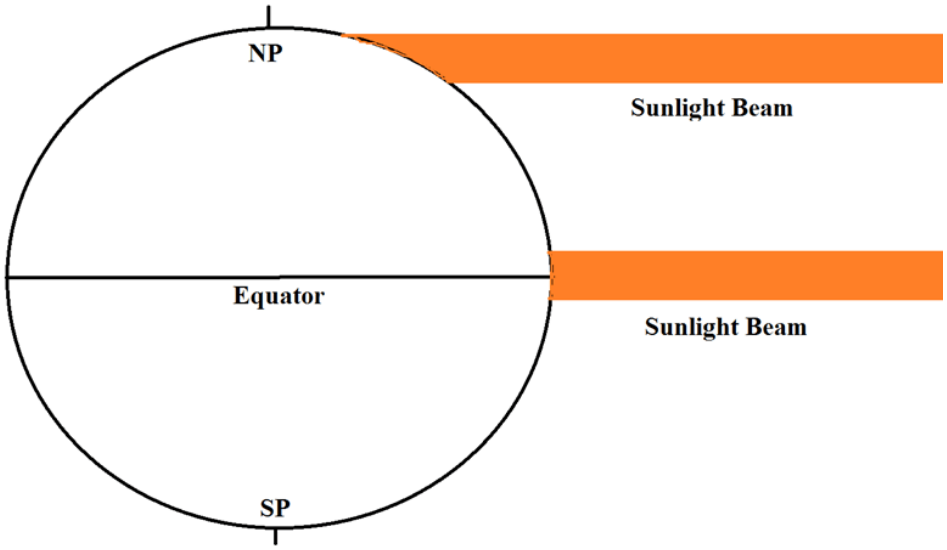


Figure 2.5.4: Sunlight over the Equator (low latitude) vs. Sunlight near the poles (high latitude). The Sun is directly over the Equator. (CC BY 4.0; Alicia Mullens). Alternative description of image.

16. Based on Figure 2.5.4, a beam of sunlight covers a _____ area over higher latitudes than near the Equator.
    a. smaller
    b. larger
17. As a result, sunlight at higher latitudes would be _____ than near the Equator.
    a. more intense
    b. less intense

This can be further reinforced by checking how average air temperatures vary with latitude worldwide. A map of global average air temperatures is shown in Figure 2.5.5. Warmer temperatures are shown in red, while cooler temperatures are shown in blue.

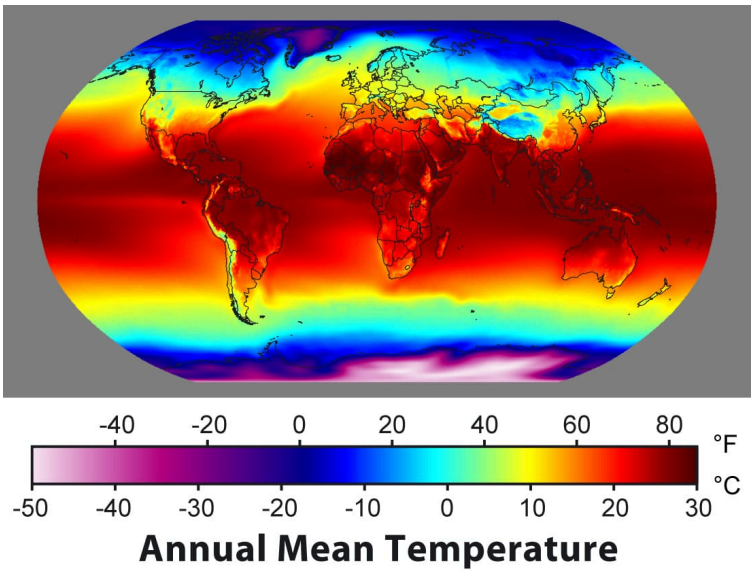


Figure 2.5.5: Global annual average air temperatures. (CC-BY-SA 3.0; Dragons flight via Wikimedia Commons). Alternative description of image.

18. While there is some variation caused by other factors (such as elevation, and ocean currents), the warmest temperatures are generally near the _____ while the coldest temperatures are usually near the _____.
    a. poles; equator

b. equator; poles

Earth's orbit.

However, our Earth *is* tilted. In fact, it is tilted at an Angle of 23.5°. The result of this is that as the Earth orbits around the sun (Figure 2.5.6), the latitude at which the sun is directly overhead changes. Figure 2.5.7 represents the conditions in June, when the sun is directly over 23.5°N, while Figure 2.5.8 represents the conditions in December, when the sun is directly over 23.5°S.

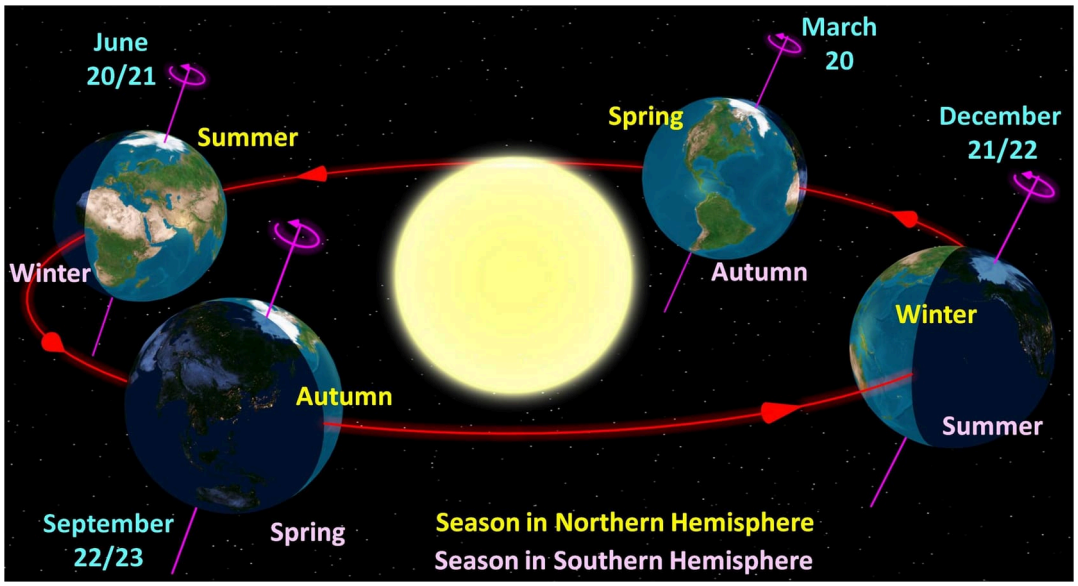


Figure 2.5.6: Earth's orbit around the sun and corresponding northern hemisphere seasons. (Public Domain; Banana Republic Wikimedia Commons). Alternative description of the image.

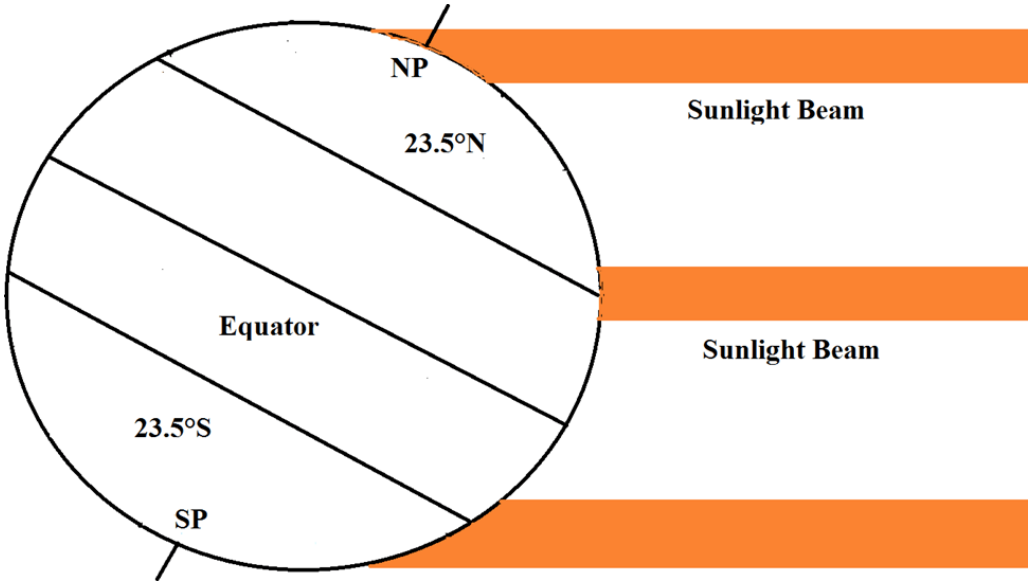


Figure 2.5.7: Conditions in June. (CC BY 4.0; Alicia Mullens). Alternative description of the image.

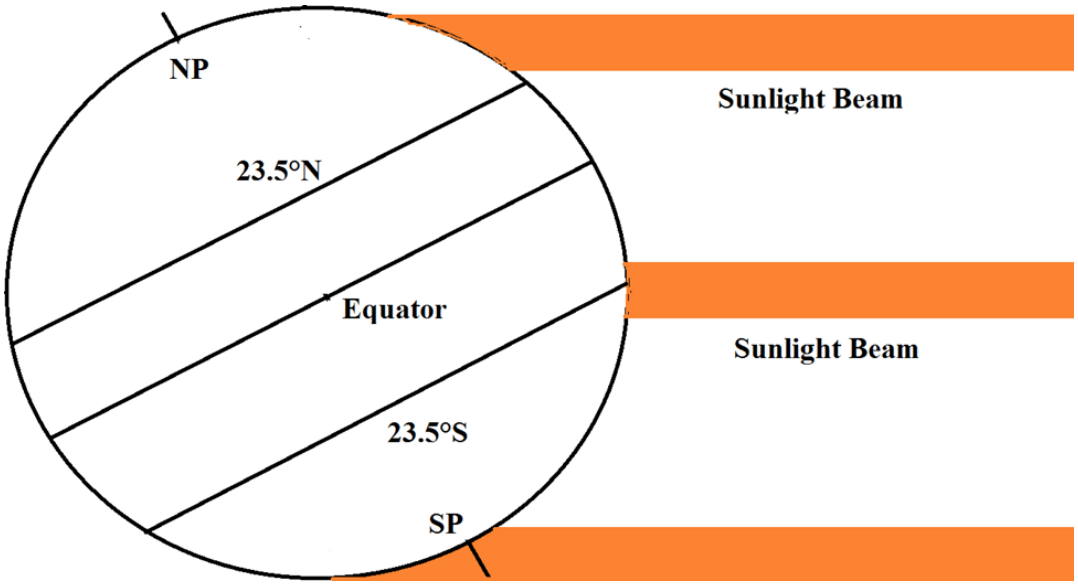


Figure 2.5.8: Conditions in December. (CC BY 4.0; Alicia Mullens). Alternative description of the image.

19. Investigate the North Pole in Figure 2.5.7. Notice that it is completely covered with sunlight. Now imagine the Earth completing one 24-hour rotation around its axis. In June, the North Pole would never:
    a. experience any sunlight
    b. experience any darkness
20. Now let's investigate Figure 2.5.8, which represents conditions in December. In December, the sun is directly over:
    a. The Equator
    b. 23.5°N
    c. 23.5°S

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2.6: Length of Day and Insolation vs. Latitude

Length of day

In the previous section, we learned that the angle of incoming sunlight received by a region varies with the season. Not only do the seasons affect the angle of incoming sunlight, but they also greatly influence the length of the day. You may have already noticed that during summer, our days are longer, while in the winter, our days are shorter. This is emphasized in Figure 2.6.1, which shows how the length of day varies monthly for several given latitudes.

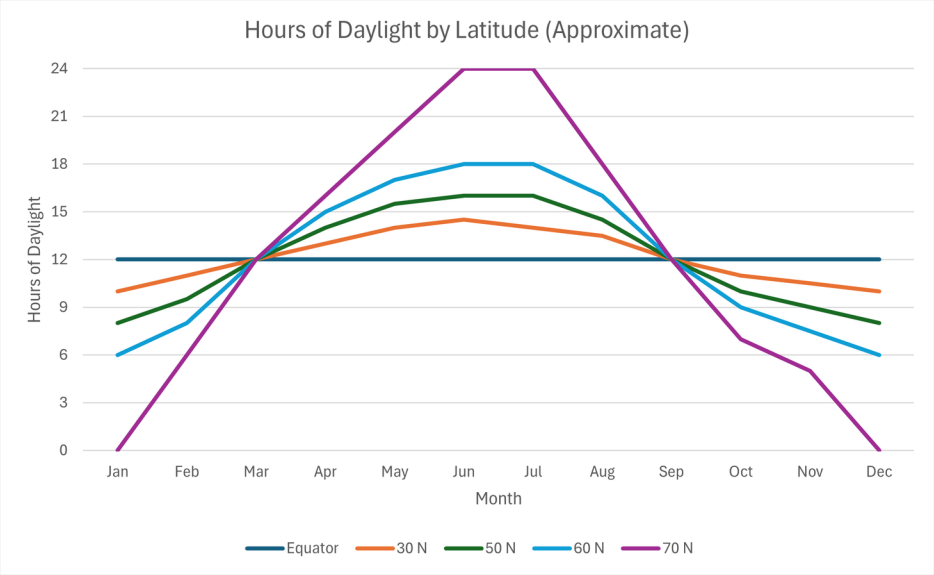


Figure 2.6.1: Length of day versus month of the year for several latitudes. (CC-BY-NC 4.0; Alicia Mullens). Alternative description of image.

Examine the monthly variation in day length for each of the latitudes provided in Figure 2.6.1, as the number of hours of sunlight received is shown on the Y-axis, while the month of the year is shown on the X-axis. The latitudinal variation in the length of day is reflected in the curve's amplitude (how high/low the line goes).

21. The Equator experiences _____ variation in day length from season to season while locations at latitude 70°N experience _____ variation in day length from season to season.
    a. significant; almost no
    b. some; significant
    c. almost no; significant
22. How does the month-to-month variation in day length change with latitude?
    a. The variation becomes smaller at higher latitudes
    b. The variation becomes larger at higher latitudes
    c. There is no variation with latitude

Total Insolation

Seasonal changes in The Angle of Insolation along with The Length of Daylight ultimately result in seasonal variations in Insolation received at a latitude, as shown in Figure 2.6.2. This is what ultimately affects how temperatures change with seasons.

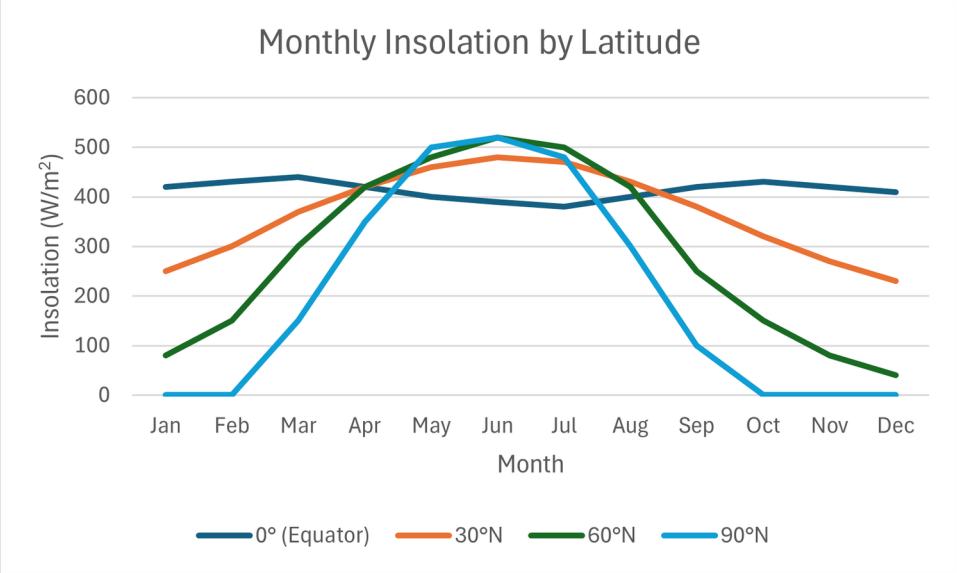


Figure 2.6.2: Insolation versus month of the year for different latitudes. (CC-BY-NC 4.0; Alicia Mullens). Alternative description of image

23. As you travel north from the Equator, the seasonal variation in Insolation:
    a. becomes larger
    b. becomes smaller
    c. does not change
24. While all other latitudes have one peak in Insolation in June, the Equator has two peaks, which occur in:
    a. June and December
    b. March and September
    c. March and December
    d. June and September
25. What is interesting, is that during June, the North Pole (90°N) receives _____ sunlight than the equator.
    a. more
    b. less

We know that with higher latitudes, the angle of insolation becomes lower, so based on what was covered earlier in this investigation, we can conclude that the biggest cause for these latitudes receiving more sunlight than the equator is the length of the day; granted, the sun may be low on the horizon during polar summer, but if the sun is out all 24 hours of the day, that grants a major opportunity for tremendous amounts of warming. As such, polar regions experience tremendous temperature differences from winter to summer, whereas tropical regions may experience a small, if noticeable, change.

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2.7: Accessible Descriptions

Figure 2.1.2 Different types of Heat Transfers

An educational diagram illustrating four methods of heat transfer: conduction, convection, radiation, and advection. A fire is at the center bottom of the image.

- Convection is shown as upward motion of warm air from the fire toward a pair of hands held above it, indicating heat transfer through the movement of heated air.
- Radiation is demonstrated by wavy lines traveling directly from the fire to another pair of hands held at a distance in front of the fire, representing direct heat transfer through electromagnetic waves.
- Conduction is depicted by a person holding a metal rod in their hand, with the opposite end placed in or near the fire. This shows heat traveling through the solid rod from the hot end to the hand.
- Advection is represented by particles or dots moving horizontally away from the heated air, symbolizing horizontal heat transfer through bulk fluid motion.

The diagram is designed to clarify how thermal energy moves in different ways depending on the medium and mechanism.

Figure 2.2.1 The Electromagnetic Spectrum

A labeled diagram of the electromagnetic spectrum focusing on the range of human-visible light. The visible spectrum is positioned between ultraviolet and infrared regions. The top section marks visible wavelengths in nanometers, ranging from 400 to 750 nm. Below it, a horizontal scale shows corresponding electromagnetic categories—such as ultraviolet radiation, infrared radiation, microwaves, and radio waves—with their associated wavelength values (from 1 femtometer to 10 megameters) and frequency values (from 10^{24} Hz to 10^{4} Hz). Key divisions like cosmic radiation, gamma rays, X-rays, radar, and alternating currents are labeled accordingly.

This diagram illustrates the full electromagnetic spectrum, highlighting the portion of light that is visible to the human eye, which spans wavelengths from approximately 400 to 750 nanometers. The spectrum is organized from left to right by increasing wavelength and decreasing frequency.

To the left of visible light are shorter wavelengths and higher frequencies, representing high-energy radiation. This includes cosmic radiation (starting near 1 femtometer), gamma rays, and various types of X-rays (hard, medium, soft). These radiations are mostly invisible and hazardous to biological tissue.

Immediately before the visible spectrum is ultraviolet radiation, divided into UV-C, UV-B, and UV-A types. The visible spectrum is situated in the middle of the chart and ranges from 400 to 750 nanometers. This is the only portion of electromagnetic radiation detectable by the human eye.

To the right of visible light, the wavelengths grow longer and frequencies drop. This includes infrared radiation, followed by terahertz radiation and microwaves, which are commonly used in communication and cooking appliances.

Beyond these lie radio waves, organized into bands such as ultra high frequency (UHF), very high frequency (VHF), and others including shortwave, medium wave, and longwave. At the far right are low-frequency alternating currents with extremely long wavelengths, used in electrical power systems.

The diagram also includes logarithmic scales along the bottom:

- Wavelength, measured in meters, ranges from 10^{-15} meters to 10^{7} meters.
- Frequency, measured in hertz (Hz), ranges from 10^{23} Hz to 10^{3} Hz.

This spectrum provides a comparative view of how electromagnetic radiation types are distributed by wavelength and frequency, with the visible portion emphasized for reference.

Figure 2.3.1: Absorption Spectrum

A scientific diagram titled "Atmospheric Transmission" showing how much electromagnetic radiation is absorbed or scattered by Earth's atmosphere at different wavelengths. The horizontal axis is labeled with wavelength in micrometers and nanometers, ranging logarithmically from approximately 10^{-3} micrometers (gamma rays) to 10^{6} micrometers (radio waves). Major sections along the wavelength axis are labeled as gamma rays, X-rays, ultraviolet, visible, infrared, and radio waves. The vertical axis represents the percentage of atmospheric absorption and/or scattering, from 0% to 100%.

On the top panel, two curves are plotted: one representing the atmosphere's transmission in the visible spectrum and another in the infrared spectrum. The diagram highlights transmission "windows" where the atmosphere allows more radiation to pass through—especially in parts of the visible and radio wave regions—while also showing regions with low transmission due to absorption by gases like water vapor, ozone, and carbon dioxide.

Labeled regions of absorption include water vapor bands in the infrared and microwave ranges, ozone absorption in the ultraviolet, and a general blocking of gamma rays and X-rays. This visualization illustrates how the composition of the Earth's atmosphere affects which parts of the electromagnetic spectrum reach the surface.

Figure 2.5.1: Lines of Latitude

A globe showing the Atlantic Ocean, parts of North and South America on the left, and parts of Europe and Africa on the right. The diagram highlights latitude lines running horizontally from the South Pole to the North Pole in 15-degree increments. The labeled lines are: 45°S, 30°S, 15°S, 0° (Equator), 15°N, 30°N, 45°N, 60°N, and 75°N. The equator is prominently labeled in bold text. The map illustrates how these latitude lines wrap around the Earth, and their values increase the further away you get from the equator.

Figure 2.5.4: Sunlight When Sun is Over Equator

Diagram of Earth showing how sunlight hits different parts of the planet. The circle represents Earth, with "NP" (North Pole) at the top, "SP" (South Pole) at the bottom, and the Equator marked across the center. Two orange sunlight beams approach from the right. One beam hits the Equator directly, showing concentrated energy in a small area. The other beam hits the upper part of Earth near the North Pole at an angle, spreading the same amount of sunlight over a larger area. This demonstrates why equatorial regions are warmer and polar regions colder.

Figure 2.5.5: Global Average Air Temperatures

World map showing average yearly temperatures. The equator region has the hottest temperatures around 20 to 30 degrees Celsius. Temperatures get cooler moving toward the poles. The coldest areas near the North and South Poles have temperatures as low as minus 50 degrees Celsius. Title reads "Annual Mean Temperature."

Figure 2.5.6: Earth's Orbit

A diagram shows Earth's orbit around the Sun, illustrating how the tilt of Earth's axis causes seasonal changes. The Sun is at the center with four labeled Earth positions around it, each representing a different season in both hemispheres.

- June 20/21 (top left): Earth's North Pole is tilted toward the Sun. The Northern Hemisphere receives the most direct sunlight, leading to summer there. The Southern Hemisphere receives less sunlight, resulting in winter.
- September 22/23 (bottom left): Earth's axis is not tilted toward or away from the Sun. Both hemispheres receive roughly equal sunlight. This marks the autumn equinox in the Northern Hemisphere and spring equinox in the Southern Hemisphere.
- March 20 (top right): Similar to September, sunlight is evenly distributed between hemispheres. It is the spring equinox in the Northern Hemisphere and autumn equinox in the Southern Hemisphere.
- December 21/22 (bottom right): Earth's South Pole is tilted toward the Sun. The Southern Hemisphere receives the most direct sunlight, experiencing summer, while the Northern Hemisphere gets less sunlight, causing winter.

Each Earth in the diagram shows a consistent tilt in its axis. Seasons in the Northern Hemisphere are labeled in yellow, and corresponding Southern Hemisphere seasons are labeled in lavender. A red arrow shows Earth's orbital direction around the Sun.

Figure 2.5.7: Conditions in June

Diagram of Earth tilted on its axis, showing how sunlight reaches different latitudes. The Earth is drawn as a circle with a tilt to the right. The North Pole (NP) is at the top, the South Pole (SP) at the bottom, and the Equator is labeled in the center. Two additional latitude lines are shown: 23.5 degrees North (Tropic of Cancer) and 23.5 degrees South (Tropic of Capricorn).

Three horizontal orange bars labeled “Sunlight Beam” enter from the right, representing sunlight:

- The top sunlight beam fully covers the North Pole and the region around 23.5°N, showing that the Arctic is in continuous sunlight—experiencing 24 hours of daylight.
- The middle beam strikes the Equator directly, indicating the most concentrated solar energy in that region.
- The bottom beam misses the South Pole, leaving it in shadow. This shows the Antarctic is in continuous darkness, experiencing 24 hours of night.

This diagram illustrates how Earth's axial tilt affects sunlight distribution during the June solstice, causing one hemisphere to experience continuous daylight while the opposite has continuous darkness.

Figure 2.5.8: Conditions in December

Diagram of Earth tilted on its axis to illustrate sunlight distribution during the December solstice. Earth is shown as a circle tilted to the left. Labels mark the North Pole (NP) at the top, the South Pole (SP) at the bottom, and the Equator across the middle. Two additional latitude lines are labeled: 23.5 degrees North (Tropic of Cancer) and 23.5 degrees South (Tropic of Capricorn).

Three orange horizontal bands labeled “Sunlight Beam” enter from the right, representing incoming solar radiation:

- The top sunlight beam does not reach the North Pole, indicating that the Arctic Circle is in full darkness, with 24 hours of night.
- The middle beam hits the Equator, showing balanced solar exposure at this latitude.
- The bottom beam directly hits the South Pole, demonstrating that the Antarctic Circle is fully illuminated, with 24 hours of daylight.

This diagram visually explains that during the December solstice, the Southern Hemisphere is tilted toward the Sun, resulting in summer and longer days. The Northern Hemisphere is tilted away, experiencing winter and shorter days, including polar night conditions near the Arctic Circle.

Figure 2.6.1: Length of Day vs. Month

Graph showing how day length changes throughout the year at different latitudes in the Northern Hemisphere. The x-axis represents months from January to December. The y-axis represents hours of daylight, ranging from 0 to 24 hours.

Five color-coded curves represent different latitudes:

- Blue curve (70°N): Shows extreme variation. Peaks at 24 hours of daylight during the June solstice and drops to 0 hours during the December solstice. Represents polar day and polar night.
- Green curve (60°N): Peaks around 19 hours in June and drops to about 5 hours in December.
- Red curve (50°N): Peaks near 16.5 hours in June and falls to about 8 hours in December.
- Orange curve (30°N): Shows less variation, with a peak just over 14 hours in June and a low around 10 hours in December.
- Horizontal purple line (Equator): Constant at 12 hours of daylight all year long.

Vertical dashed lines mark four key astronomical events:

- March Equinox and September Equinox show where all curves intersect near 12 hours, indicating equal day and night at all latitudes.
- June Solstice shows maximum daylight in the Northern Hemisphere.
- December Solstice shows minimum daylight in the Northern Hemisphere.

The graph illustrates that the closer a location is to the poles, the more variation it experiences in day length throughout the year.

The Equator receives consistent daylight year-round.

Figure 2.6.2: Total Insolation vs. Month

Line graph showing how solar insolation (incoming solar radiation) varies over the months at different latitudes in the Northern Hemisphere. The x-axis represents months from January (J) to December (D). The y-axis measures insolation in watts per square meter (W/m^2), ranging from 0 to 600.

There are four color-coded lines representing different latitudes:

- Orange line (90°N, North Pole): Insolation is zero for much of the year, rising sharply in April and peaking around 500 W/m^2 at the June Solstice, then dropping to zero again by September. This line shows extreme seasonal variation due to polar night and polar day.
- Red line (60°N): Starts low in winter, rises steeply through spring, peaking just under 500 W/m^2 in June, then gradually declines through fall and winter.
- Green line (30°N): Shows a more moderate curve, peaking just above 450 W/m^2 in June and dipping to about 250 W/m^2 in winter.
- Blue line (0°, Equator): Relatively flat line around 400 W/m^2 throughout the year, indicating minimal seasonal variation in solar radiation at the Equator.

Four vertical dashed lines mark the March Equinox, June Solstice, September Equinox, and December Solstice, indicating key points in Earth's solar calendar.

The graph shows that higher latitudes receive more variable insolation throughout the year, while the Equator receives consistent sunlight. Peaks in insolation occur around the June Solstice for all Northern Hemisphere locations.

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3: AIR TEMPERATURE

Introduction

Air temperature is one of the most fundamental weather variables, influencing nearly every aspect of daily life. It dictates how we dress, the food we eat, and even shapes our moods and activities. But what is air temperature? We know temperature is a measure of how hot or cold an object is. Similarly, air temperature is a measure of how hot or cold the air around us is. While this explanation provides us with a basic understanding of temperature, it doesn't reveal what temperature really is. On a fundamental level, temperature is the measure of the average kinetic energy in the molecules of an object. Thus, when we talk about air temperature, we're talking about how energetic the air molecules are. Warm air molecules have more kinetic energy than cold air molecules. It's commonly measured using a thermometer (Figure 3.1), typically in degrees Celsius (°C) or Fahrenheit (°F).

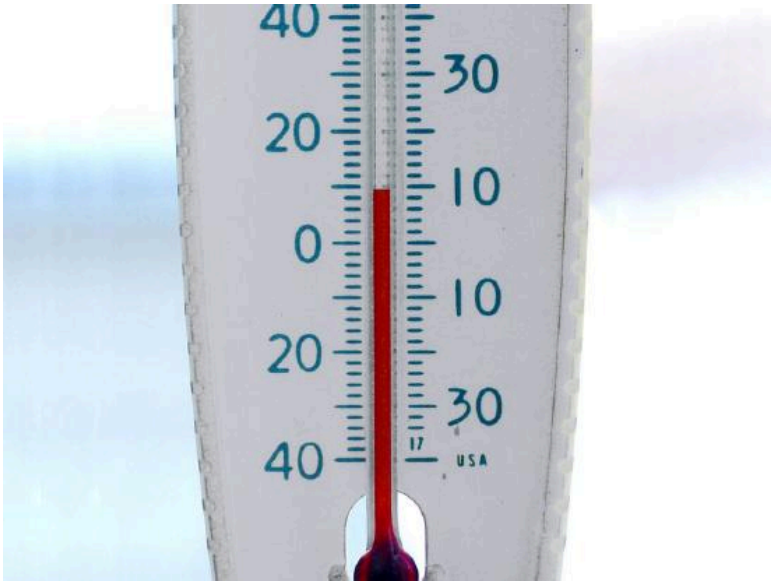


Figure 3.1: A thermometer is commonly used to measure the ambient air temperature. (CC BY 2.0; Don via Wikimedia Commons)

But beyond personal experience, air temperature has far-reaching implications. It plays a crucial role in agriculture, determining growing seasons and affecting crop yields. Extreme temperatures pose significant health risks—heatwaves can lead to heat exhaustion and dehydration, while cold spells increase the risk of frostbite and hypothermia. Infrastructure is also influenced; temperature fluctuations can expand and contract materials, affecting roadways, buildings, and transportation systems. All these different weather phenomena occur because the Sun heats the Earth unevenly. Thus, Meteorologists study air temperature to predict weather patterns, monitor climate changes, and prepare for extreme events. As global temperatures rise due to climate change, understanding temperature trends becomes increasingly vital for adapting to environmental shifts and mitigating their impacts.

Learning Objectives

By the end of this investigation, you should be able to:

- Identify temperatures at any given location on a weather map.
- Identify types of advection at any given location using isotherms and wind barbs.
- Measure human comfort levels using temperature indices.

Navigational Note

Investigation 3 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

3.1: Measurements
3.2: Mapping
3.3: Advection
3.4: Applications
3.5: Accessible Descriptions

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3.1: Measurements

Measuring Air Temperature

Before we can analyze air temperature measurements from around the world, a set of rules must govern how they are measured. These rules establish uniformity among weather stations, enabling the accurate comparison and analysis of air temperatures worldwide. Let's cover these rules:

1. Temperatures near the ground vary widely over a 24-hour day because the ground is the first surface to receive heat during the day and the first to lose it at night. Thus, **a thermometer needs to be placed approximately 1.5-2 meters above the ground (at eye level).**
2. Solar radiation is powerful and warms up everything it touches, including your face, the ground... and a thermometer. In fact, by warming a thermometer, solar radiation could lead to an inaccurate temperature reading. Thus, **a thermometer needs to be placed in the shade.**
3. However, in the open, numerous factors can "contaminate" the thermometer reading, making it less accurate. For instance, dust, pollen, moisture, and other substances can come into contact with the thermometer. To prevent these things from interfering with the thermometer reading**, the thermometer should be placed in a shelter.**
4. However, a completely enclosed shelter will trap heat, causing the thermometer reading to differ from the open-air temperature. Thus, **the shelter in which we house the thermometer must be well-ventilated.**



Figure 3.1.1: A Cotton Region Shelter, also known as a Stevenson screen, is a standard housing unit for meteorological instruments. (CC BY-SA 3.0; Famartin via Wikimedia Commons)

To recap, air temperature must be measured at 1.5-2 meters above the ground, in a shaded, but well-ventilated shelter. In the U.S., this type of shelter is known as the Cotton Region Shelter (Figure 3.1.1). With this information, let's try to answer the following question.

1. Suppose you and a friend went outside to measure the temperature, and your friend held the thermometer, gripping the bulb, up to eye level in the shade. Would your friend's measurement be accurate? Why or why not?

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3.2: Mapping

Air Temperature on a Map

Meteorologists need to understand how air temperature varies across the country to warn specific regions about current weather conditions (e.g., heatwaves, cold fronts) and to predict future changes (e.g., future heatwaves or cold fronts). Thus, once air temperature data is collected from weather stations across the country using the previously mentioned methods, it is then plotted on a temperature map similar to Figure 3.2.1. This map provides Meteorologists a broad perspective of current weather conditions across the country.

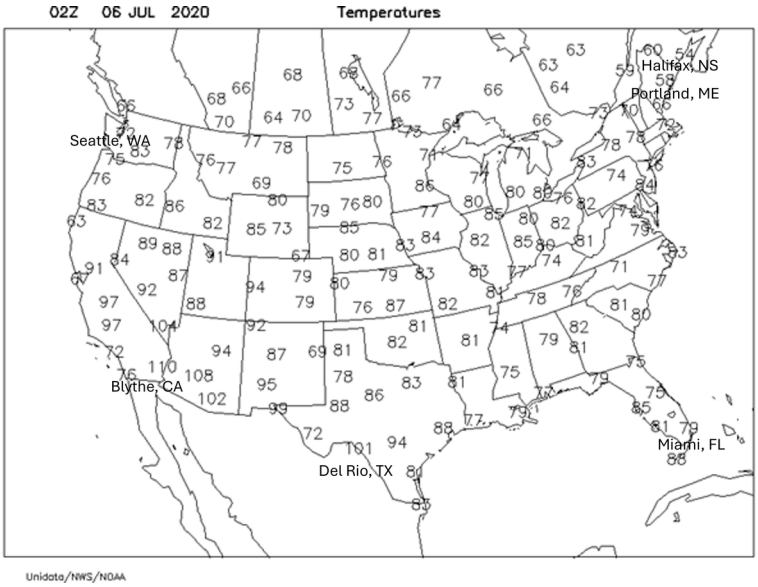


Figure 3.2.1: Surface air temperature data for the Continental United States at 0200 UTC on July 6, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of the image.

Let's identify any notable air temperature patterns on the weather map.

2. The coldest air temperature on the map is 54°F, which is located near:
   a. Seattle, Washington
   b. Halifax, Nova Scotia
   c. Portland, Maine

3. The warmest air temperature on the map is 110°F, which is located near:
   a. Miami, Florida
   b. Del Rio, Texas
   c. Blythe, California

Isotherms

It probably took some time to find the maximum and minimum temperatures on the map. Well, the good news is that to make it easier to identify air temperature patterns, we can plot lines of constant temperature on the map. These lines are called Isotherms and are formed by connecting nearby points at the same temperature. Figure 3.2.2 is for an hour earlier than Figure 3.2.1, with isotherms along with station temperatures on it.

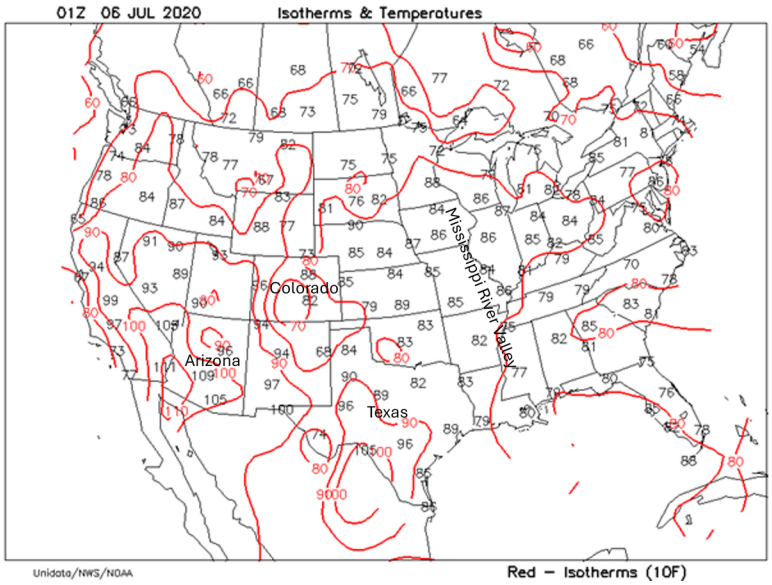


Figure 3.2.2: Surface Air Temperature data with isotherms for the Continental United States at 0100 UTC on July 6, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of the image.

4. Based on Figure 3.2.2, there are isotherms for temperatures of:
   a. 40, 50, 60, 70
   b. 50, 60, 70, 80, 90
   c. 60, 70, 80, 90, 100, 110
   d. 60, 65, 70, 75

5. The interval, or the difference in value between two consecutive isotherms, is:
   a. 5
   b. 10
   c. 20

If you were now asked again to find temperatures like 54°F or 110°F on the map, you don't need to read the temperature at every station. You can search through fewer isotherm lines to find one with a similar number. The station temperature you are searching for should be close to that line. Attempt to answer questions 2 and 3 again, using the isotherm map in Figure 3.2.2. Now that we have understood how isotherms can help us understand the temperature patterns across a region, there are a few key properties of isotherms that we need to understand first:

- Isotherms indicate that all locations beneath a given isotherm experience the same temperature.
- Isotherms divide temperatures greater than the isotherm's value from temperatures lower than the isotherm's value. For example, the 80°F isotherm goes through the Mississippi River Valley, which includes the area between Arkansas and Mississippi, Missouri and Tennessee, and Kentucky. Notice that station temperatures on the immediate right (East) side of the isotherm are lower than 80°F, while temperatures to the left of the isotherm are greater than 80°F.
- Isotherms that close upon themselves to form a complete circle do the same thing. They divide lower-temperature regions from higher-temperature regions. Focus on the 100°F circle over South-Eastern California, Southern Nevada, and Western Arizona. Every station outside that circle has a temperature below 100°F, while every station inside it has a temperature above 100°F. The 70°F circle over Southern Colorado also behaves similarly. Everything outside of the circle has a temperature greater than 70°F, while everything inside of it has a temperature lower than 70°F.

6. Focus on the isotherm Bullseye over Central Colorado. As you approach the center of the Bullseye from Texas or Arizona, the isotherm values _____.
   a. increase
   b. decrease
7. Therefore, the temperature in the center of the Bullseye over Central Colorado is ___ than the temperature of the areas surrounding the Bullseye.
   a. higher
   b. lower

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3.3: Advection

Types of Advection

Advection is defined as the horizontal movement of a substance or property due to the bulk motion of a fluid, such as air or water. Imagine smoke from a chimney being transported horizontally towards you by the wind. While many factors, such as humidity and dust, can advect, weather forecasters often focus on the advection of heat in the atmosphere. There are two types of advection: warm-air and cold-air advection.

- Warm air advection occurs when warmer air moves into a region, displacing cooler air.
- Cold-air advection occurs when cooler air moves into a region, displacing warmer air.

We can use a combination of Isotherms and wind barbs to determine whether any advection is occurring. This is summed up in Figure 3.3.1.

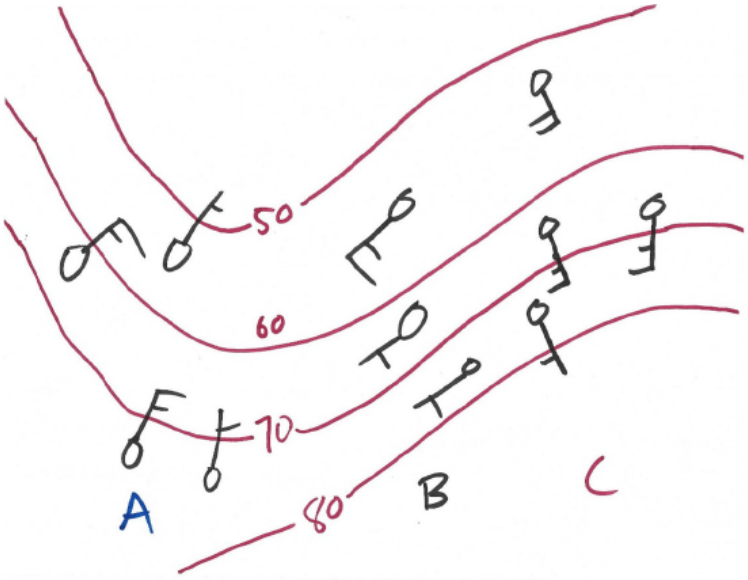


Figure 3.3.1: Advection shown using isotherms and wind barbs. (CC BY 4.0; Alicia Mullens) Alternative description of the image.

First, suppose the wind barbs are perpendicular (or nearly perpendicular) to their nearest isotherm. In that case, some form of advection is occurring, as the wind appears to be blowing from warmer to cooler, or from cooler to warmer, temperature regions. Warm air advection (station C) occurs when the wind barbs point toward warmer air or higher isotherm values. Cold air advection (station A) occurs when the wind barbs point toward cooler air or lower isotherm values. If the wind barbs are parallel (or nearly parallel) to their nearest isotherm, we say the station isn't experiencing advection (station B).

Now, let's investigate advection on a U.S. map, with city weather stations represented by letters A through F. Figure 3.3.2 is a simplified map of select isotherms, wind barbs, and frontal systems. A cold front is defined as the leading edge of a cooler, denser air mass that replaces a warmer air mass, causing a noticeable drop in temperature. It is represented on a weather map by a long, blue, curved line with spikes to indicate direction of movement. A warm front is the leading edge of a warmer, less dense air mass replacing a cooler air mass, causing a noticeable increase in temperature. On a weather map, it is represented by a long, red, curved line with semicircular humps. Cold and warm fronts illustrate air movement and should corroborate surface station wind directions. Using this information, let's answer the following questions.

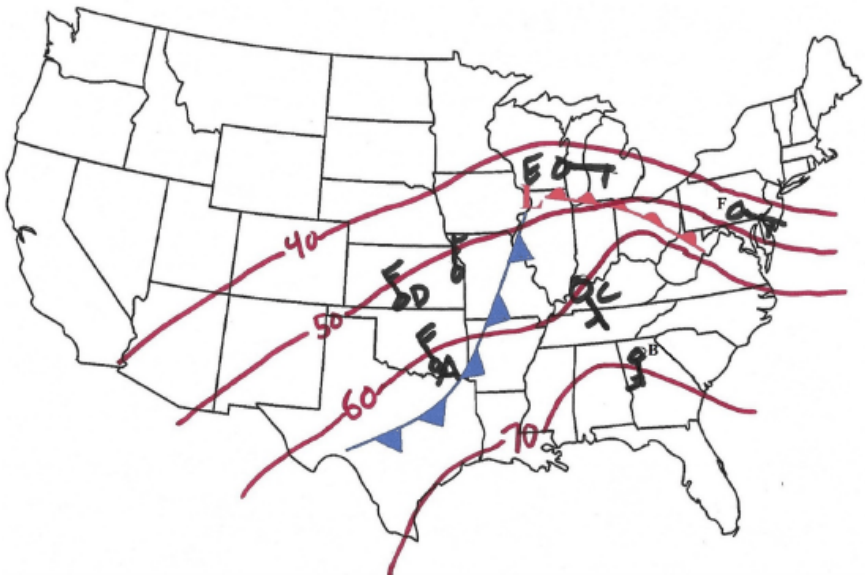


Figure 3.3.2: Simplified map of Isotherms, Fronts and Wind Barbs. (CC BY 4.0; Alicia Mullens) Alternative description of the image.

8. In Figure 3.3.2, cities ___ are experiencing Warm-Air advection on this map.
   a. A & D
   b. E & F
   c. A & C
   d. B & C

9. Cities ___ are experiencing Cold-Air advection on this map.
   a. A & D
   b. B & F
   c. C & D
   d. E & F

10. Cities ___ aren't experiencing any advection on this map.
    a. A & D
    b. C & F
    c. E & F
    d. C & B

Now let's use what we learned to investigate a real-life weather map setup in Figure 3.3.3. The map displays Isotherms, Station Models, and Fronts for the Continental United States at 1300 UTC on February 8, 2017.

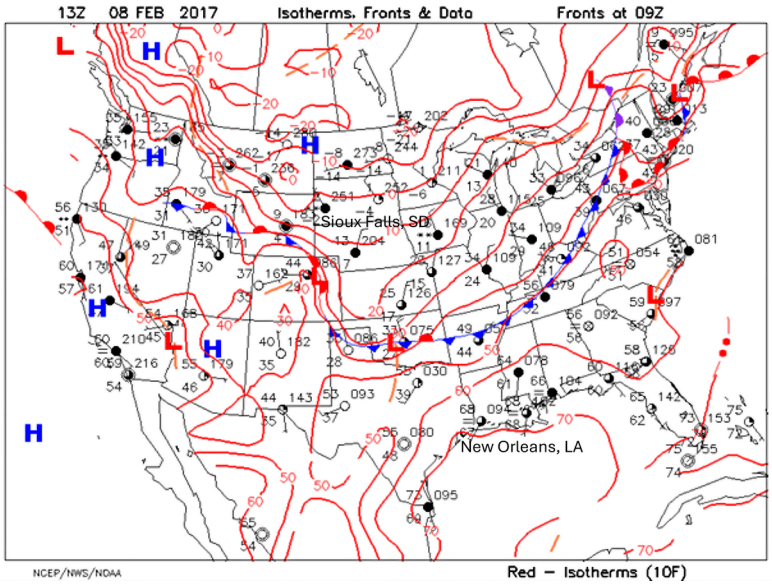


Figure 3.3.3: Isotherms, Station Models, and Fronts for the Continental United States at 1300 UTC on February 8, 2017. (Public Domain; American Meteorological Society via NCEP/NWS) Alternative description of image.

11. Areas in the south-eastern United States, ahead of the cold front, primarily had temperatures in the:
    a. 30s and 40s
    b. 50s and 60s
    c. 70s and 80s

12. New Orleans, in southeastern Louisiana, had a temperature of 68°F and a dew point of 68°F. Winds were blowing from the South at:
    a. 5 knots
    b. 10 knots
    c. 15 knots

13. Note that New Orleans' wind barb is nearly perpendicular to the 70 isotherm it intersects. That is a sign of advection. Based on where New Orleans' wind barb is pointing, in New Orleans, the air is blowing:
    a. From colder air in the south to warmer air in the north
    b. From warmer air in the south to colder air in the north

14. Therefore, New Orleans is experiencing ___ advection, as is much of the southeastern United States.
    a. warm air
    b. cold air
    c. no

15. Let us investigate Sioux Falls in eastern South Dakota. Sioux Falls' air temperature is 1°F with a dew point of -4°F. Winds at Sioux Falls are blowing from the northwest at ___.
    a. 10 knots
    b. 20 knots
    c. 30 knots

16. Similar to the wind barb at New Orleans, Sioux Falls' wind barb is almost perpendicular to the nearby 0°F isotherm. Based on where the wind barb is pointing, winds are blowing ___ at Sioux Falls.
    a. from warm air to cold air
    b. from cold air to warm air

17. Therefore, Sioux Falls is experiencing ___ advection.
    a. warm air
    b. cold air
    c. no

Finally, let's infer an observation based on the overall pattern of winds both ahead and behind the cold front in Figure 3.3.3. You can also refer to Figure 3.3.2 for a more simplified version. Based on the information provided, we can typically expect warm-air advection ahead of a Cold Front and cold-air advection behind it. Similarly, one can typically expect cold-air advection ahead of a warm front and warm-air advection behind it.

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3.4: Applications

Applications of Temperature

As previously noted, air temperature is often considered the most critical weather variable for the general public. When you open a weather app, chances are that the first thing you notice is the air temperature. The primary reason is that air temperature is essential to human comfort. Our bodies, which are constantly metabolizing, strive to maintain an average body temperature of 98.6°F. If it's too cold outside, our bodies lose heat faster than they can generate it, and begin to cool below 98.6°F. This can cause hypothermia. On the other hand, if it's too hot outside, our bodies lose heat too slowly, leading to an increase in body temperature. This causes heat exhaustion, and in extreme cases, heat stroke.

Because temperature is so essential to our comfort, we often resort to using heating or cooling devices when temperatures fall outside our comfort zone. Utility companies (such as Pacific Gas and Electric in Northern California) are aware of this and closely monitor weather conditions to ensure adequate generation to meet demand. There are numerous tools for this, but in this investigation, we focus on Heating and Cooling degree days. We will also investigate other important temperature metrics, e.g., growing degree days, wind chill, and heat index.

Heating and Cooling Degree Days

To forecast the amount of energy typically required for heating or cooling, energy companies use heating and cooling degree days as a key metric. Here's how they work:
Average Temperature: The average between the day's daytime high temperature and the nighttime low temperature.

- For example, if the high temperature is 85°F and the low temperature is 65°F. The average would be 75°F. You can calculate the average by adding the high and low temperatures and then dividing the sum by 2.
- When the calculated average temperature is not an integer, we round up to the next integer. For example, if the high temperature is 76°F and the low temperature is 67°F, the average temperature is 71.5°F, which rounds up to 72°F.

Heating Degree Days: One heating degree day (HDD) is accumulated for every degree that the day's average temperature is below 65°F. For example, if the high temperature is 70°F and the low temperature is 50°F, the average temperature would be 60°F. If we subtract 65°F from 60°F, we get --5°F. This would equate to 5 Heating Degree Days for that day.

18. On May 17, 2019, the weather station at San Jose airport recorded a high temperature of 62°F and a low temperature of 48°F. The average temperature on that day would be:
    a. 55°F
    b. 54°F
    c. 56°F
    d. 53°F

19. Therefore, on May 17, 2019, San Jose airport accumulated _____ HDDs.
    a. 11
    b. 5
    c. 10
    d. 9

Now, let's compare two cities, Chicago, in northeastern Illinois, and the coastal town of Eureka, in northwestern California. Figure 3.4.1 graphs the monthly average temperatures for both Chicago and Eureka, with a line representing a constant 65°F monthly temperature for the entire year.

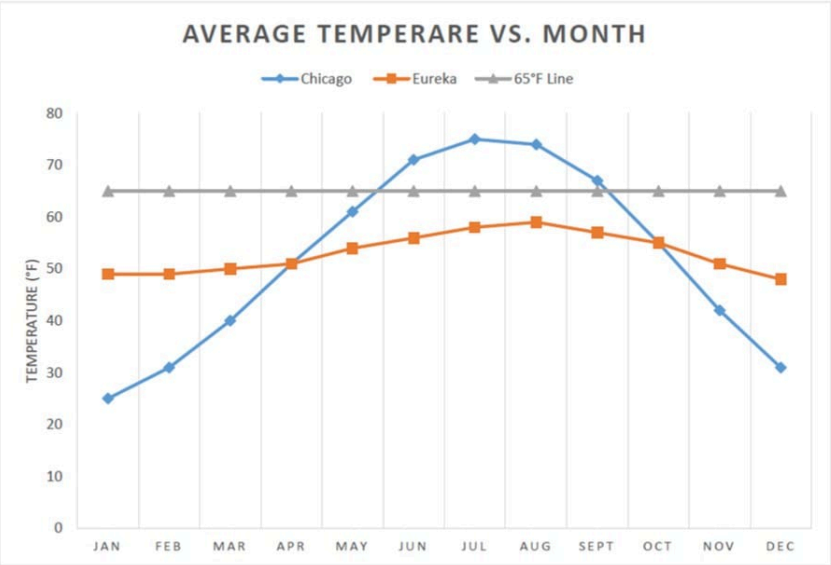


Figure 3.4.1: Average monthly temperatures for Chicago and Eureka with a constant 65°F temperature line. Table 3.4.1 presents the data in a tabular form. (CC BY 4.0; Alicia Mullens)

Table 3.4.1: Average monthly temperatures for Chicago, IL, and Eureka, CA in °F.

Month	Chicago	Eureka
Jan	27	50
Feb	32	50
Mar	42	51
Apr	53	53
May	64	55
Jun	72	57
Jul	75	58
Aug	74	58
Sep	66	57
Oct	54	55
Nov	42	52
Dec	30	50

20. Based on Figure 3.4.1 or Table 3.4.1, _____ has more months per year with HDD accumulation. Remember, we don't need to calculate the daily HDDs. We need to compare the number of months in which HDDs accumulate across the cities, based on the data.
    a. Eureka
    b. Chicago

21. Eureka likely has substantially lower variation in average temperature because, compared to Chicago, Eureka is:
    a. Much closer to the ocean
    b. At a much lower altitude
    c. Both of these

Cooling Degree Days are accumulated when the daily average temperature at a location exceeds 65°F. On these days, energy is used to cool a household rather than to warm it. For example, if the high temperature is 83°F and the low is 68°F, the average temperature for the day is 75.5°F, rounded to 76°F. 76°F – 65°F = 11°F above 65°F, which would equal 11 CDDs.

22. Based on 3.4.1 or Table 3.4.1, Chicago has _____ months with accumulated CDDs.
    a. 0
    b. 2
    c. 4
    d. 6

23. On the other hand, Eureka has _____ months with accumulated CDDs.
    a. 0
    b. 2
    c. 4
    d. 6

This suggests that inland locations, such as Chicago, IL, and St. Louis, MO, experience strong seasonal temperature patterns, with cold winters and warm summers. Meanwhile, coastal locations such as Eureka and San Francisco, CA, experience relatively stable temperatures year-round, fluctuating only slightly. Similarly, due to warmer average temperatures, locations in the southern half of the United States will accrue more CDDs and fewer HDDs. Meanwhile, due to cooler average temperatures, locations in the northern half of the United States will accrue more HDDs and fewer CDDs.

Wind Chill

While temperature is essential to human comfort, other factors, such as wind, can significantly affect how temperature feels to the body. Wind does not directly affect air temperature, but it does affect how it feels to our bodies. Our bodies warm up the air immediately above our skin, creating a thin "blanket" layer of warmth that keeps us warm. On windy days, this layer of warmth is displaced, forcing the body to radiate more heat, thereby making it feel cooler. This may be a pleasant surprise on hot days, but it could create potentially dangerous conditions on cold days. To quantify this, the National Weather Service has developed the Wind Chill Index, which provides Wind Chill Equivalent Temperatures (WETs) for given air temperatures and wind speeds. Figure 3.4.2 is a WET conversion chart commonly used by the National Weather Service to warn residents about wind chill. To use the chart, first start with air temperature on the "x" axis, and then travel down that column until you intersect the row for your given wind speed.

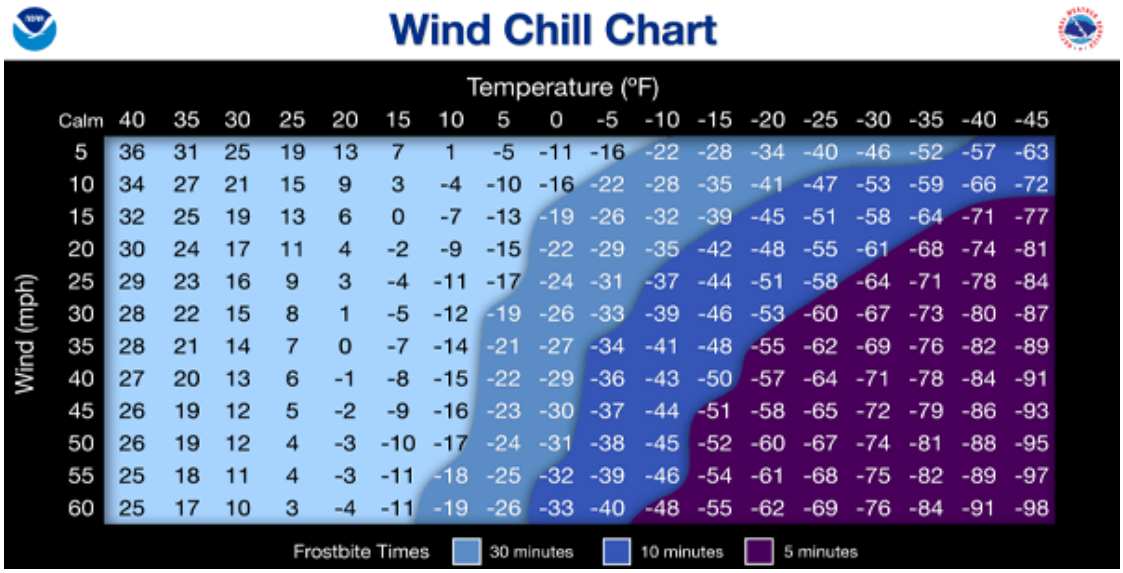


Figure 3.4.2: A Wind Chill chart shows how the wind makes you feel colder. Table 3.4.2 presents the WET conversion in a tabular form. (Public Domain; Understanding Wind Chill via NWS)

Table 3.4.2: Wind Chill Equivalent Temperatures (°F) by NWS

Wind speed (mph)↓	Temperature (°F)																	
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-15	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	26	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-28	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-29	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-30	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-31	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-32	-40	-48	-55	-62	-69	-76	-84	-91	-98

For example, at 25°F (first row) and 30 mph (left column), the WET would be 8°F. Note that WETs are provided only for cold air temperatures that may cause frostbite (freezing, discoloration, and potential loss of external limbs) or hypothermia. Frostbite on exposed skin can occur within a few minutes, based on wind chill values:

- 30 minutes or less: Wind chill below -20°F
- 10 minutes or less: Wind chill below -35°F
- 5 minutes or less: Wind chill below -45°F

24. On March 11, 2019, the weather station at De Anza College recorded a minimum temperature of 40°F and a peak wind speed of 15 mph. Assuming that the peak wind happened at the same time as the low temperature, the wind chill at De Anza College would be:
    a. 40°F
    b. 36°F
    c. 32°F

Heat Index Temperature

The final human comfort metric we'll investigate is the Heat Index Temperature. When our body temperature increases, we sweat to cool ourselves. Cooling occurs because sweat evaporating from the body cools us. However, when relative humidity is high (we'll cover relative humidity more in depth in Investigation 4), it is more difficult for water to evaporate, resulting in less cooling. As a result, air temperatures feel hotter than they are. This can be summed up in the common phrase: "It's not the heat, it's the humidity." However, just as wind chill does not affect air temperature, humidity does not either. Instead, it affects perceived temperature by reducing evaporation. Figure 3.4.3 is a Heat Index chart, which works similarly to the Wind Chill chart in Figure 3.4.2, but we replace wind speed with relative humidity instead.

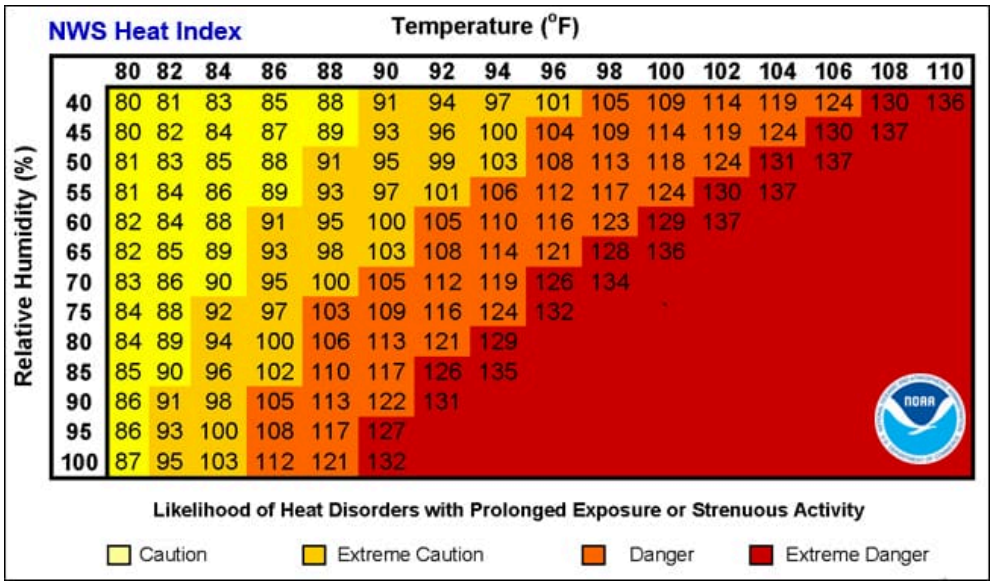


Figure 3.4.3: A Heat Index chart shows how higher humidity makes you feel warmer. Table 3.4.3 provides the data in a tabular form. (Public Domain; What is the Heat Index via NWS)

Table 3.4.3: Heat Index Temperatures (°F) by NWS

Relative Humidity (%) ↓ Temp (°F) →	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	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										

25. A high Relative Humidity can make relatively mild temperatures unbearable. For example, a temperature of 84°F and a relative humidity of 95% would yield a heat index of:
    a. 90°F
    b. 100°F
    c. 98°F
    d. 102°F

Desert Cities, like Phoenix, Arizona, are typically protected from the worst of summer conditions by their low relative humidity. For example, at 4 pm on June 26, Phoenix had a temperature of 100°F, and a Relative Humidity of 13%. While this calculation cannot be done using the condensed version of the Heat Index in Figure 3.4.3 or Table 3.4.3, you can use a heat index calculator (on the NOAA Heat Index webpage) to determine that Phoenix has a heat index of 95°F. In this case, the heat index of Phoenix is lower than the actual air temperature! At the same time, New Orleans, Louisiana, had an air temperature of 92°F and a relative humidity of 45%. This yields a heat index of 96°F, which is warmer than Phoenix's, even though the air temperature in New Orleans was lower.

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3.5: Accessible Descriptions

Figure 3.2.1: Surface Air Temperature data

This is a surface air temperature map of the continental United States, showing temperatures in degrees Fahrenheit at various weather stations. The map is valid for 06 Z (2:00 AM EDT) on July 6, 2020, and was produced by the NWS/NOAA (National Weather Service/National Oceanic and Atmospheric Administration).

General Layout:

- The map outlines each of the 48 contiguous U.S. states with numerical temperature values displayed at station locations.
- All temperatures are shown in plain black numerals, distributed across the country without any color shading.
- Temperatures range from the 60s°F in the northern tier to over 100°F in the Southwest, especially in the desert regions.

Regional Highlights:

- Western U.S.:
  - California and Arizona show extremely high temperatures, including 110°F in southeastern California and 102°F in southern Arizona.
  - Nevada, Utah, and New Mexico report widespread temperatures in the 90s.
  - Pacific Northwest is cooler, with readings in the 60s to 70s.
- Central U.S.:
  - States like Kansas, Oklahoma, and Texas show temperatures in the 80s and low 90s.
  - Colorado and Wyoming exhibit a broader range, from 70s in the north to upper 80s and 90s in the south.
- Eastern U.S.:
  - Temperatures are mostly in the 70s and 80s, with cooler readings (mid-60s to low 70s) along parts of the Appalachians and Northeast coast.
  - Southeast states (Florida, Georgia, Alabama) show temperatures in the upper 70s to mid-80s, with Florida reporting 86°F to 88°F.
- Northern Plains and Great Lakes Region:
  - Temperatures are generally cooler, ranging from 60°F to 75°F, with the Upper Midwest seeing some temperatures below 70°F.

Figure 3.2.2: Surface Air Temperature data with isotherms

This is a surface temperature map of the continental United States, valid for 01Z on July 6, 2020, and includes both temperature observations (in °F) and isotherms (contour lines of equal temperature).

Key Features:

- Numerical temperature values are displayed at numerous observation points across the U.S., representing air temperatures in degrees Fahrenheit.
- Lines on the map are labeled isotherms, representing contours of equal temperature, drawn at 10°F intervals.
- The isotherms create closed loops and bands across the map, visually depicting temperature gradients and regional heat patterns.

Regional Observations:

- Southwest U.S. (California, Arizona, Nevada)
  - The hottest region on the map, with isotherms for 90°F, 100°F, and 110°F clearly marked.
  - Southern California and Arizona show stations with temperatures as high as 110°F to 112°F.
  - Dense packing of isotherms indicates a steep temperature gradient.

- Central and Southern Plains (Texas, Oklahoma, Kansas):
  - A broad area enclosed by 90°F and 100°F isotherms, with many stations reporting temperatures between 90°F and 100°F.
  - An enclosed "bullseye" region in southern Texas suggests localized peak temperatures.
- Midwest and Great Plains:
  - Isotherms span from 80°F to 90°F, curving through states like Nebraska, Iowa, and Illinois.
  - Cooler readings of 70°F to 80°F are found in parts of Colorado and the northern Midwest.
- Southeast and East Coast
  - Generally warm and uniform, with most stations between 80°F and 90°F.
  - Isotherms are more widely spaced, indicating weaker temperature gradients.
- Pacific Northwest and Northern Rockies:
  - Cooler regions, with isotherms indicating 60°F to 70°F, especially in higher elevations and coastal zones

Figure 3.3.1: Advection shown using isotherms and wind barbs

This diagram illustrates temperature advection using simplified station models and isotherms (lines of equal temperature).

Visual Elements:

- Station Models:
  - Each station is represented by a circle with a wind barb extending from it, pointing in the direction wind is coming from.
  - The length and shape of the barbs suggest wind speed (not numerically labeled).
- Contour Lines (Isotherms):
  - There are five curved, horizontal lines labeled 50, 60, 70, and 80, denoting temperature in degrees Fahrenheit.
  - These lines curve from upper left to lower right, separating areas of different surface temperature.
- Wind Patterns and Zones:
  - Winds in region A (left) mostly flow parallel to isotherms, indicating little to no temperature advection.
  - Winds in region B (center) are crossing isotherms from cooler to warmer zones (from left to right), suggesting warm air advection.
  - Winds in region C (right) are flowing from warmer to cooler zones, indicating cold air advection.
- Labels:
  - Three large capital letters—A, B, and C, marking different zones for interpretation.

Figure 3.3.2: Simplified map of Isotherms, Fronts, and Wind Barbs

This hand-drawn weather map of the continental United States shows surface isotherms, a cold front, and wind barbs, along with labels A through F marking specific city locations for analysis. The image is instructional, highlighting the spatial relationship between wind direction and temperature fields.

Key Elements:

- Isotherms (Lines of Equal Temperature)
  - Curved lines are labeled 40°F, 50°F, 60°F, and 70°F.
  - These lines span from the Southwest (California and Texas) to the Northeast, marking areas of consistent surface temperature.
- Cold Front:
  - A line with triangles pointing eastward stretches from eastern Texas to the Midwest, indicating the location of a cold front.
- Labeled Cities (A–F):
  - The map uses letters A through F to indicate six city locations, each placed to illustrate how local wind barbs relate to surrounding isotherms.
- Wind Barb Interpretation at Each City:
  - City A (Eastern Texas): Wind barb is oriented perpendicular to the isotherms, blowing across them from lower to higher temperature values.
  - City B (Georgia): Wind barb is angled moderately across the isotherms, not fully perpendicular, but still cutting across several temperature contours.

- City C (Kentucky/Tennessee area): Wind barb is nearly parallel to the isotherms, indicating little directional crossing between temperature zones.
- City D (Oklahoma): Wind barb is oriented sharply across the isotherms, intersecting them at a steep angle from cooler to warmer values.
- City E (Southern Wisconsin / Chicago area): Wind barb is almost perpendicular to the isotherms, intersecting multiple temperature lines in a short distance.
- City F (Northeastern U.S.): Wind barb is angled across isotherms, showing a noticeable but not steep cross-contour flow.

Interpretation:

- The map demonstrates temperature advection, particularly in the context of a frontal boundary.
  - Warm air advection occurs ahead of the cold front, where southerly winds cross isotherms from warmer to cooler areas.
  - Cold air advection occurs behind the front, where northwesterly winds transport cooler air into warmer regions.
- The curvature and spacing of isotherms, combined with wind direction, help visualize where warming or cooling is occurring at the surface.

Figure 3.3.3: Isotherms, Station Models, and Fronts

This image is a detailed surface weather analysis map of the continental United States, valid at 13Z (8:00 AM EST) on February 8, 2017. It shows isotherms, surface fronts, station data, and areas of high and low pressure.

Key Elements:

- Isotherms (lines of equal temperature):
  - Labeled in 10°F increments (e.g., 20, 30, 40, 50, 60, 70).
  - These lines curve across the country, helping visualize temperature gradients and regions of advection.
- Surface Fronts:
  - A cold front extends from Arkansas to New York, pushing southeastward. It features triangle markers pointing in the direction of movement.
  - A warm front connects to a low-pressure center in the eastern U.S.
  - An occluded front is visible near the northeastern states.
  - A stationary front in the central U.S. marks the boundary between different air masses.
- Highs and Lows (H and L Symbols):
  - Hs denote areas of high pressure, found in parts of the West, Northern Rockies, and Midwest.
  - Ls mark low-pressure centers, including one in the Southern Plains and another off the Pacific Northwest coast.
- Station Models (Black Symbols):
  - Small circular plots represent weather stations, showing temperature, wind barbs, cloud cover, and pressure trends.
  - Temperatures range from single digits (°F) in the northern Plains to 60s and 70s in the Southeast.
- Specific Wind Barbs:
  - New Orleans, Louisiana: The wind barb shows a south wind at 10 knots, indicated by a single full barb pointing straight upward (from the south).
  - Sioux City, Iowa: The wind barb shows a north-northwest wind at 25 knots, indicated by two full barbs and one half barb, with the shaft pointing from the northwest toward the station.
- Regional Highlights:
  - Cold Arctic air is present in the Upper Midwest and Northern Plains, with temperatures as low as single digits Fahrenheit and tightly packed isotherms.
  - Mild, moist air is present in the Southeast, with temperatures above 60°F and widespread southerly flow ahead of the cold front.
  - Strong temperature advection is evident where winds cross isotherms, especially near and ahead of the cold front in the eastern U.S.

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4: MOISTURE AND CLOUDS

Introduction

Have you ever wondered how a cloud, which consists of trillions of tiny liquid droplets, is able to form almost out of "thin air?" Or why dew can spontaneously form on surfaces in the middle of the night (Figure 4.1)? How about why you can have a "bad hair day"? All of those involve an interesting fact about our atmosphere. Our atmosphere is composed of 78% Nitrogen, 21% Oxygen, and at **least some Water Vapor** (between 0-4%). Indeed, the air that you are breathing right now consists of a certain amount of water vapor (also referred to as "moisture" in this investigation) in addition to the other gases you are taking in. This investigation explores the role that moisture plays in relative humidity, temperature, and cloud formation.



Figure 4.1: Dew commonly occurs when relative humidity is near 100%. (CC BY-NC 3.0; fir0002 via Wikimedia Commons)

Learning Objectives

- Discern how air temperature influences relative humidity.
- Investigate the effects of air pressure on humidity.
- Determine where clouds are present in the atmosphere on a Stuve Diagram.

Navigational Note

Investigation 4 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

4.1: What is Relative Humidity?

4.2: Relative Humidity Diurnal Cycle

4.3: Saturation and Clouds

4.4: Clouds in the Vertical Atmosphere

4.5: Accessible Descriptions

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4.1: What is Relative Humidity?

Humidity

Humidity is defined as the amount of water vapor in the air. Unlike the concentrations of Oxygen and Nitrogen in our atmosphere, which are fairly constant, humidity can vary greatly depending on location and time of day. This explains why some locations feel bone-dry while other locations feel muggy and gross. There are several variables meteorologists use to quantify humidity, but the one most commonly used by the public is **Relative Humidity**.

If you have a smartphone (Apple iPhone, any Android Phone, etc.), open the phone's weather app and check your current conditions. If you don't have a smartphone, you can view current weather information from the National Weather Service (NWS) for San Jose Airport. Scroll until you find Humidity.

1. On these apps, and/or the NWS weather page, humidity is given as a:
    a. Mass (grams, kilograms)
    b. Weight (pounds, ounces)
    c. Temperature (°C, °F)
    d. Percentage (%)

But what does that number mean? How does it change? Relative Humidity is the ratio of the amount of moisture in the atmosphere to the amount that the atmosphere could potentially contain at a given temperature and pressure. Some definitions refer to it as the ratio of existing water vapor to the maximum water vapor the air can "hold". It is important to know that the atmosphere doesn't really "hold" moisture. Instead, the atmosphere can contain a certain amount of moisture before it becomes saturated. To calculate Relative Humidity, there are two terms we need to learn:

- Vapor Pressure: The Mass of the moisture currently in the atmosphere.
- Saturation Vapor Pressure: The Mass of moisture that would be present in a saturated atmosphere.

In short, **Vapor Pressure** is the pressure exerted by the current amount of moisture in the atmosphere, whereas **Saturation Vapor Pressure** is the pressure exerted by the maximum amount of moisture that the air can contain. Vapor pressure is determined by the rates of evaporation and condensation, rather than by the physical space in the atmosphere available for moisture. If there is more moisture in the air, the vapor pressure would be high; if there were less moisture, it would be low.

On the other hand, saturation vapor pressure occurs when the rate of evaporation balances the rate of condensation. In this case, temperature is the primary factor that determines this pressure value. A cooler atmosphere favors less evaporation and more condensation, thus decreasing the amount of moisture in the atmosphere and the saturation vapor pressure. On the other hand, a warmer atmosphere favors greater evaporation and less condensation, thereby increasing atmospheric moisture and the saturation vapor pressure.

Vapor pressure (the amount of moisture in the atmosphere) can only be determined by actual observation. However, there is an equation, called the Clausius-Clapeyron equation, that models the saturation vapor pressure. While the equation, its derivation, and plot are beyond the scope of this class, Table 4.1.1 is a nifty table that we will use to determine saturation vapor pressure for a given temperature.

Table 4.1.1 Saturation vapor pressure table

Temperature (deg F)	Temperature (deg C)	Vapor Pressure (mb)
40	4.4	8.4
41	5.0	8.7

Temperature (deg F)	Temperature (deg C)	Vapor Pressure (mb)
42	5.6	9.1
43	6.1	9.4
44	6.7	9.8
45	7.2	10.2
46	7.8	10.6
47	8.3	11.0
48	8.9	11.4
49	9.4	11.8
50	10.0	12.3
51	10.6	12.7
52	11.1	13.2
53	11.7	13.7
54	12.2	14.2
55	12.8	14.8
56	13.3	15.3
57	13.9	15.9

Temperature (deg F)	Temperature (deg C)	Vapor Pressure (mb)
58	14.4	16.4
59	15.0	17.0
60	15.6	17.7
61	16.1	18.3
62	16.7	19.0
63	17.2	19.6
64	17.8	20.3
65	18.3	21.1
66	18.9	21.8
67	19.4	22.6
68	20.0	23.4
69	20.6	24.2
70	21.1	25.0
71	21.7	25.9
72	22.2	26.8
73	22.8	27.7

Temperature (deg F)	Temperature (deg C)	Vapor Pressure (mb)
74	23.3	28.7
75	23.9	29.6
76	24.4	30.6
77	25.0	31.7
78	25.6	32.7
79	26.1	33.8
80	26.7	35.0

2. Based on Table 4.1.1, a temperature of 55°F would yield a saturation vapor pressure of _____.
   a. 15.3 mb
   b. 14.8 mb
   c. 14.4 mb
   d. 55.0 mb
3. On the other hand, a temperature of 75°F would yield a saturation vapor pressure of:
   a. 23.2 mb
   b. 31.3 mb
   c. 29.6 mb
   d. 35.0 mb

What is the relationship that you observe between temperature and saturation vapor pressure?

4. Saturation vapor pressure _____ when the temperature _____.
   a. increases, increases
   b. decreases, increases
   c. does not change, increases
   d. increases, does not change

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4.2: Relative Humidity Diurnal Cycle

Daily Changes in Relative Humidity

Because temperature affects saturation vapor pressure, there can be a daily change in relative humidity, even if the actual amount of moisture in the atmosphere doesn't change. As temperatures warm, saturation vapor pressure increases, causing relative humidity to decline. Meanwhile, at night, the air temperature cools, lowering the saturation vapor pressure and increasing relative humidity. Let's investigate this more in-depth: Figure 4.2.1 is a plot of air temperature taken over a 24-hour period at the De Anza College weather station on January 24, 2019.

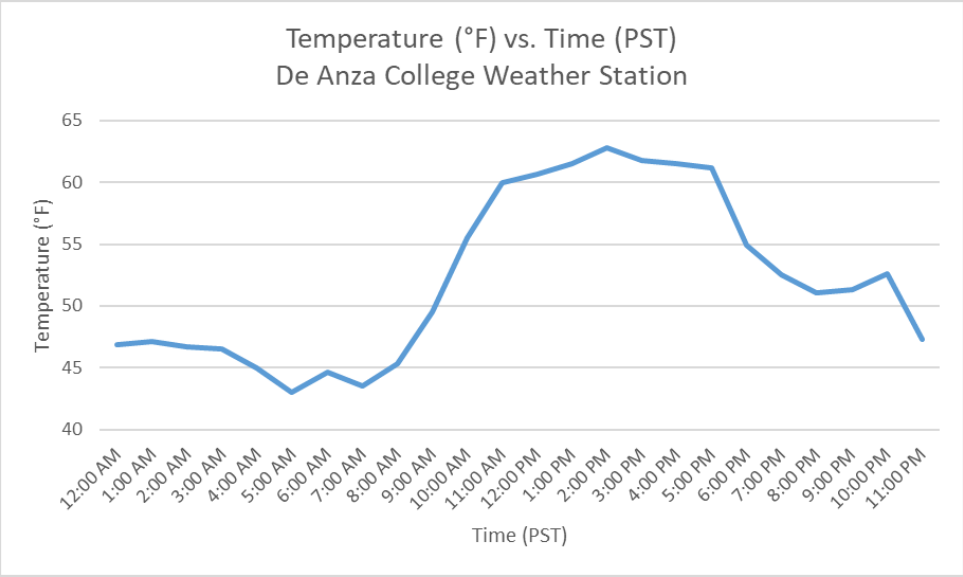


Figure 4.2.1: Temperature vs Time from the De Anza College Weather station, taken on January 24, 2019. (CC BY 4.0; Alicia Mullens)
Alternative description of image.

5. The high temperature on January 24, 2019, was approximately 63°F at:
   a. 12 pm
   b. 2 pm
   c. 4 pm
   d. 6 pm
6. The low temperature on January 24, 2019, was approximately 43°F at:
   a. 12 am
   b. 3 am
   c. 5 am
   d. 9 am
7. At the warmest time of the day, the saturation vapor pressure would be (based on the saturation vapor pressure table):
   a. 17.7 mb
   b. 20.3 mb
   c. 18.9 mb
   d. 19.6 mb
8. At the coldest time of the day, the saturation vapor pressure would be (based on the saturation vapor pressure table):
   a. 9.4 mb
   b. 10.2 mb
   c. 8.7 mb
   d. 11.8 mb

As previously mentioned, relative humidity is the RATIO of the amount of moisture in the atmosphere (vapor pressure) to the amount of moisture that the air can "hold" (saturation vapor pressure). A simple equation for relative humidity is:

$$RelativeHumidity = \frac{VaporPressure(mb)}{SaturationVaporPressure(mb)} * 100 \quad (4.2.1)$$

Let's assume that the vapor pressure is 9 mb, and there was no change in the amount of moisture (vapor pressure) in the atmosphere during the period from 12 am on January 24, 2019, to 12 am on January 25, 2019. Reminder: You can obtain the saturation vapor pressure using Table 4.1.1 or the online table.

9. The relative humidity at De Anza College would be _____ when the temperature is highest. (Hint: Use the saturation vapor pressure table.)
   a. 40%
   b. 46%
   c. 48%
   d. 53%
10. The relative humidity at De Anza College would be _____when the temperature is the lowest:
   a. 96%
   b. 89%
   c. 100%
   d. 92%
11. Just using the results from questions 9 and 10, we can say that relative humidity _____ as air temperature increases.
   a. increases
   b. decreases.
12. Therefore, during the day, the relative humidity will be the highest when:
   a. The temperature is the highest.
   b. The temperature is the lowest.

13. And the relative humidity will be the lowest when:
   a. The temperature is the highest.
   b. The temperature is the lowest.

We can confirm this result by examining the plot of Temperature, Dew Point Temperature AND Relative Humidity for that day (Figure 4.2.2). This data isn't directly available for the De Anza College weather station, but is available for nearby Moffett Field, in Mountain View, CA.

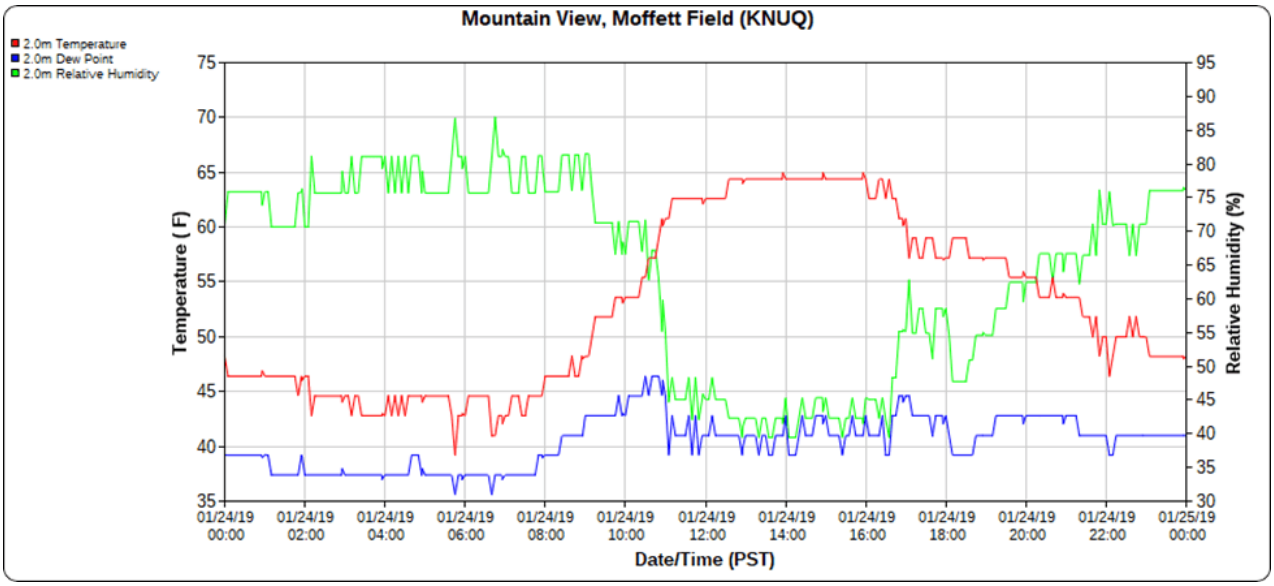


Figure 4.2.2: A plot of air temperature (red), dew point temperature (blue), and relative humidity (green), from Moffett Field on January 24, 2019. (CC BY-NC 4.0; MesoWest) Alternative description of image.

14. Assuming little change in moisture, the temperature (red line) and relative humidity (green line) on Figure 4.2.2 are _____ related:
   a. directly (when one increases, the other increases too)
   b. inversely (when one increases, the other decreases).

15. This _____ the conclusion we made in question 12 and 13.
    a. confirms
    b. cannot confirm.

Dew Point Temperature

In Figure 4.2.2, there is a third line that we haven't discussed yet – the blue line represents Dew Point Temperature, which is the temperature that the air needs to be cooled to in order for the atmosphere to become saturated. The Dew Point temperature is directly related to the amount of moisture in the air – a high dew point means the air is close to saturation, so it doesn't need to cool much. Whereas a low dew point means that the air is significantly unsaturated, and thus needs to be cooled substantially to become saturated.

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4.3: Saturation and Clouds

Cloud in a Bottle

When the air temperature equals the dew point, the atmosphere is saturated, and clouds begin to form. A fun (and easy) way to demonstrate this is by constructing a Cloud-in-a-Bottle. To do this, you need the following things:

- A squeezable plastic bottle
- Some water to pour into the bottle
- Some kind of smoke, or particulate matter (aerosols from an aerosol can are a good choice if you're uncomfortable with creating smoke)
- (Optional) A temperature strip that you can purchase at a fish supply store or on Amazon.com.

Once you have all of your equipment together, do the following steps:

1. Add a small amount of water to the bottle and close the lid. After a few minutes, the air in the bottle will become saturated. A good setup is shown in Figure 4.3.1.
2. Open the bottle and either spray in some aerosol, or light a match, blow it out, and squeeze and release the opened bottle to "suck in" the smoke
3. Place the lid back on the bottle, squeeze it for a minute, then release!

Caution

The fire produced by the matches can be dangerous if not handled properly, and the smoke can cause respiratory problems to sensitive groups... make sure to have a fire extinguisher nearby and to perform this in a well-ventilated location.



Figure 4.3.1: Cloud being generated inside a plastic bottle. (Public Domain; Alicia Mullens) Alternative description of the image.

16. When you release the bottle, the air inside the bottle becomes:
    a. Clear
    b. Foggy
17. Now, squeeze the bottle again. The air inside the bottle becomes:
    a. Clear
    b. Foggy

Squeezing the bottle raises the temperature inside, forcing all the water droplets in the air to evaporate. Once you let go of the bottle, its temperature decreases to the dew point. Remember from Step 1, the air inside the bottle was saturated. Squeezing the bottle de-saturated the air, while releasing it caused it to cool back to saturation. This brings us to an important point: **When air temperature equals the dew point, the air is saturated, and clouds form.** If the air near the surface is saturated, fog forms; if the air higher above the surface is saturated, clouds form.

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4.4: Clouds in the Vertical Atmosphere

Upper-level clouds

Whenever air temperature and dew point are close to each other, the chances of cloud formation are higher. Most clouds are caused either by rising air (vertical, or "cumuliform clouds") or by an influx of moisture into a layer of the atmosphere, creating layered "stratiform" clouds. Regardless of type, clouds form when the air temperature and the dew point are either very close to each other or exactly the same. With the exception of fog (which is a type of stratus cloud), clouds typically occur at higher altitudes, anywhere from a few hundred feet to over 30,000 feet above the surface. Let's investigate this a bit. Figure 4.4.1 shows weather conditions at 0400 UTC on July 15, 2025.

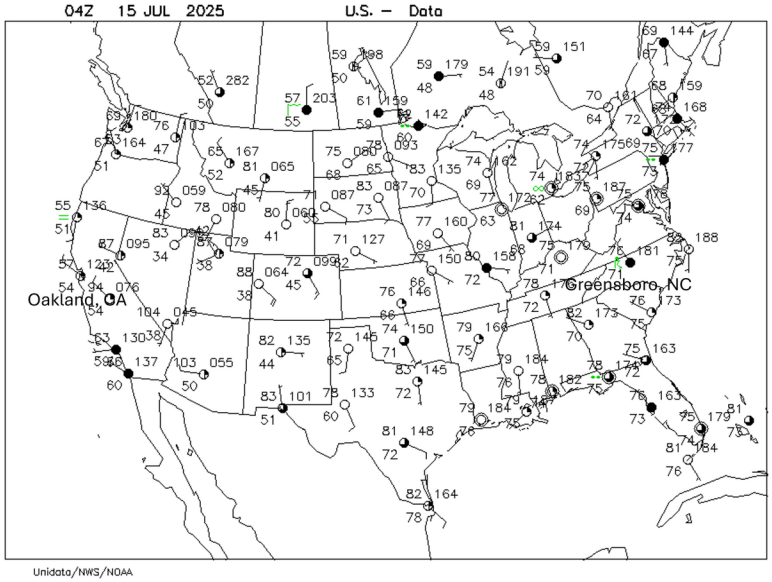


Figure 4.4.1: Surface observation data for the Contiguous United States at 0400 UTC on July 15, 2025. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of image.

18. Greensboro, in Central North Carolina, is reporting an air temperature of 76°F and a dew point of 71°F. As such, the air at the surface in Greensboro _____ saturated.
    a. is
    b. is not
19. However, sky conditions (in the center circle) indicate that there _____ some clouds present overhead in Greensboro.
    a. are not
    b. are
20. Therefore, there _____ at least one height above the surface over Greensboro where the air is saturated.
    a. is
    b. is not

Figure 4.4.2 is a Stüve Diagram plot of air temperature (the right black line) and dew point temperature (the left black line) conditions over Blacksburg, a town in Virginia that is near Greensboro. The data is from a weather balloon launch at 0000 UTC on July 15, 2025 (about four hours before the conditions shown in Figure 4.4.1).

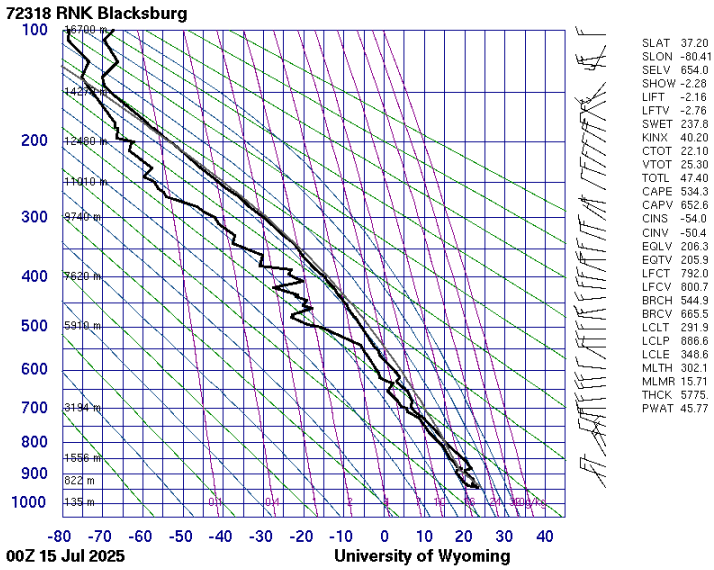


Figure 4.4.2: Upper-Air Conditions for Blacksburg, Virginia, at 0000 UTC on July 15, 2025. (CC-BY-NC 4.0; University of Wyoming) Alternative description of image.

21. The air is saturated whenever the two bold black lines (representing air temperature and dew point temperature) are very close to or overlap. The data plotted in Figure 4.4.2 indicates that _____ levels of saturated air above the surface near Blacksburg (and thus Greensboro).
    a. are
    b. are not any
22. The air is saturated at pressure levels between _____.
    a. 800 mb and 600 mb
    b. 1000 mb and 940 mb
    c. 940 mb and 700 mb
    d. The air isn't saturated anywhere.
23. This _____the sky condition observations for Greensboro shown in Figure 4.4.1.
    a. confirms
    b. cannot confirm

Figure 4.4.3 shows radiosonde data for Oakland, Central California, from a weather balloon launch at 0000 UTC on July 15, 2025, about 4 hours before the surface conditions map in Figure 4.4.1.

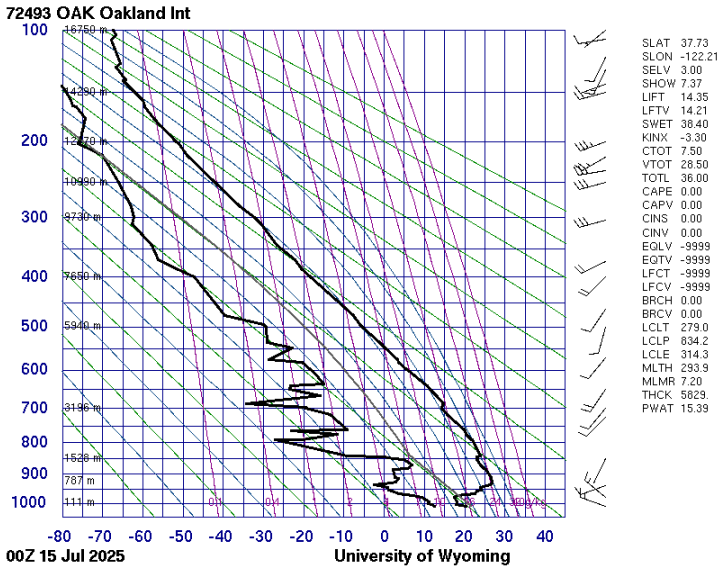


Figure 4.4.3: Upper-Air Conditions for Oakland, California, at 0000 UTC on July 15, 2025. (CC-BY-NC 4.0; University of Wyoming). Alternative description of the image.

24. Based on the data in Figure 4.4.3, there _____ above the surface where air is saturated (remember: air is saturated when temperature and dew point lines overlap).
    a. are some heights
    b. are no heights.
25. This _____ the sky cover reported over Oakland, California near the time in Figure 4.4.1.
    a. confirms
    b. cannot confirm

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4.5: Accessible Descriptions

Figure 4.2.1: Temperature vs. Time for De Anza College

A line graph titled “Temperature (°F) vs. Time (PST)” from De Anza College Weather Station. The horizontal axis represents time in hourly increments from 12:00 AM to 11:00 PM (Pacific Standard Time). The vertical axis represents temperature in degrees Fahrenheit, ranging from 40°F to 65°F.

The graph shows a general pattern where temperatures start near 47°F at midnight, decrease slightly to around 43°F between 5:00 AM and 7:00 AM, then steadily rise to a peak of approximately 64°F around 1:00 PM. After that, the temperature gradually decreases through the evening, dropping to around 48°F by 11:00 PM. This data illustrates a typical daily temperature cycle with cooler early morning temperatures, a midday peak, and a decline in the evening.

Figure 4.2.2: Temperature, Dew Point, and Relative Humidity vs. Time for Moffett Field, California.

A line graph titled “Mountain View, Moffett Field (KNUQ)” showing weather data over a 24-hour period on January 24, 2019. The horizontal axis displays date and time in Pacific Standard Time, marked at two-hour intervals from midnight (00:00) to the next midnight (00:00). The left vertical axis shows temperature in degrees Fahrenheit, ranging from 35°F to 75°F. The right vertical axis shows relative humidity in percent, from 30% to 95%.

Three separate lines represent:

- 2.0m Temperature: Starts around 46°F at midnight, slightly decreases to around 44°F by sunrise, then rises sharply between 09:00 and 12:00 to reach a peak of about 72°F around midday. The temperature remains steady in the early afternoon, then gradually drops through the evening, reaching about 50°F by the end of the day.
- 2.0m Dew Point: Begins around 40°F and shows minor fluctuations through the early morning. It slowly rises, peaks just below 50°F around 10:00–12:00, then remains fairly stable, ending the day slightly above 40°F. The dew point consistently remains lower than the temperature line, indicating drier air in the warmer part of the day.
- 2.0m Relative Humidity: Starts near 65% just after midnight. It declines sharply in the late morning as temperature rises, reaching a low point near 35–40% around midday. It then rises again in the late afternoon and evening, peaking around 75–80% by the end of the day.

The graph shows the relationship between rising temperature and falling relative humidity during daylight hours, with the opposite trend occurring at night. Dew point shows smaller variation, reflecting more gradual changes in atmospheric moisture. Together, the data illustrate a typical daily weather cycle with warmer, drier midday conditions and cooler, more humid nighttime conditions.

Figure 4.3.1: Cloud in a Bottle

A clear plastic bottle partially filled with water. The bottle has a blue screw-on cap. Inside the bottle, there is a vertical black strip that functions as a temperature strip or thermometer, displaying numbers that indicate temperature in degrees Celsius and Fahrenheit. Small droplets of condensation are visible on the inside surface of the bottle above the water level. The water appears still and fills the lower half of the bottle. The thermometer strip shows temperature markings ranging approximately from 18°C to 29°C (about 64°F to 84°F).

Figure 4.4.1: Surface Observations for Continental United States

A weather map of the contiguous United States dated 04Z (UTC) on July 15, 2025. The map shows dozens of weather station plots distributed across the country. Each station plot displays coded meteorological data including temperature, dew point, wind speed and direction, sea-level pressure, and present weather conditions.

At each station:

- The temperature in Fahrenheit is typically shown in the upper-left corner.
- The dew point temperature in Fahrenheit is shown in the lower-left corner.
- Wind is indicated by a small line with barbs extending from a central circle, showing wind direction and speed in knots.
- Sea-level pressure in millibars, usually coded, is displayed nearby.
- Present weather symbols such as dots or other marks may appear near the station circle to indicate precipitation or visibility.

Across the map, temperatures vary widely: in the western states, temperatures are generally in the 50s to 80s; in the south and southeast, temperatures often exceed 80°F; and in the northeast and Great Lakes region, temperatures are mostly in the 60s to low 70s. Wind barbs show varied wind directions and speeds, with some stations reporting calm conditions (circle without a barb).

Dew point values vary but tend to be higher in the eastern and southeastern U.S., indicating more humid conditions, and lower in the western interior and mountain regions, reflecting drier air.

The map provides a snapshot of weather conditions across the continental U.S., useful for analyzing temperature distribution, humidity, and wind patterns at this specific date and time.

Figure 4.4.2: Upper-Air Observations for Blacksburg, Virginia

This is a Stüve diagram for Blacksburg, Virginia (station 72318) from 00Z on July 15, 2025. It shows how temperature and moisture change with height in the atmosphere. The vertical axis is air pressure, which decreases with height (from the surface near 1000 mb to the upper atmosphere near 100 mb). The black lines represent the temperature and dew point at different altitudes.

The diagram also shows wind barbs on the right, which tell us wind direction and speed at various levels.

The main features necessary for this investigation are below:

The temperature and dew point lines are close together near the surface, meaning the air is humid near the surface, and again at approximately 900 mb, 725 mb and 640 mb.

Overall, this sounding shows warm, moist, and somewhat unstable air—conditions that could support thunderstorms if lifting mechanisms are present.

Figure 4.4.3: Upper-Air Observations for Oakland, California

This is a Stüve diagram for Oakland, California (station 72493), from 00Z on July 15, 2025. It displays how temperature and moisture change with height in the atmosphere, using pressure (in mb) as the vertical axis. Temperature and dew point profiles are shown in black lines. Isotherms are vertical, and pressure decreases with height from the surface (1000 mb) to the upper atmosphere (100 mb).

Wind barbs are shown on the right side and indicate wind speed and direction at different altitudes. Winds are generally weak and variable in direction throughout much of the atmosphere.

The main features necessary for this investigation are below:

The temperature and dew point lines are widely separated through most of the profile, showing dry air from the surface to upper levels. Winds are light and show little shear. The environment is strongly stable, with no signs of convective activity or instability.

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5: RISING AIR AND STABILITY

Introduction

Some birds, such as eagles and vultures, tend not to flap their wings as much as other birds when they fly. Their flight seems effortless, almost as if they were gliding through the air. How is this possible? Figure 5.1 shows a Bonelli's eagle soaring effortlessly above a mountain range.



Figure 5.1: A Bonelli's eagle gliding effortlessly through the air. (CC by-SA 4.0; Mukul Pandey via Wikimedia Commons)

They use the fact that as the Sun heats the Earth's surface, warm air near the surface rises to higher altitudes. Birds such as eagles and vultures use their large wings to catch the rising air columns, called thermals, to soar high into the sky and even across mountains, much like glider aircraft. Hot air balloons also utilize the buoyancy of warm air to rise to higher altitudes, offering passengers spectacular views. (Figure 5.2).



Figure 5.2: Hot air balloons use the buoyancy of warm air to rise above the surface. (CC by-SA 3.0; Tomas Castelazo via Wikimedia Commons)

Investigation 4 introduced the concept of saturation and cloud development in rising air. However, one thing that has yet to be covered is what allows air to rise and form clouds. This brings us to the concept of Atmospheric Stability, which is a key weather maker. The difference between a clear, sunny day and a tornado outbreak can be determined by atmospheric stability. The same is true between a clear day and a polluted day. Before we can determine the stability of the atmosphere, we must first explore the concepts of rising and sinking air and how air temperature changes as it travels through the atmosphere.

Learning Objectives

By the end of this investigation, you should be able to:

- Calculate the air parcel temperature at different altitudes using the lapse rate.
- Track the properties of a rising air parcel using Stüve diagrams.
- Determine atmospheric stability using measures such as CAPE and CIN.

Navigational Note

Investigation 5 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

5.1: Rising Air

5.2: Charting Air Parcels

5.3: A Case Study

5.4: Atmospheric Stability

5.5: Accessible Descriptions

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5.1: Rising Air

Adiabatic Processes

Have you ever used a hairspray, deodorant spray, or any kind of aerosol spray and wondered why it feels so cold, even though the spray can is at room temperature? If you haven't done that before, find a spray can and briefly spray some of it onto your forearm. This happens because it's an adiabatic process, similar to what happens to air as it rises and sinks in the atmosphere. Before we examine how changes in altitude and pressure affect air temperature, it is important to state a few assumptions and rules that guide this analysis:

a. Rather than thinking of the atmosphere as a single, large blob of air, meteorologists treat it as trillions of tiny "bubbles" of air called air parcels. The air inside a spray can behaves similarly.
b. Air parcels are completely isolated from the surrounding environment. They neither exchange heat nor gases with other parcels. We'll call this the "Las Vegas Rule: what happens in the parcel, stays in the parcel".

Ok, now that we have stated the assumptions and rules, let's examine what happens to the air parcel as it rises or sinks in the atmosphere:

i. When an air parcel rises into the atmosphere, it enters a region of lower pressure. This causes the parcel to expand. The same thing happens to air parcels that escape the spray can's compression.
ii. Expansion requires the parcel to do work *on the environment*, which requires energy. The energy used in the expansion is taken from the kinetic energy (heat) of the air parcel molecules. Therefore, as the parcel expands, it cools.
iii. On the other hand, when a parcel sinks, it enters a higher-pressure environment. This causes the parcel to compress.
iv. Compression adds energy to the parcel because the environment does work *on it*, forcing the parcel molecules together and increasing their kinetic energy (heat). Therefore, as the parcel compresses, it heats up.

Figure 5.1.1 sums these concepts up succinctly – As air rises, it expands and cools, and as air sinks, it compresses and warms.

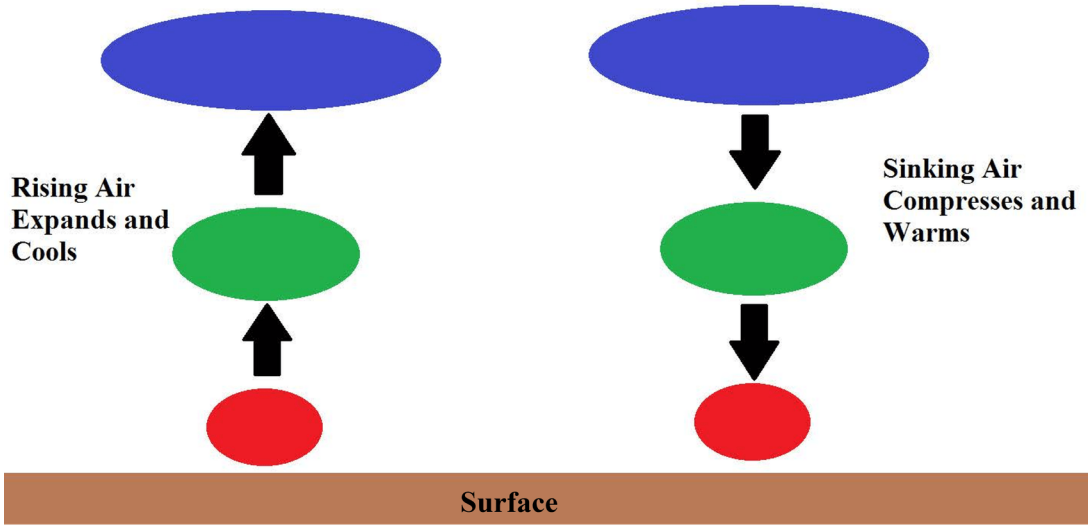


Figure 5.1.1: Rising air expands and cools, while sinking air contracts and warms. (CC BY 4.0; Alicia Mullens)

Because these parcels follow the "Las Vegas Rule," they exchange no heat with their surroundings. This is what an adiabatic (a = without; diabatic = two or more heat sources) process is: a process in which no heat is exchanged with its surroundings. This makes life easier for meteorologists because instead of accounting for all the possible heat sources like advection from other regions, radiation emitted from the sun, ground, surroundings, convection by contact with surrounding parcels, etc., we only need to focus on expansion and contraction. Because of this, meteorologists have a straightforward method for determining the temperature of a parcel as it rises or sinks in the atmosphere. They can use a 'Lapse Rate' to determine the parcel's temperature

at a given height if they know the parcel's surface temperature. A lapse rate is the rate at which temperature changes with height in the atmosphere. There are two lapse rates, depending on whether the parcel is dry or saturated with water vapor:

- **Dry Adiabatic Lapse Rate:** An unsaturated parcel of air cools at a rate of 10°C/1000 m. For every 1000 meters a dry parcel rises, its temperature decreases by 10°C.
- **Moist Adiabatic Lapse Rate:** A saturated parcel of air cools at a rate of 6°C/1000 m. For every 1000 meters it rises, a moist parcel loses 6 °C in temperature.

Based on this information, let's answer the following questions.

1. Consider a parcel of unsaturated (dry) air at the Earth's surface with a temperature of 15°C. If the parcel rises to 1000 meters, it will have a temperature of:
   a. 9°C
   b. 25°C
   c. 15°C
   d. 5°C

Typically, a parcel of air begins its ascent as an unsaturated parcel. However, as the parcel rises, it eventually cools to its **dew point** and becomes saturated with water vapor.

2. Suppose the parcel from question 1 became saturated at 1000 m, but continued to rise. Its temperature at 2000 m would be:
   a. 6°C
   b. -1°C
   c. 11°C
   d. 5°C

We can also use the same lapse rates mentioned previously to track sinking parcels. The only difference is that instead of subtracting 10°C (dry) or 6°C (moist) for every 1000 meters, you would add the corresponding amount to account for sinking parcels.

3. For example, suppose an unsaturated parcel of air at 6°C and 1000 meters sinks back to the ground. At the surface, it would have a temperature of:
   a. 16°C
   b. 0°C
   c. 12°C
   d. -4°C

4. Now, suppose the same parcel in question 3 were moist (saturated) instead of dry, but still at 6°C at 1000 meters. If it sinks to the surface, it will have a temperature of:
   a. 16°C
   b. 0°C
   c. 12°C
   d. -4°C

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5.2: Charting Air Parcels

Using Stüve Diagrams

As you may have noticed, calculating air parcel temperatures at different altitudes can be computationally intensive. The good news is that there is another way! Stüve Diagrams include a helpful set of lines that represent the lapse rates for rising parcels. These lines are called 'Adiabats' and are shown in Figure 5.2.1. Dry air parcels follow the dry adiabat, represented by the solid green lines, while saturated parcels follow the moist adiabat, represented by the dashed blue lines. The dotted orange lines represent a constant water-vapor mixing ratio, but we'll ignore them for now as we focus on the adiabats. By drawing a line on the adiabat, you can track the temperature of any parcel at any given altitude.

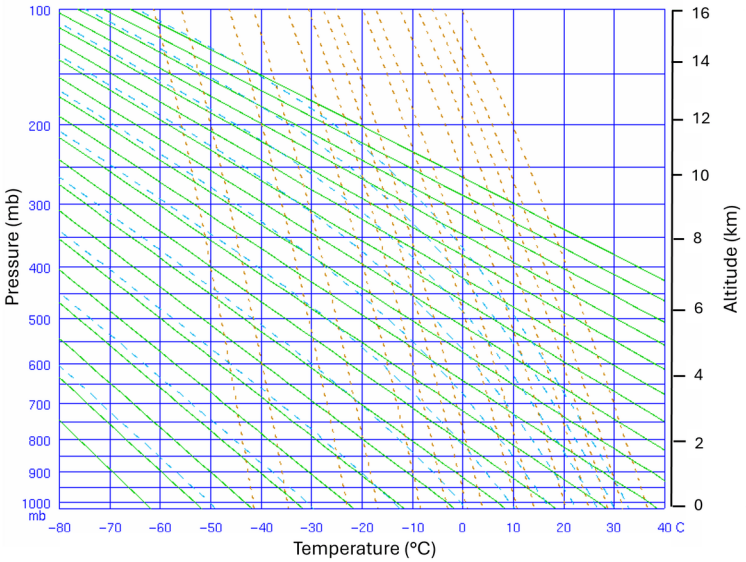


Figure 5.2.1: A blank Stüve Diagram with dry adiabats shown using solid green lines and moist adiabats shown using dotted blue lines. (CC BY-SA 3.0; Daelomin via Wikimedia Commons) Alternative description of the image.

Here's how to do it: You need two pieces of information to start, the altitude (or pressure level) at which you need to find the parcel's temperature, and the temperature of the parcel before rising. Start at the bottom of the diagram, i.e., at 0 km altitude or the altitude of the parcel before it begins to rise, and place a dot at the temperature of the parcel before it starts to rise in the atmosphere. Then draw a line as you travel along (or parallel to) the nearest dry or moist adiabat, depending on your air parcel's condition, until you reach your desired pressure level. The temperature on the X-axis at the point where you stopped is the parcel's temperature at your desired altitude. For example, consider a dry parcel of air at the surface with a temperature of 17°C.

5. Because the parcel is dry, it will travel along the nearest:
    a. Solid-green dry adiabat
    b. Dashed-blue moist adiabat

Figure 5.2.2 is a Stüve Diagram for a parcel of air starting at the surface with a temperature of 17°C. The figure shows two lines: one for a dry parcel and one for a moist parcel as they rise through the atmosphere.

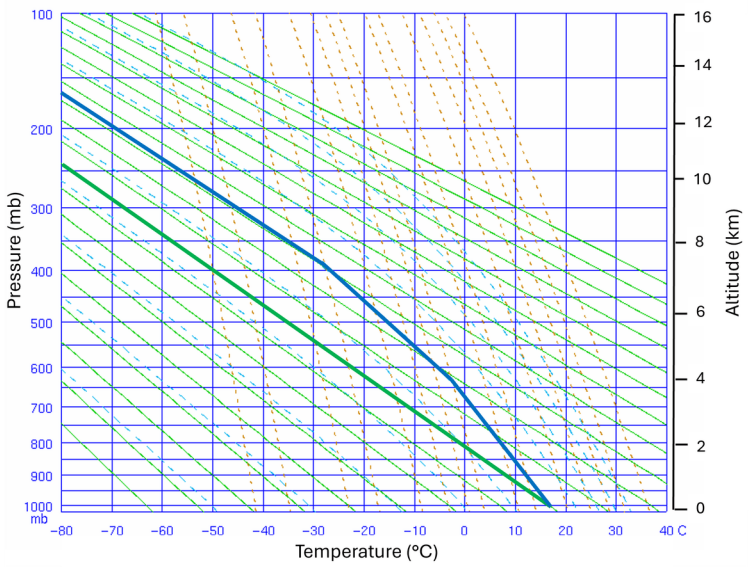


Figure 5.2.2: Stüve Diagram with plotted lines for a dry (green) and moist (blue) parcel of air that begins at the surface with a temperature of 17°C. (CC BY-SA 4.0; Modified from Daelomin via Wikimedia Commons) Alternative description of the image.

6. Using the lines in Figure 5.2.2, a moist parcel will have the temperature of approximately ____ at 400 mb.
   a. -50°C
   b. -27°C
   c. -35°C
   d. -15°C

7. On the other hand, a dry parcel will have a temperature of approximately _____ at 400 mb.
   a. -50°C
   b. -27°C
   c. -35°C
   d. -15°C

8. As expected, given its lower lapse rate, the _____ parcel is warmer than the other at 400 mb.
   a. dry
   b. moist

Let's practice tracking rising and sinking air parcels using a Stüve Diagram. Print out a blank Stüve Diagram for the following few problems. Consider a parcel of dry air at 28°C at the surface. Draw a dot for that parcel on your blank diagram. Now follow the parcel up to 800 mb. Hint: If your dot doesn't exactly fall on a dry or a moist adiabat, draw a line parallel to the nearest dry or moist adiabat.

9. At 800 mb, the parcel will have a temperature of:
   a. -8°C
   b. 18°C
   c. 8°C
   d. 28°C

Suppose that at 800 mb, the parcel has cooled to its dew point and is now saturated.

10. Continuing upwards, the parcel will now travel along the:
    a. Solid-green dry adiabat
    b. Dashed-blue moist adiabat

11. At 400 mb, the temperature of the parcel is:
    a. -43°C
    b. -28°C
    c. -35°C

d. -50°C

Now let's allow the parcel to sink. There is one exception to the Las Vegas rule that hasn't been covered yet. Once a parcel becomes saturated, the moisture within it condenses into liquid water and ceases to be part of the air parcel. If the saturated parcel continues to rise, it can continue to condense more moisture and thus must follow the moist adiabat. However, as soon as any parcel begins to sink, it becomes unsaturated (dry).

12. Based on the previous information, the parcel of air from questions 9-11 will now follow the _____ as it sinks.
    a. Solid-green dry adiabat
    b. Dashed-blue moist adiabat

Follow the parcel on the Stüve Diagram by drawing a line from 400 mb back down to the surface, and note its temperature at the surface.

13. Once it sinks back to the surface, the parcel is _____ than it was when it initially rose from the surface.
    a. warmer
    b. cooler

14. Because it lost moisture to condensation as it rose, it will also be _____ than it was when it initially rose from the surface.
    a. drier
    b. wetter

15. Submit the Stüve Diagram.

Congratulations! You created a Stüve diagram that tracks the temperature of an air parcel as it rises and sinks in the atmosphere.

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5.3: A Case Study

Topographic Lifting

The rising and sinking behavior of air parcels has a crucial impact on a region's climate. Air parcels near the surface may rise to higher levels during the day due to solar heating. As we noticed during the Stüve Diagrams exercise, such parcels carry water vapor from the surface, which condenses as they cool to their dew point. This condensation leads to cloud formation and can also result in precipitation. However, solar heating isn't the only process that causes surface air to rise. Topographical lifting occurs when air is forced to rise along the side of a mountain range by horizontal winds. Many regions across the world receive significant rainfall due to topographic lifting of air parcels. It can also significantly impact the precipitation a region, a state, or even a country receives annually. Let's try to understand how the average annual precipitation (Figure 5.3.1) varies over the San Francisco Bay Area due to its topography (Figure 5.3.2) and answer the following questions.

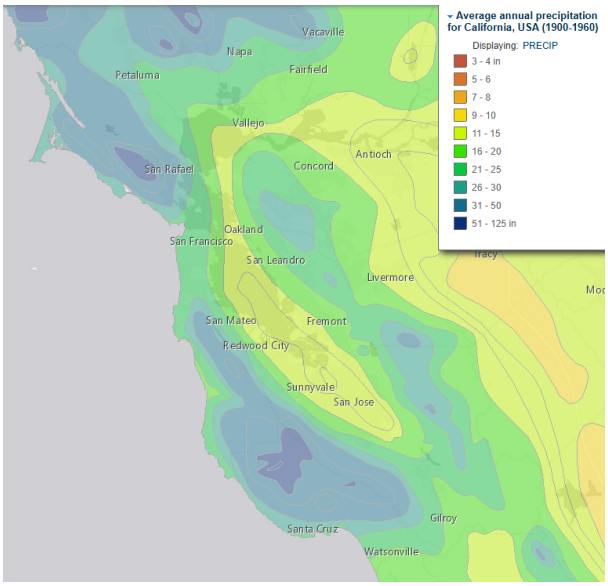


Figure 5.3.1: Annual precipitation in inches over the San Francisco Bay Area. (CC BY 3.0; USGS via databasin). Alternative description of the image.



Figure 5.3.2: Topography of the San Francisco Bay Area. (CC BY 4.0; Topographical maps via USGS). Alternative description of the image.

16. According to Figure 5.3.1, the city of Santa Cruz, California, receives between 26 and 30 inches of rain annually. Meanwhile, San Jose, in the southern San Francisco Bay Area, about 30 miles north of Santa Cruz, receives _____ inches of rain per year.
    a. 11-15
    b. 16-20
    c. 21-25

17. According to Figure 5.3.1 and Figure 5.3.2, between Santa Cruz and San Jose is a mountain range that receives ___ rainfall annually than either Santa Cruz or San Jose.
    a. significantly more
    b. significantly less

18. This occurs because air coming from the Pacific Ocean travels eastward over the Santa Cruz Mountains, and it _____ over the mountains.
    a. cools, condenses, and rains out
    b. warms and evaporates

19. Once the air sinks down the east side of the mountain, near San Jose, it is significantly _____.
    a. colder and wetter
    b. warmer and drier

20. This _____ the concept explored in questions 9-14, where rising air cools and condenses. While the air that sinks back down to the surface warms and dries.
    a. confirms
    b. contradicts

Mountains produce a natural rain shadow, where areas on the windward (front) side of the mountain range receive more rainfall than areas on the leeward (back) side of the mountain range. In the Santa Cruz-San Jose case study, winds blow onshore from Santa Cruz, up the mountain range, and then sink into the Santa Clara Valley.

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5.4: Atmospheric Stability

CAPE and CIN

In addition to topographic lifting, it is important to understand how air parcels behave as they rise, as this determines atmospheric stability. This is because rising air parcels are often completely isolated from the rest of the atmosphere, meaning that they have a different temperature than the surrounding atmosphere, which can be heated/cooled by other factors. The stability of the atmosphere is determined by comparing the parcel's temperature (which has risen from the surface) with the temperature of the surrounding atmosphere.

- Suppose the parcel of air is warmer than the surrounding atmosphere. In that case, its adiabatic temperature line lies to the right of the weather-balloon-measured temperature on a Stüve diagram. The parcel will continue to rise because it is less dense than the surrounding atmosphere. A layer in the atmosphere in which an air parcel is warmer than its surroundings is called the Convective Available Potential Energy (CAPE).
- Suppose the air parcel is cooler than the surrounding atmosphere. In that case, its adiabatic temperature line lies to the left of the weather-balloon-measured temperature on a Stüve diagram. The parcel will sink because it is denser than the surrounding atmosphere. This phenomenon is known as Convective Inhibition (CIN).
- If the parcel temperature matches the surrounding air temperature, the parcel will neither rise nor sink. This is called the Equilibrium Zone (EZ).

Figure 5.4.1 is a Stüve Diagram of air temperature, represented by a black line on the right, dew point temperature, represented by a black line on the left, and parcel temperature, represented by a red line taken from a weather balloon launch over Dallas-Fort Worth International Airport at 0000 UTC (6 pm local time) on May 20, 2019. In this figure, a layer of CIN, where the air parcel is cooler than the surrounding atmosphere, exists between 750 mb and 600 mb, and a layer of CAPE, where the air parcel is warmer than the surrounding atmosphere, exists between 600 mb and approximately 160 mb. In this case, if a parcel of air were “pushed” to the 600 mb pressure level, it would quickly rise on its own. Situations like this are ideal for the formation of severe weather, including Tornadoes, Hail, High Winds, severe lightning, and other interesting weather phenomena. Indeed, the Storm Prediction Center issued a “High Risk” alert for the Dallas area on this particular day, and the region experienced several tornadoes.

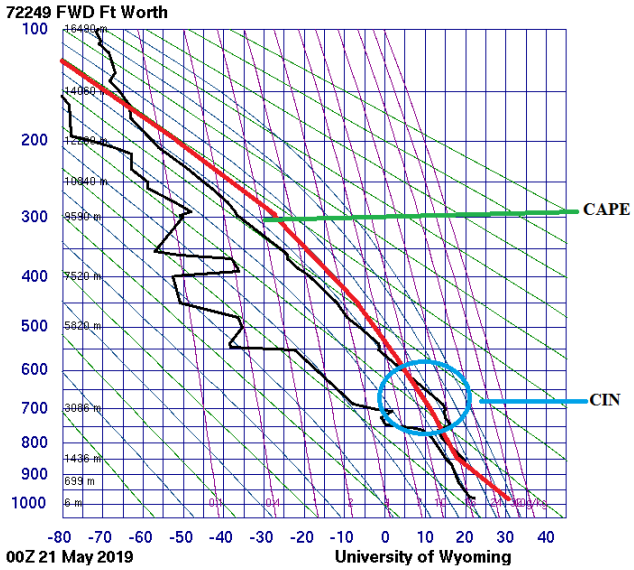


Figure 5.4.1: Weather Balloon collected temperature (right-black line), dew point (left-black line), and calculated air parcel (red line) data for Dallas-Fort Worth International airport at 0000 UTC on May 21, 2019 (6 pm local time on May 20, 2019). (CC BY-NC 4.0; Larry Oolman via University of Wyoming). Alternative description of the image.

Let us determine atmospheric stability and tornado potential for another location using a similar upper-air plot. Figure 5.4.2 shows a Stüve Diagram plot of weather balloon data and calculated parcel temperatures (red line) from Topeka, Kansas, at 0000 UTC on

May 29, 2019, which corresponds to 6 pm local time on May 28, 2019. Using this information, let's answer the following questions.

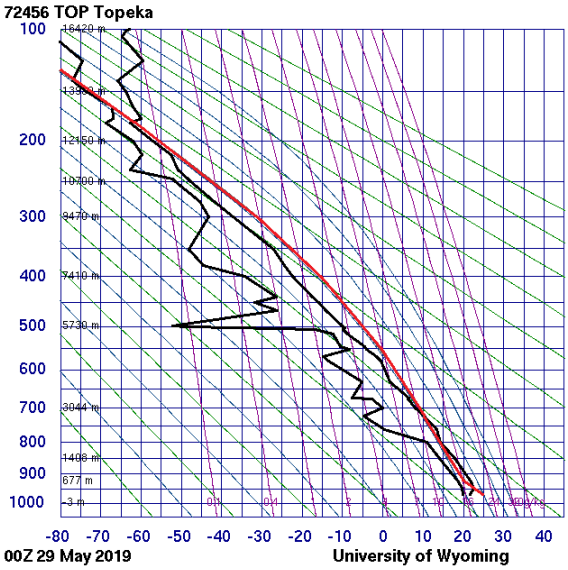


Figure 5.4.2: Weather Balloon collected temperature (right-black line), dew point (left-black line), and calculated Parcel Temperature (red line) for Topeka, Kansas, at 0000 UTC on May 29, 2019. (CC BY-NC 4.0; Larry Oolman via University of Wyoming). Alternative description of the image.

21. According to Figure 5.4.2, a layer of CIN ____ present between 950 mb and approximately 700 mb over Topeka, Kansas, at 0000 UTC on May 28.
    a. is
    b. is not

22. Above the 700 mb level, a layer of CAPE _____ present.
    a. is
    b. is not

23. Conditions for Topeka at this time _____ similar to conditions experienced at Dallas-Fort Worth on May 20 (Figure 5.4.1), when a tornado outbreak occurred near Dallas.
    a. are somewhat
    b. are not at all

Let's verify our atmospheric stability conclusions by checking the NOAA Severe Weather reports for the United States on May 28, 2019, shown in Figure 5.4.3.

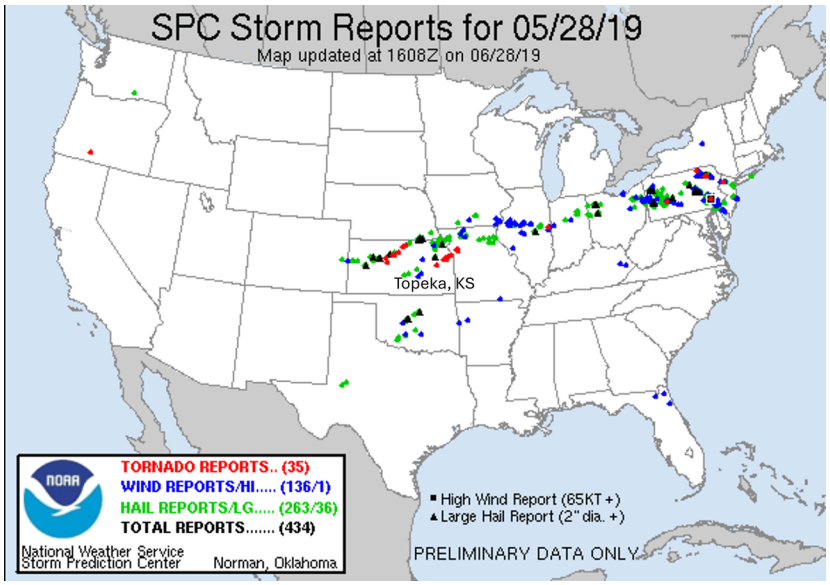


Figure 5.4.3: A Severe Weather Report generated by the NOAA Storm Prediction Center (SPC) on May 28, 2019. (Public Domain; SPC Storm Reports via NOAA/SPC) Alternative description of the image.

24. According to Figure 5.4.3, there ____ several reports of tornadoes in the Kansas region on May 28.
    a. were not
    b. were
25. This _____ that the conditions shown in Figure 5.4.2 indicated severe weather for Topeka, Kansas on May 28, with the possibility of tornadoes.
    a. confirms
    b. contradicts

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5.5: Accessible Descriptions

Figure 5.2.1: A Blank Stüve Diagram

This is a Stüve diagram, a type of thermodynamic chart used in meteorology to analyze vertical profiles of the atmosphere. It displays how temperature varies with pressure and altitude, and is used to assess atmospheric stability, moisture, and wind data.

Axes:

- Temperature (°C) ranges from -80°C to +40°C in 10°C intervals.
- Pressure (mb) ranges from 1000 mb (near surface) to 100 mb at upper levels, in a logarithmic scale.
- Altitude (km) ranges from 0 km to 16 km, linearly spaced to correspond with pressure levels.

Grid Lines:

- Horizontal lines: Represent constant pressure levels.
- Vertical lines: Represent constant temperature values.
- Dry adiabats, sloped from lower left to upper right, showing the temperature change for rising or sinking unsaturated air parcels.
- Moist adiabats represent the temperature change for saturated air parcels during ascent or descent.
- Shallower slope lines are Isotherms, running vertically to track constant temperature values.
- Near-vertical dashed brown lines represent mixing ratio lines, indicating constant values of water vapor in grams per kilogram of dry air.

Figure 5.2.2: Stüve Diagram with lines

This is a Stüve diagram, labeled “Vertical Atmospheric Chart (Stüve),” used in meteorology to analyze vertical profiles of the atmosphere. It plots temperature versus pressure and altitude, and overlays highlighted examples of a dry adiabat and a moist adiabat.

Axes:

- Temperature in degrees Celsius (°C), ranging from -80°C to +40°C.
- Pressure in millibars (mb), ranging from 1000 mb (surface) at the bottom to 100 mb near the top, on a logarithmic scale.
- Altitude in kilometers (km), from 0 km to 16 km, increasing linearly upward.

Grid Lines and Background:

- Vertical lines: Constant temperature.
- Horizontal lines: Constant pressure (or height).
- Dry adiabats, sloping upward.
- Moist adiabats, also upward sloping but more curved and variable.

Highlighted Features:

- A Dry Adiabat is shown, beginning at approximately 20°C and 1000 mb, extending upward to around -80°C and 250 mb. This line represents the temperature change of a rising unsaturated air parcel, cooling at about 10°C/km.
- A Moist Adiabat is also plotted, starting near the same surface point but curving slightly to the right as it rises. This line represents the cooling of a saturated air parcel, which cools more slowly with height because latent heat released by condensation reduces the parcel's cooling rate.

Figure 5.3.1: Average Annual Rainfall

This map depicts the average annual precipitation across parts of Northern California, including the San Francisco Bay Area, based on data collected from 1900 to 1960. The geographic region extends from the coastline near San Francisco and Santa Cruz inland to Livermore, Tracy, and parts of the Central Valley.

Map Overview:

- City names such as San Francisco, Oakland, San Jose, Fremont, Sunnyvale, Santa Cruz, and Livermore are labeled on the map for spatial reference.
- The base map uses colored contours to indicate zones of average annual precipitation in inches.
- The map legend on the right categorizes precipitation into 13 ranges, from 3–4 inches up to 125 inches per year.

Precipitation Ranges and Patterns:

The color-coded contour regions represent the following precipitation ranges (in inches):

- 3–4
- 5–6
- 7–8
- 9–10
- 11–15
- 16–20
- 21–25
- 26–30
- 31–50
- 51–125

Key patterns:

- Lowest precipitation areas (3–10 inches per year) are concentrated in valleys and interior lowlands, especially near San Jose, Fremont, and parts of the East Bay.
- Moderate precipitation zones (15–25 inches) appear in much of the San Mateo Peninsula, Redwood City, and parts of the inland hills near Livermore and Concord.
- Higher precipitation zones (over 30 inches) are found along the coastal mountains, including the Santa Cruz Mountains west of San Jose and near Santa Cruz and parts of the coastal Pacific slope.
- A small area near Big Basin or the Santa Cruz Mountains may reach over 50 inches per year.

Figure 5.3.2: Topography of the San Francisco Bay Area

This is a topographic map of central coastal California, with a focus on the San Francisco Bay Area and adjacent terrain. The map uses shaded relief to represent elevation and terrain texture, but does not include contour lines, colors, or elevation labels beyond land shading.

Geographic Scope:

- Several prominent cities are labeled, including San Francisco (located in the northwest corner of the map, near the ocean), San Jose (in the center of the map, inland from the bay), Santa Cruz (in the southwest portion of the map, near the coast), and the Pacific Ocean to the west.
- The San Francisco Bay is visible, extending inland toward the east and splitting into multiple channels.

- The Santa Clara Valley, where San Jose is located, is surrounded by mountainous terrain.
- The Santa Cruz Mountains lie to the west of San Jose and extend south toward Santa Cruz.
- The Diablo Range lies to the east of the Santa Clara Valley.
- The elevated terrain is represented by darker-shaded areas that form ridges and valleys.

- Lowland valleys and plains are shown in lighter shading and are mainly located around San Jose and east of San Francisco Bay.

Figure 5.4.1: Weather Balloon data for Dallas, TX

This is a Stüve diagram for Fort Worth, Texas (station ID: 72249), valid at 00Z on May 21, 2019, providing an atmospheric profile of:

- Observed environmental temperature (black line)
- Dew point temperature (black dashed line)
- Theoretical parcel ascent curve (red line)

Axis Information:

- Vertical Axis (left): Atmospheric pressure in millibars (mb), decreasing from 1000 mb at the bottom to 100 mb at the top. Corresponding altitude in meters is labeled alongside, ranging from 0 to 16,440 meters (~54,000 feet).
- Vertical Axis (right): Altitude in kilometers (km), ranging from 0 to 16 km.
- Horizontal Axis: Temperature in degrees Celsius, ranging from -80°C to +40°C.

Key Features:

CAPE (Convective Available Potential Energy):

- Labeled on the right side of the diagram at the 300 mb pressure level, corresponding to an altitude of approximately 9.5 km (31,200 feet).
- CAPE is the region where the red parcel path is to the right of the environmental temperature line (black), meaning the parcel is warmer and buoyant relative to its surroundings.
- In this diagram, CAPE exists from roughly 650 mb (~3.8 km or 12,500 ft) up to 300 mb (~9.5 km or 31,200 ft).

CIN (Convective Inhibition):

- Highlighted by a blue oval around the 700 to 850 mb pressure levels, corresponding to an altitude range of approximately 1.5 to 3 km (5,000 to 10,000 ft).
- CIN is the region where the parcel path is cooler than the environment (i.e., the red line is left of the black line), meaning the parcel is negatively buoyant and will resist upward motion unless forced.

Figure 5.4.2: Weather Balloon data for Topeka, Kansas

This is a Stüve diagram for Topeka, Kansas, valid at 00Z on May 29, 2019. It provides a vertical atmospheric profile of temperature, dew point, and parcel trajectory for assessing atmospheric stability.

Axes and Grid:

- Vertical axis (left): Pressure in millibars (mb), decreasing from 1000 mb at the bottom (surface) to 100 mb at the top, corresponding approximately to altitudes from 0 to 16.4 km or 0 to 54,000 feet (labels in both meters and feet).
- Vertical axis (right): Altitude in kilometers (0 to 16 km).
- Horizontal axis: Temperature in degrees Celsius, ranging from -80°C to +40°C.
- Blue vertical lines: Constant temperature (isotherms).
- Green sloped lines: Dry adiabats (constant potential temperature).
- Purple curved lines: Moist adiabats (for saturated ascent).
- Dashed brown lines: Mixing ratio lines (constant moisture content).

Plotted Lines:

- Black jagged line (right side): Environmental temperature profile.
- Black jagged line (left side): Dew point temperature profile (moisture).
- Red smooth line: Parcel path, showing theoretical temperature of a surface air parcel if lifted.

Stability Interpretation:

- The parcel path (red) closely follows the environmental temperature (black) throughout the troposphere, indicating a neutrally stable or weakly unstable atmosphere.
- There is no clear region of significant Convective Available Potential Energy (CAPE) where the red line is warmer than the environment, suggesting low thunderstorm potential.
- No obvious Convective Inhibition (CIN) region is present either, as the surface parcel follows the environment without major suppression.

Approximate Altitudes of Interest:

Feature	Pressure (mb)	Approx. Altitude (km)	Description
Surface	1000	0	Starting level of the sounding
Tropopause (near 200 mb)	200	~12	Near the top of the diagram, no CAPE is evident
LCL (not labeled)	~850–900	~1.2	Expected lifting condensation level, near the surface

Figure 5.4.3: Severe Weather Report on May 28, 2019

This is a NOAA/NWS Storm Prediction Center map displaying filtered severe weather reports across the United States for May 28, 2019. The map includes tornadoes, damaging wind events, and hail reports, as recorded by the National Weather Service.

General Layout:

- The map covers the contiguous U.S. with state boundaries outlined.
- The location of Topeka, Kansas, is labeled near the central part of the map.
- Symbols are used to denote different types of storm reports:
  - Tornadoes
  - Damaging wind (including high wind reports)
  - Hail (including large hail over 2 inches in diameter)

Storm Report Totals:

- Tornado Reports: 35
- Wind Reports: 136 total, including 1 high wind report (gusts ≥ 65 knots or ~75 mph)
- Hail Reports: 263 total, including 36 large hail reports (hail ≥ 2 inches in diameter)
- Total Reports: 434

- A dense band of storm reports stretches from eastern Kansas and northern Oklahoma eastward through Missouri, Illinois, Indiana, Ohio, and into the Northeast U.S., including Pennsylvania and New York.
- The highest concentration of tornado reports is near Topeka, Kansas, and the surrounding region.
- Hail reports are widespread across the central U.S., with many reports from Kansas, Missouri, and farther east.
- Wind damage reports (including the one high wind report) are scattered along the same path from the Plains through the Northeast.
- A few isolated storm reports also appear in Oregon, Texas, and parts of the Southeast U.S.

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6: AIR PRESSURE, ISOBARS, AND THE HAND-TWIST MODEL

Introduction

Have you ever experienced your ears popping while on an airplane or going through a tunnel? The reason this happens is due to changes in air pressure, which is the weight of the air above/around you pressing down on you. The air molecules within your ears, along with other objects such as the air in a water bottle, match the external air pressure by exerting an equal outward force. When external air pressure decreases rapidly, the air in your ear needs to equalize, exerting a net outward pressure on your ear, which is why your ears pop. The same principle applies to other objects containing air, such as water bottles, as shown in Figure 6.1. At higher elevations, there is less air pressure pushing down on the bottle, causing it to "inflate." As elevation decreases, air pressure increases, compressing the bottle slightly. You can recreate this phenomenon yourself: buy a sealed bag of chips (don't open it, as that will let outside air in), and drive up a tall hill or mountain. After ascending a few thousand feet, the bag will appear to have puffed up. Now drive back down, and you'll see the bag deflate.

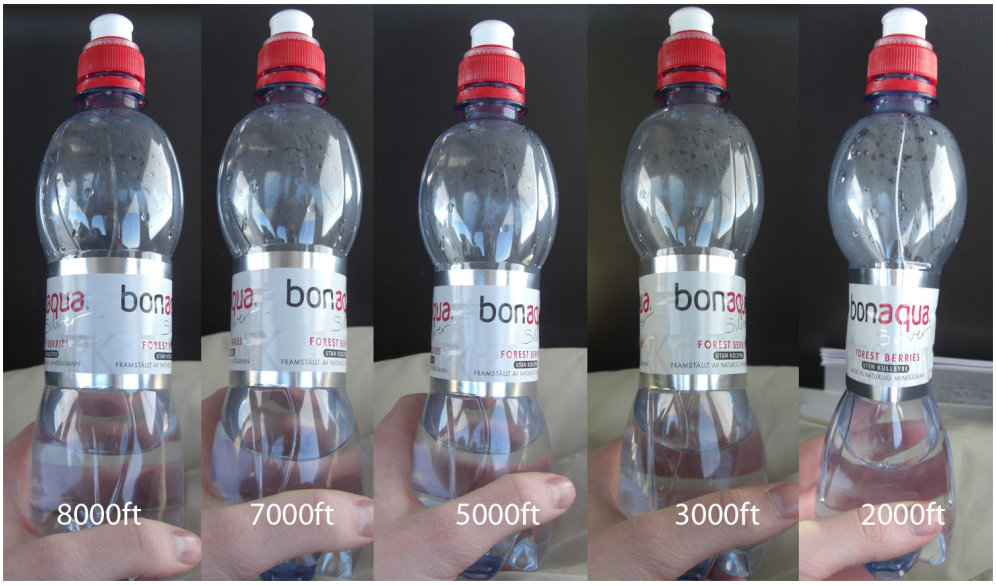


Figure 6.1: The effects of air pressure on a water bottle at 8000 feet elevation, decreasing to 2000 feet. At higher elevations, there is less atmospheric air pressure squeezing the bottle, thus, causing it to inflate. As elevation decreases, external air pressure increases, compressing the bottle. (Public Domain; M9matr0902 via Wikimedia Commons)

Air pressure is an essential component of weather for two main reasons: first, differences in air pressure at Earth's surface cause wind. Second, air spirals into areas of low pressure and is forced to rise, producing clouds and stormy weather. Conversely, air spirals out of high-pressure areas, sinking and resulting in clear skies and sunny weather. Thus, surface air pressure patterns significantly influence the weather conditions. For example, hurricanes are centers of very low surface pressure. Fire weather conditions, such as heat and high winds, are created by the movement of air from high pressure to low pressure. Even the movement of air masses is strongly governed by air pressure systems. Because of this, meteorologists want to detect air pressure patterns so they can more accurately forecast storm position and movement, wind patterns, the advection of warm/cold/moist/dry air, and the potential for hazardous weather.

In this investigation, we will explore how air pressure varies at the Earth's surface, identify areas of low and high pressure, and then examine how air behaves near these pressure zones.

Learning Objectives

- Draw isobars on a weather map.
- Using an isobar map, identify areas of low and high pressure.

- Using the hand-twist model, distinguish how air behaves near low pressure from high pressure, and explore how that affects weather

Navigational Note

Investigation 6 has 23 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

6.1: Air Pressure on a Weather Map

6.2: High and Low Pressure Systems

6.3: Cyclonic and Anticyclonic Flow - The Hand Twist Model

6.4: Cyclonic and Anticyclonic flow in real life.

6.5: Accessible Descriptions

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6.1: Air Pressure on a Weather Map

What is Air Pressure?

While the air around us feels light, it still has mass. Because of gravity, this mass exerts a force called weight. Air pressure is the weight of the air above you. If you consider an imaginary column of air extending from sea level to the top of the atmosphere, it will weigh approximately 14.7 pounds. If you live close to sea level, the weight of the air above you is weighing down on every square inch of your body. Thankfully, our bodies exert an equal outward force, preventing us from being crushed by the weight of the air. Meanwhile, if you live in a high-altitude location like Denver, Colorado, which sits at 5280 feet above sea level, there is less air in the column above you, up to the top of the atmosphere. Thus, the air pressure in Denver will be significantly lower than at sea level. Meteorologists measure atmospheric pressure at weather stations using a device called a barometer.

Sea-Level Pressure

There are two important considerations we need to make before plotting air pressure on a weather map: first, air pressure decreases with increasing elevation, so locations that are not at sea level will have lower pressure simply because of their elevation, rather than any meteorological reason. Second, topography varies greatly across the United States, so any surface map would, in theory, have "low pressure" on every mountain peak and "high pressure" in every valley. However, these areas of higher and lower pressure are not relevant to any actual weather patterns because they are simply caused by differences in elevation. To adjust for this, every weather station across the nation measures station air pressure and then calibrates it to sea-level air pressure, which is the pressure the location would have if it were at sea level. Rather than using station air pressure, weather maps use sea-level-calibrated pressure, which removes the effects of elevation on air pressure and allows us to focus on the meteorology. Sea-level air pressure values (expressed in millibars, the metric unit of air pressure) are then plotted on a weather map, as shown in Figure 6.1.1.

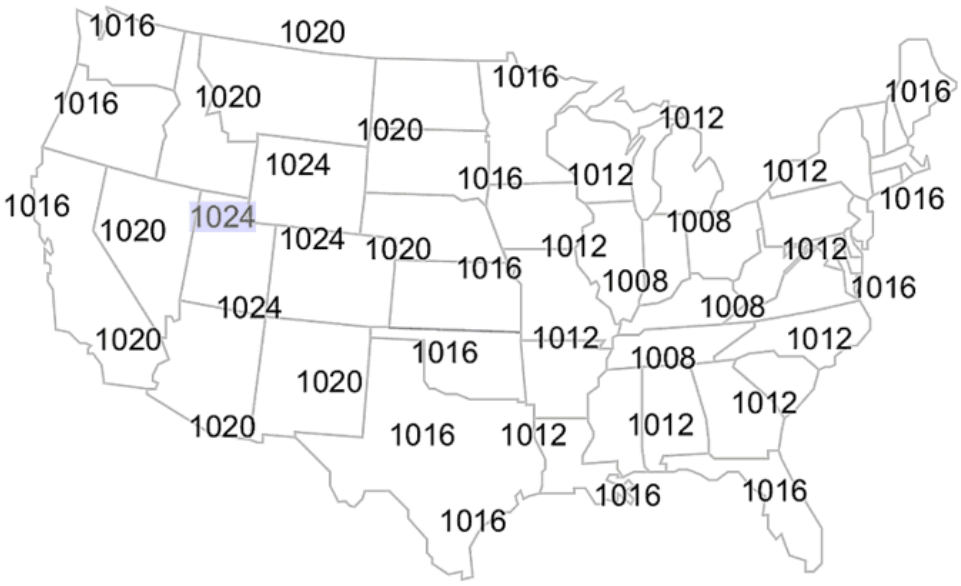


Figure 6.1.1: A map of Sea Level Air Pressures over the United States. (CC BY-NC 4.0; American Meteorological Society via Unidata)
Alternative description of image.

The average sea level pressure is 1013.25 mb. We use this number as a benchmark to identify areas of high and low pressure.

1. Since there is more air above you at sea level than there would be in a city like Denver, sea level air pressures are generally _____ than station-measured air pressures.
   a. higher
   b. lower

2. The highest pressure shown in Figure 6.1.1 is _____.
   a. 1016 mb
   b. 1020 mb
   c. 1024 mb
   d. 1032 mb.

3. The lowest pressure present shown on the map is _____.
   a. 1012 mb
   b. 1004 mb
   c. 1000 mb
   d. 1008 mb.

This map is a relatively simplified version of an air pressure map. The difference between two consecutive values displayed is called an interval. For this map, the interval is 4 mb.

4. Based on the interval provided, this map should only display data for station pressures of:
   a. 1006 mb, 1008 mb, 1010 mb, 1012 mb, 1014 mb, 1016 mb, 1018 mb.
   b. 1004 mb, 1008 mb, 1012 mb, 1016 mb, 1020 mb, 1024 mb.
   c. 1009 mb, 1012 mb, 1015 mb, 1018 mb, 1021 mb, 1024 mb.

Similar to a weather map showing temperatures, a map showing detailed pressure values across the country would be overcrowded. Meteorologists want to identify patterns quickly. Thus, they use isobars – lines of constant pressure – to present patterns visually in an easily identifiable manner. Let us attempt to draw isobars on Figure 6.1.1 and analyze whether they allow us to better examine the pressure patterns. Here are some guidelines for drawing isobars on a weather map:

- Drawing isobars is like connecting dots. Isobars should connect every location with the same air pressure. For example, the 1024 mb isobar should connect every location with a pressure of 1024 mb.
- Draw isobars every 4 mb, only for multiples of 4.
  - HINT: Should I draw an isobar for a particular pressure? Divide the pressure by 4. If it's still an integer, then yes. If not, then no!
- Isobars do not cross or branch.
- Isobars either extend to the edge of a map or close to form a full circle.
- If you're drawing on paper, use a pencil because mistakes happen.
- Label your isobars.

5. Draw isobars on Figure 6.1.1, and save the final image.

6. On your map, you'll notice that the isobars created two bull's-eyes with centers located:
   a. one on the East Coast of the U.S. and another in California.
   b. one in Texas and another on the East Coast of the U.S.
   c. one in California and another in Canada.
   d. one in Utah and another in Kentucky.

7. For one of the bull's-eyes, the air pressure increases as you approach the center. This represents a center of _____ pressure.
   a. high
   b. low

8. For the other bull's-eye, the air pressure decreases as you approach the center. This represents a center of _____ pressure.
   a. high
   b. low

While isobars are only drawn every 4th millibar, they provide an excellent indication of air pressure elsewhere. A location between two isobars will have an air pressure value between those two isobars.

9. For example, on the isobar map in Figure 6.1.1, El Paso, in extreme western Texas, lacks a plotted sea-level pressure value, and no isobars cross it. However, based on the two closest isobars, it likely has a sea level pressure of approximately.
   a. 1016 mb
   b. 1018 mb

c. 1020 mb
d. 1022 mb

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6.2: High and Low Pressure Systems

Areas of high and low pressure

Once isobars are plotted on a weather map, they can be used to identify pressure patterns and the locations of high and low-pressure systems. For example, if the isobars form a "bull's-eye" pattern, the center of that bull's-eye is a pressure system. If isobar values decrease as you approach the center of the pressure system, it represents a low-pressure system, while a bull's-eye with increasing values as you approach the center represents an area of high pressure. Figure 6.2.1 is a weather map of computer-generated high- and low-pressure systems and isobars. This map is for 0100 UTC on July 20, 2020, and is a more realistic representation of air pressure than Figure 6.1.1, which was simplified.

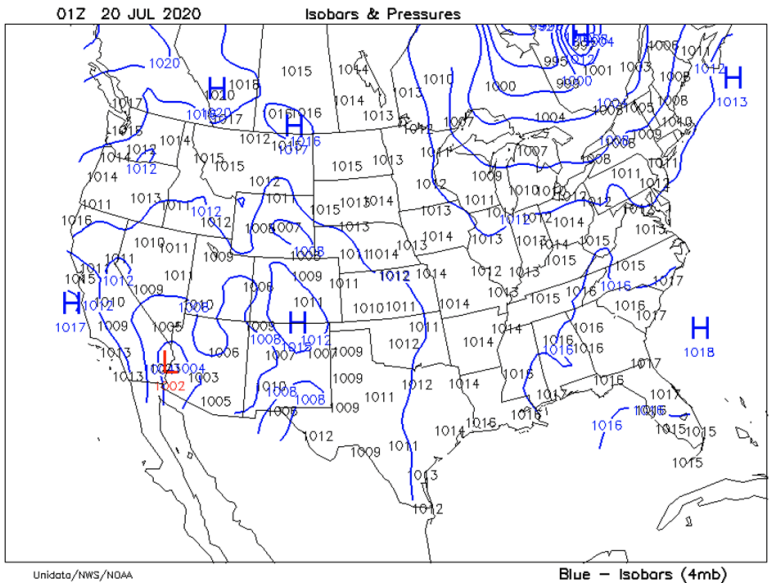


Figure 6.2.1: Sea Level Air Pressures at 0100 UTC on July 20, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of the image.

10. While isobars are plotted every 4 mb, recorded sea-level air pressures are also displayed for values between two isobars. Such a location is San Francisco, which is reporting an air pressure of:
    a. 1013 mb
    b. 1015 mb
    c. 1017 mb
    d. 1019 mb.

We learned in Investigation 5 that when air parcels rise, they often cool and condense, forming clouds. When air rises from the surface, it often leaves behind a low-pressure region. Thus, low pressure is often associated with cloudier, stormier weather, while areas of high pressure are associated with fair-to-clear weather.

11. From Figure 6.2.1, which of these regions should expect stormy weather?
    a. The Pacific Northwest (Oregon and Washington)
    b. The New Mexico/Colorado state Line
    c. The California/Arizona State Line
    d. All of these regions

Figure 6.2.2 is a full weather analysis of the continental U.S. at the same time as Figure 6.2.1. This includes radar precipitation data along with previously shown isobars, fronts, and station data.

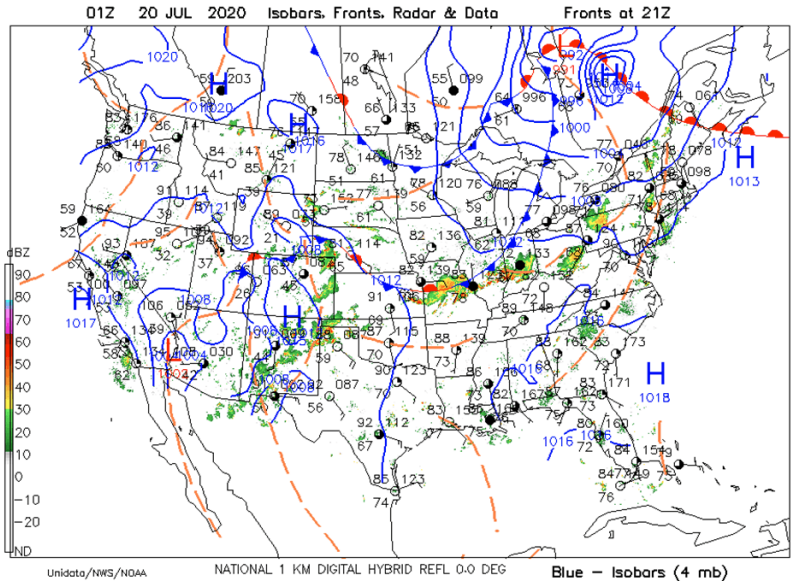


Figure 6.2.2: Surface weather conditions for the entire continental U.S. at 0100 UTC on July 20, 2020. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image

12. In Figure 6.2.2, do you see large green or orange blobs from the radar that indicate precipitation over the regions you expected stormy weather in question 11?
    a. Yes
    b. No

One of the big caveats of using only high- and low-pressure systems to diagnose weather conditions is that they are only one factor that can influence stormy weather. Other factors, such as moisture availability (in the case of the thermal low pressure over the CA/AZ border), Frontal Systems (such as the long cold front extending across Indiana, Illinois, and Missouri), troughs (the dashed brown lines), mountains (such as over New Mexico and Colorado), and even the time of year can greatly influence the ability of a pressure system to produce stormy weather. We will investigate these large-scale weather patterns in Investigations 7 and 8.

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6.3: Cyclonic and Anticyclonic Flow - The Hand Twist Model

Flow around pressure systems.

Air pressure systems, as identified at the end of the last section, are essential components of larger-scale weather patterns. As we continue in this course, we will begin shifting from smaller-scale physical properties (such as humidity and temperature) to larger-scale weather systems, including mid-latitude cyclones, hurricanes, and thunderstorms. But first, we need to understand the general behavior of air around high- and low-pressure systems, and we can introduce a simple model to demonstrate it.

Cyclonic Flow



Figure 6.3.1: Blank map of the United States with a low-pressure center in the middle. (Public Domain; John M Wolfson via Wikimedia Commons)

Cyclonic flow describes how air flows around a low-pressure system at Earth's surface. We'll cover the "whys" of cyclonic flow more in depth in Investigation 7, but for now, we'll focus on the general behavior of air as it flows around a low-pressure system. To demonstrate the flow, a simple model, the Hand-Twist model, can be employed. Perform the following process:

Step 1: Print out Figure 6.3.1, which is a map of the United States with a low-pressure system in the middle indicated by a red "L".

Step 2: Place your non-writing hand, with your fingers fully spread out, over the map with your palm over the center of the red "L".

Step 3: Using a pencil, label your fingers 1, 2, 3, 4, and 5. It doesn't matter in which order you label the fingers. However, once you label a finger, that finger should keep its number for the remainder of the exercise.

Step 4: Twist the hand, one quarter turn counter-clockwise (to the left) and bring your fingers into the center of the red "L" as you do so.

Step 5: Label the position of your fingers using the same numbers as you did in Step 3.

Step 6: Draw arrows connecting the labels for each corresponding finger. For example, draw an arrow connecting the first "1" from step 3 to the second "1" from step 5. The arrow should point in the direction of the second position.

13. The five lines you drew following the Hand-Twist model steps create what appears to be a:

a. triangle
b. spiral
c. square
d. octagon

14. From the direction of the arrows, we can say that air rotates _____ a low pressure:
    a. clockwise and away from
    b. clockwise and into
    c. counter-clockwise and away from
    d. counter-clockwise and into

15. Additionally, the palm of your hand is a good indicator of rising/sinking motion in a pressure system. As you progressed through the steps of the hand-twist model, the palm of your hand _____, indicating that air _____ in a low-pressure region.
    a. rose, rises
    b. rose, sinks
    c. sank, rises
    d. sank, sinks

Anticyclonic Flow

While cyclones are areas of low pressure, anticyclones are areas of high pressure. Therefore, the behavior of the air around a high-pressure system is called Anti-Cyclonic flow. We can use the Hand-Twist model again to demonstrate Anti-Cyclonic flow, as we did for Cyclonic Flow. To do it, perform these tasks:

Step 1: Print out Figure 6.3.2, which is similar to Figure 6.3.1, but has high pressure at the center.

Step 2: Start by bunching the fingers of your non-writing hand together, and place them over the center of the blue "H."

Step 3: Label the position of each finger 1-5, just like you did with the low pressure.

Step 4: Turn your hand one-quarter twist clockwise (to the right) and extend out your fingers fully as you do so.

Step 5: Label the new position of each finger, using the same numbers for each finger as you did in Step 3.

Step 6: Draw arrows connecting each position, with the arrow pointing in the direction of the second position.

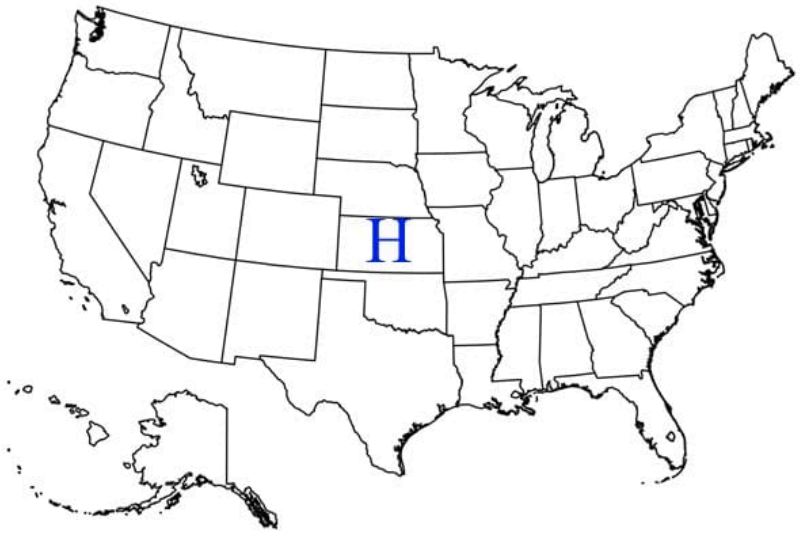


Figure 6.3.2: Blank map of the United States with a high-pressure center in the middle. (Public Domain; John M Wolfson via Wikimedia Commons)

The five arrows should create a pattern very similar to that of the hand-twist model for low pressure, but there are a few key differences.

16. From the arrows you drew on Figure 6.3.2, we can say that air flows _____ the high-pressure region.
    a. clockwise and away from
    b. clockwise and into
    c. counter-clockwise and away from
    d. counter-clockwise and into

17. Moreover, the palm of your hand _____ while doing the hand-twist model for high pressure, indicating that air _____ in a center of high pressure.
    a. rose, rises
    b. rose, sinks
    c. sank, rises
    d. sank, sinks

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6.4: Cyclonic and Anticyclonic flow in real life.

Finding Pressure based on Winds

Now that we have learned how winds behave around low- and high-pressure systems, we can use wind direction to estimate the air pressure at a location. Figure 6.4.1 is a map of surface observations at 1900 UTC on August 30, 2017. Remember that the long poles extending from the station model point in the direction from which the wind is coming. There is a “mystery” pressure system over Eastern Louisiana, indicated by a green “?” Your mission, should you choose to accept it, is to identify the type of pressure system.

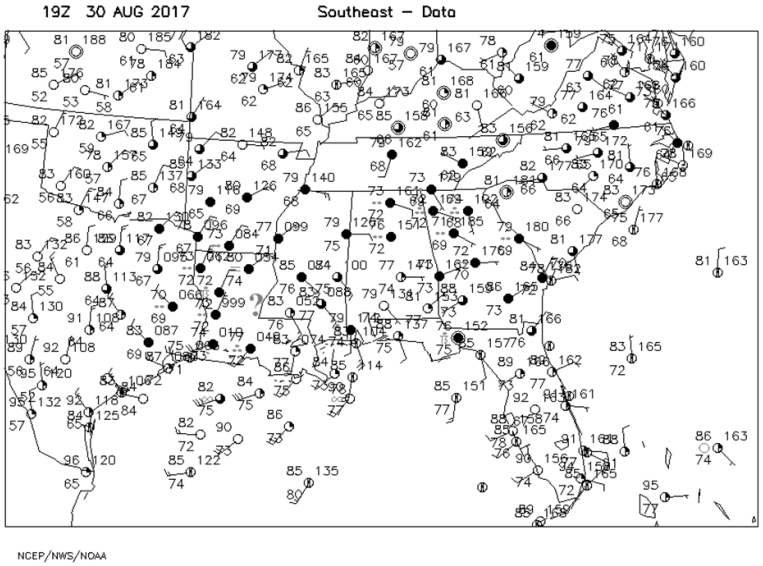


Figure 6.4.1: Surface weather data at 1900 UTC on August 30, 2017. Note that a "mystery pressure" system is identified as a question mark in Eastern Louisiana. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

18. In general, winds on the western side of the “mystery” pressure are blowing from the:
    a. northwest, and northeast.
    b. west, and southwest
    c. south and southeast
    d. east, and northeast

19. In general, winds on the eastern side of the “mystery” pressure are blowing from the:
    a. northwest, and northeast.
    b. west, and southwest
    c. south and southeast
    d. east, and northeast

Draw arrows indicating the motions you selected for questions 18 and 19 on Figure 6.4.1 to help you visualize the wind directions.

20. Putting these two findings together, the motion around this mysterious pressure is generally:
    a. clockwise
    b. counter-clockwise

You should also notice that the center circle of the station model shows cloud conditions, while the symbols on the left-hand side of the center show precipitation. You can reference the National Weather Service page for the station model to refresh your memory.

21. Thus, based on the direction of the rotation, the presence of clouds, and precipitation data, the conditions indicate that this mystery pressure system is indeed a:
    a. high-pressure system
    b. low-pressure system.

Convergence and Divergence

The previous situation demonstrates Convergence. It occurs when air flows toward a center of pressure from different directions. Once it reaches the center, it has nowhere to go but rise upwards. When air rises, it cools, forms clouds, and often produces precipitation, such as showers or thunderstorms.

22. Thus, convergence must occur in a _____ pressure system.
    a. low
    b. high

On the other hand, Divergence occurs when surface air is moving away from a center of pressure. In this case, air from above must sink to fill the space previously occupied by the escaping surface air. This causes sinking motion over an area of divergence, inhibiting cloud formation and leading to clear skies.

23. Thus, divergence must occur in a _____ pressure system.
    a. low
    b. high

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6.5: Accessible Descriptions

Figure 6.1.1: Surface Air Pressure for the United States

This map of the United States shows surface pressure values in millibars (mb) for each state. The data appears to be a simplified national surface pressure distribution, with numeric values displayed in black text within each state's outline.

- Higher pressure values are found in the western half of the U.S., especially in the Rocky Mountains and the Great Basin, where values reach 1024 mb.
- Lower pressure values are observed across the eastern U.S., particularly from the Ohio Valley to the Southeast, with values dropping to around 1008 mb.

Table 6.5.1: Pressure values shown on the weather map are provided with the nearest states.

Region	States and nearby Pressures (mb)
West	California (1020), Nevada (1020), Utah (1024), Colorado (1024), New Mexico (1024)
Central Plains	Nebraska (1020), Kansas (1020), Oklahoma (1016), Texas (1020)
Midwest	Iowa (1016), Illinois (1012), Indiana (1008), Missouri (1016)
Southeast	Florida (1016), Georgia (1012), Alabama (1012)
Northeast	New York (1016), Pennsylvania (1016), New Jersey (1016)
Mountain West	Wyoming (1020), Montana (1020), Idaho (1020)

Figure 6.2.1: Isobar Map for the United States at 0100 UTC on July 20, 2020

Surface weather map of the continental United States valid at 01 Z on July 20, 2020, showing isobars (lines of equal sea-level pressure) in blue, labeled in millibars (hPa), at 4 mb intervals. The map also marks areas of high pressure ("H") and low pressure ("L") to show the general surface pressure pattern across the country.

Key features:

- High-pressure systems (H) are located in several regions:
  - One over the Pacific Northwest (centered near 1017 mb),
  - Another across the Southern Plains (around Oklahoma, ~1012 mb),
  - One over the Southeast (Florida, ~1018 mb),
  - And a broad high across the Northeast U.S. (~1013 mb).
- A well-defined low-pressure system (L) is centered over southern Arizona and southeastern California, with a central pressure of 1002 mb. This low is likely associated with the Southwest Monsoon pattern. Surrounding isobars form a closed loop, with pressure gradually increasing outward (1003, 1004, 1005 mb, etc.), indicating a tight pressure gradient that could lead to increased winds or convective activity in the region.
- Another low-pressure area is found in the far northern Great Lakes region, with pressures dropping below 996 mb, and dense isobar spacing suggesting a stronger synoptic system, possibly with organized winds or precipitation.
- Elsewhere, isobars are generally more spaced out, especially across the central and southeastern U.S., indicating weaker pressure gradients and likely calmer surface winds.
- The isobar pattern also shows a trough extending from the low in Arizona northeastward into the central Plains and upper Midwest.

This map helps students identify areas of rising and sinking air, anticipate potential wind direction and speed based on isobar spacing and curvature, and recognize typical summer surface pressure patterns, such as thermal lows in the desert Southwest and broad subtropical highs in the Southeast.

Figure 6.2.2: Surface Weather Analysis for the Continental United States

Surface weather map of the continental United States valid at 01 Z on July 20, 2020. This composite map shows multiple features including:

- Isobars (lines every 4 mb) representing sea-level pressure patterns,
- Surface fronts (plotted as of 21 Z), including cold fronts (lines with triangles), warm fronts (lines with semicircles), stationary fronts, and troughs,
- Radar reflectivity indicating precipitation intensity,
- Surface observations at individual stations (using standard station models showing temperature, dew point, wind, pressure, and cloud cover).

A few key features include:

- A low-pressure system is centered over the Desert Southwest (southern Arizona), with a pressure of 1002 mb and counterclockwise flow around it. This is likely a monsoonal thermal low, common in summer over this region, accompanied by radar returns showing scattered convection (thunderstorms).
- Another low is located over the Great Lakes, centered near Michigan, with a strong cold front extending southwest through the Midwest and into the southern Plains. This front is followed by cooler, drier air and is associated with a line of thunderstorms, seen on radar from Illinois to Tennessee.
- A stationary front lies across the central Plains and into the Ohio Valley, where scattered showers and storms are visible on radar, indicating an active boundary with warm, moist air on one side and cooler air on the other.
- Several high-pressure centers ("H") are noted:
  - One over the Pacific Northwest (~1020 mb),
  - Another across the central U.S., around Oklahoma (~1012 mb),
  - A third over the Southeast and Florida (~1018 mb), promoting more stable conditions in those areas.
- Widespread radar echoes, especially in the Midwest and Southeast, indicate areas of active precipitation, some likely convective (thunderstorms), with stronger reflectivity (yellows and reds) indicating heavier rainfall.
- Surface station plots show warm, humid conditions across much of the country, with temperatures commonly in the 70s to 90s °F and dew points mostly in the 60s to 70s °F, confirming unstable air in many regions.

Figure 6.4.1: Surface Analysis for Southeast United States

Surface station plot for the southeastern United States valid at 19 Z (2:00 PM CDT) on August 30, 2017. The map displays surface observations from numerous locations using standard station models, which include:

- Temperature (in degrees Fahrenheit),
- Dew point,
- Sea-level pressure (in milibars with leading "10" or "9" omitted),
- Pressure tendency,
- Cloud cover (represented by the shading of the circle),
- Wind barbs (showing wind direction and speed extending from the circle),
- Present weather symbols (e.g., rain or fog), where applicable.

Across the broader region:

- Temperatures mostly range from the upper 70s to mid-80s °F.
- Dew points are generally high—in the 70s °F—indicating moist and humid surface conditions.
- Winds vary, but southerly to southeasterly surface flow dominates much of the Southeast.

Over Louisiana and parts of Mississippi and eastern Texas, there is a clear cyclonic (counterclockwise) wind pattern. Wind barbs surrounding this region show:

- Easterly winds across southern Mississippi and Alabama,
- Southerly to southeasterly winds over southeastern Louisiana,
- Westerly winds in southern Texas,
- Northerly winds in northern Louisiana and southern Arkansas.

Cloud cover in this region is generally overcast, and the high dew points indicate the presence of deep moisture, supportive of widespread rainfall or ongoing showers—though specific present weather symbols are limited in this plot.

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7: SURFACE WINDS

Introduction

Wind is simply air in motion. The atmosphere is composed of countless molecules that are constantly in motion, creating the sensation of wind. Winds can be gentle like a warm summer breeze, or they can be gusty and cold like a winter gale. In 1805, Sir Francis Beaufort, an Irish hydrographer and naval officer, created the Beaufort Scale, a measure of wind speed and observed conditions at sea or on land. It classifies wind conditions by wind speed, ranging from calm (0 mph) to hurricane-level (over 74 mph). Figure 7.1 shows a NASA satellite image of Hurricane Katrina before landfall in the Gulf of Mexico, where winds reached 175 mph! These high wind speeds can pack a significant punch. Figure 7.2 shows a 2x4 wood beam driven forcefully through a tree by strong winds during a Hurricane in Puerto Rico.

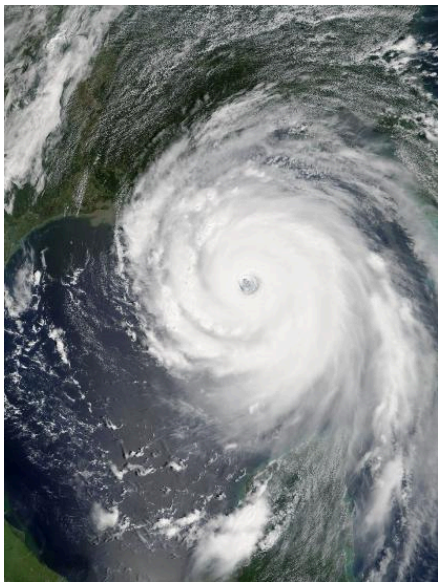


Figure 7.1: Satellite view of Hurricane Katrina, moments before landfall, on August 28, 2005 (Public Domain; NASA Worldview via Wikimedia Commons)



Figure 7.2: Hurricane winds drive a 10-foot 2x4 through a palm tree in Puerto Rico in 1928 (Public Domain; NOAA digital collections via Wikimedia Commons)

But what determines how strong the wind blows? What determines its direction? How do cyclonic and anticyclonic flows form? These are the questions that we aim to address in this investigation.

Learning Objectives

By the end of this investigation, you should be able to:

- Distinguish between surface winds and winds aloft.
- Identify the three forces that determine wind speed and direction.
- Determine the combined effect of all the forces on wind speed and direction on a map.

Navigational Note

Investigation 7 has 23 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

7.1: Surface vs Aloft

7.2: Why the wind blows

7.3: Other forces acting on the wind

7.4: Accessible Descriptions

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7.1: Surface vs Aloft

Surface weather vs upper air weather

Winds and weather occur at all heights in our Troposphere. Meteorologists are not only interested in weather conditions at the Earth's surface, but also at various altitudes above it. This is because weather conditions at those heights can greatly influence weather conditions at the surface. In this investigation and the next, you will encounter the words “Surface” and “Aloft” quite a bit. But what do they mean? While weather conditions can be measured at various altitudes in the atmosphere, the terms surface and aloft exist primarily to present a dichotomy. Here are their definitions:

- Surface: The portion of the atmosphere directly above the land/ocean surface of Earth.
- Aloft: The portion of the atmosphere at any height above the surface, or higher than 1000 meters. 1000 meters is an arbitrary height used by meteorologists to separate surface from weather conditions aloft.

Using this information, let's try to answer the following questions:

1. Weather stations near the ground (Figure 7.1.1) record weather conditions:
   a. At the surface
   b. Aloft

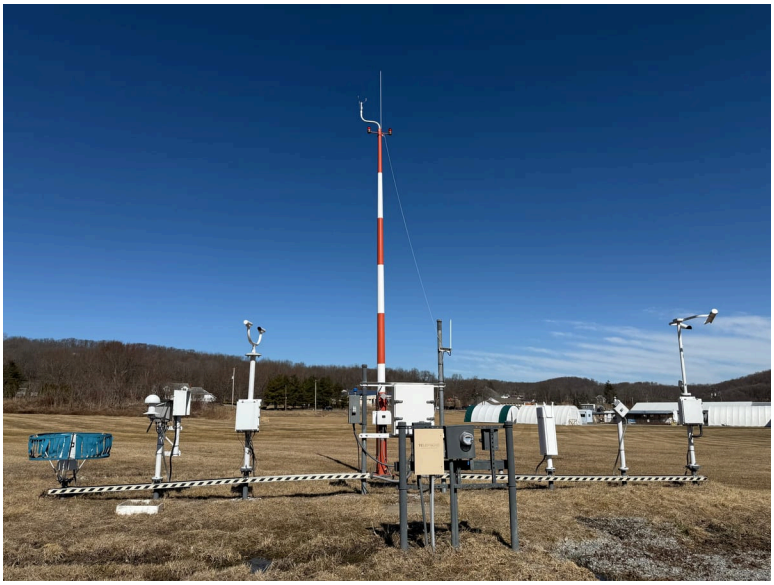


Figure 7.1.1: The Automated Observing System (ASOS) at Sussex Airport in New Jersey. Instruments include (from left to right) a precipitation collection drum, radiation and temperature sensors, a surface wind anemometer, a 5 m wind anemometer on a tower, a radio transmitter, and a wind vane. (CC BY-SA 4.0; Famartin via Wikimedia Commons)

2. After being released, weather balloons (Figure 7.1.2) record weather conditions:
   a. At the surface
   b. Aloft



Figure 7.1.2: A launched Weather Balloon with an attached radiosonde. (Public Domain; Carla Thomas via NASA).

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7.2: Why the wind blows

Forces that act on the wind

Because wind is air in motion, it is governed by Newton's three laws of motion, which are as follows:

- First Law: An object in motion stays in motion, and an object at rest stays at rest, unless acted upon by a net force.
- Second Law: The net force exerted on an object is equal to the object's mass times its acceleration: $\sum F = m * a$
- Third Law: Every action has an equal and opposite reaction. (We won't need it here.)

Assuming that the mass of the atmosphere stays constant, the net force on the air is proportional to the air's acceleration. In short, forces acting on air accelerate is to cause wind. There are three types of acceleration that we'll cover, and three forces that accelerate the wind are:

- Pressure Gradient Force: Speeds up the wind.
- Coriolis Force: Changes the wind's direction.
- Friction: Slows the wind down.

Pressure Gradient Force

Surface air pressures can vary horizontally between two locations on the Earth's surface. This results in a difference in the number of molecules between the two locations, creating an imbalance. Natural systems tend to seek equilibrium, so air travels from one location to another until the two have the same air pressure. This movement of air results from a force called the Pressure Gradient Force. Here's what you need to know about the pressure gradient force:

- The Pressure Gradient Force exists due to a pressure imbalance between two locations.
- The Pressure Gradient Force moves air from areas of high pressure to areas of low pressure.
- The strength of the Pressure Gradient Force is determined by the ratio of the pressure difference between a high-pressure area and a low-pressure area, and the distance between them.

A good demonstration of how the pressure gradient force works can be made by connecting two identical tanks: one filled with water and the other only half full (Figure $7.2.1$). A connector near the bottom allows water to flow between the tanks. Because there is a difference in the water level, a pressure difference exists near the bottom between the two tanks, and water will flow from the fuller tank to the less full tank until the two tanks have the same water level (Figure $7.2.2$).

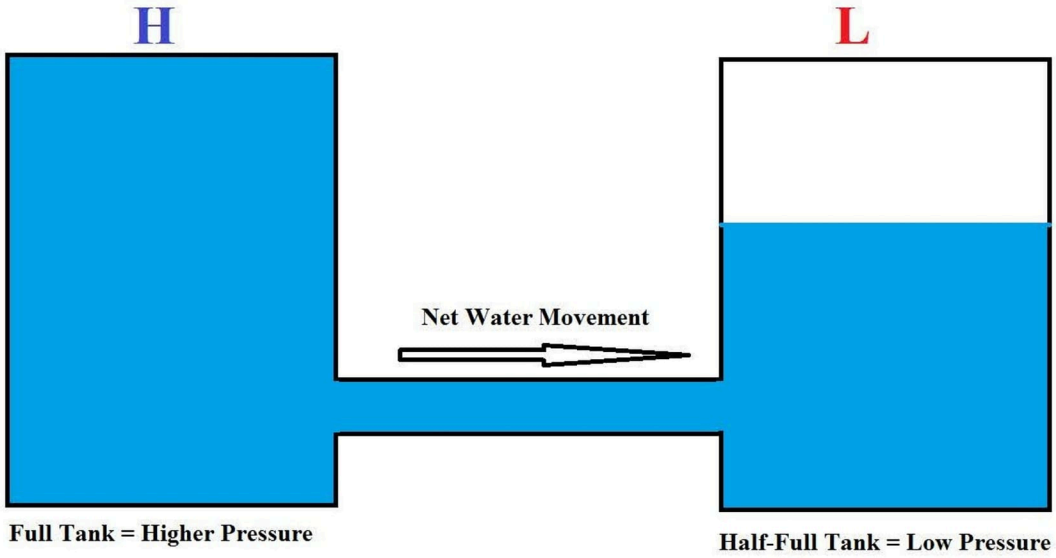


Figure 7.2.1: Imagine two tanks are filled with unequal amounts of water and are connected to each other near the bottom. The full tank will have higher pressure near the base, while the half-full tank will have lower pressure. Net water movement occurs from the higher-pressure region to the lower-pressure tank. (CC BY 4.0; Alicia Mullens)

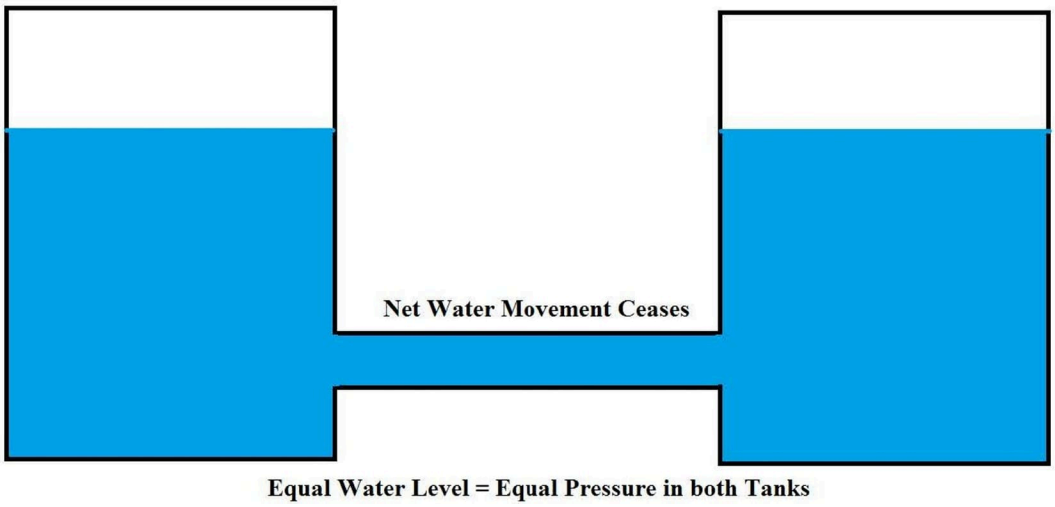


Figure 7.2.2: If both the tanks have equal levels of water, they have equal pressure, and net water movement ceases. (CC BY 4.0; Alicia Mullens)

Let's consider how a similar situation can occur in the atmosphere. Figure 7.2.3 is a simplified weather map, consisting of three isobars that are each 50 km apart, and have a difference of 4 mb from the other. A parcel of air, represented by a red dot, is located at point A, and lies on the 1012 mb isobar.

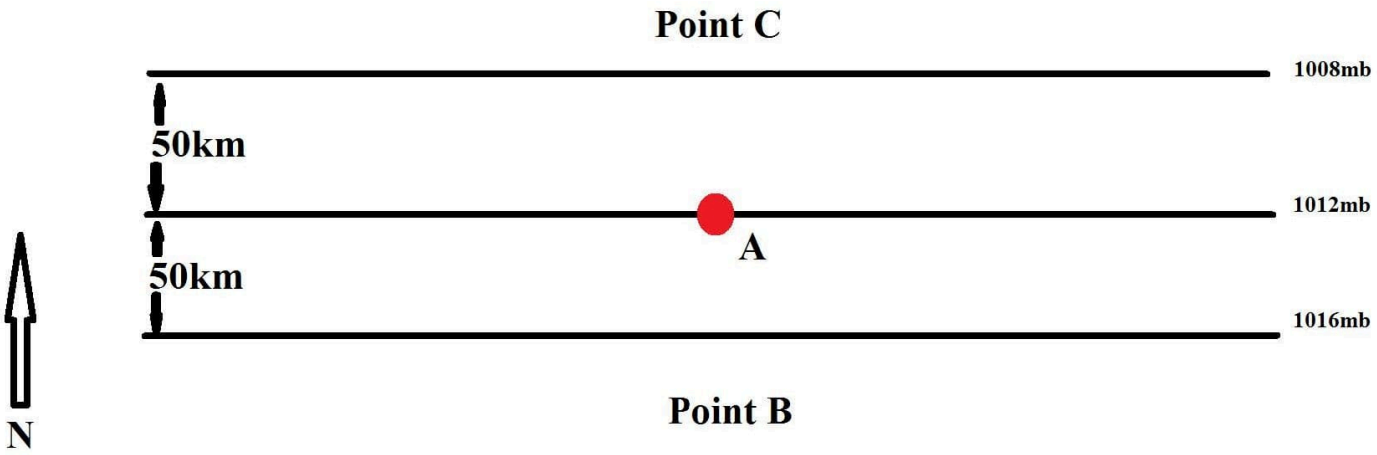


Figure 7.2.3: A simplified surface weather map shows three horizontal isobars separated by 50 km from each other. The 1008 mb pressure isobar is to the north, the 1012 mb isobar is in the middle, and the 1016 mb isobar is to the south. Point A lies on the 1012 mb isobar, Point B lies to the south of the 1016 mb isobar, while Point C lies to the north of the 1008 mb isobar. (CC BY 4.0; Alicia Mullens)

3. Based on the information in Figure 7.2.3, higher pressure is on the _____ side of this map.
   a. north
   b. south

4. If released from rest at point A, and allowed to travel on its own, a parcel of air will travel towards _____ due to the pressure gradient force.
   a. point B
   b. point C

5. The magnitude of the pressure gradient force, which is determined by the pressure difference divided by the distance between consecutive isobars, would be:
   a. 4 mb/50 km
   b. 8 mb/25 km
   c. 4 mb/100 km
   d. 4 mb/25 km

Using a calculator, divide the difference by the distance to obtain a decimal number for the Pressure Gradient Force, expressed in mb/km.

6. Suppose we changed Figure 7.2.3 so that the distance between each isobar was doubled to 100 km instead of 50 km. Assuming that the pressure difference (4 mb) stays the same, the pressure gradient force will:
   a. double
   b. decrease by 50%
   c. stay the same

7. On the other hand, suppose we halve the distance between isobars, so each isobar is only 25 km from the others. Assuming that the difference (4 mb) stays the same, the pressure gradient force will:
   a. double
   b. decrease by 50%
   c. stay the same

8. The pressure gradient force directly affects the motion of air. As the pressure gradient force increases, wind speeds increase. Based on questions 5-7, winds would be strongest when:
   a. The isobars are far apart from each other
   b. The isobars are closer to each other

Let's investigate this more using a real weather map. Figure 7.2.4 is a map of weather conditions, fronts, data, and isobars for the continental United States at 1200 UTC on October 23, 2016.

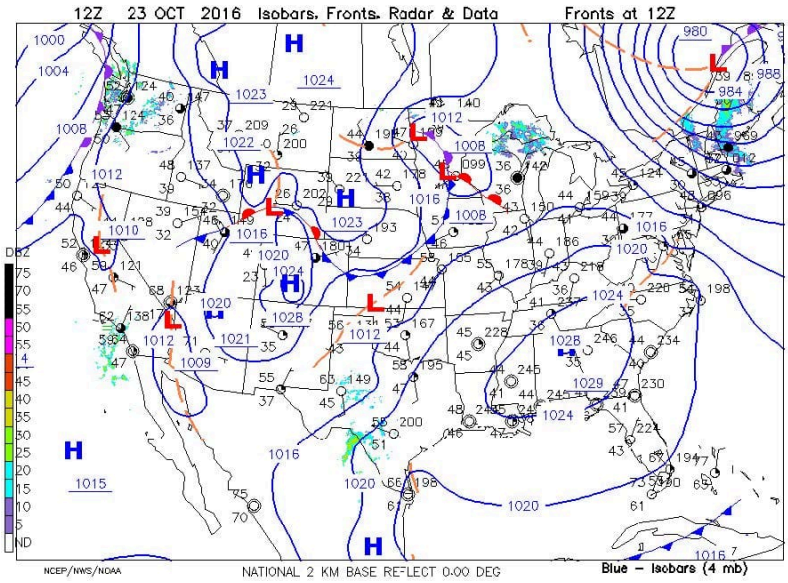


Figure 7.2.4: Surface Weather conditions for the United States at 1200 UTC on October 23, 2016. (Public Domain; American Meteorological Society via NCEP/NWS) Alternative description of image.

9. Based on the conclusions we made in question 8, the strongest winds should be present over:
   a. California
   b. Alabama and Mississippi
   c. Montana and North Dakota
   d. Maine, Vermont, and New Hampshire

10. On the other hand, winds are much calmer elsewhere, such as in the _____ where many locations have a “circle” outlining their station model instead of a wind pole, indicating calm winds.
   a. Northeast
   b. Southeast
   c. Northern Great Plains

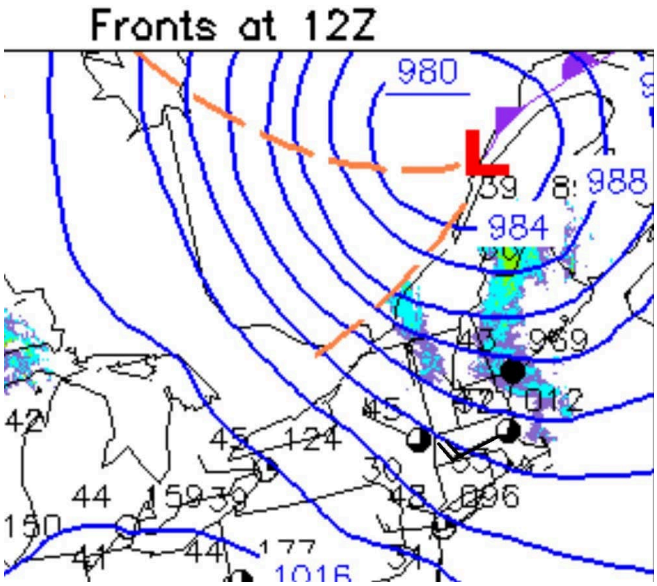


Figure 7.2.5: A zoomed in version of Figure 7.2.4, focused on the Northeast United States. Boston's wind barb has been enhanced to make it more visible. (Public Domain; American Meteorological Society via NCEP/NWS) Alternative description of image.

Let’s examine the influence of the Pressure Gradient Force on a location’s wind direction. Figure 7.2.5 is the same map as Figure 7.2.4, but zoomed in on the Northeast United States so that we can see the wind directions more clearly. Boston, in eastern Massachusetts, has an air pressure of 1001.2 mb (its upper-right number is 012), and winds from the West-Southwest at 20 kts.

11. If the wind is coming from the West-Southwest, it is traveling towards the:
    a. West-Southwest
    b. East-Northeast
    c. North-Southeast
    d. East-Southeast

Print out Figure 7.2.5 or open it in a computer paint program to answer the following few questions. Draw an arrow extending out of Boston in the direction that the wind is blowing towards. This is the direction of the net force on the wind. Now, we will break this force down into its components, starting with the pressure-gradient force. The pressure gradient force causes air to move from areas of high pressure to areas of low pressure. To determine the direction of the pressure gradient force, draw a red arrow, pointing out of Boston's station circle that is perpendicular to the nearest isobar (which is just northeast of Boston), and pointing towards the direction of low pressure.

12. The pressure gradient force over Boston should be moving the wind towards the:
    a. North
    b. East
    c. West
    d. South

But the net wind direction is different. This suggests that other forces, in addition to the pressure gradient force, influence the wind's speed and direction.

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7.3: Other forces acting on the wind

The Coriolis Force

As a parcel of air accelerates due to the Pressure Gradient Force, it will begin to experience a new force caused by atmospheric rotation. This force is called the Coriolis Force (Figure 7.3.1). It is an apparent force that appears to change the direction of a moving object due to Earth's rotation. The apparent deflection of a moving object due to the Coriolis Force is called the Coriolis Effect.

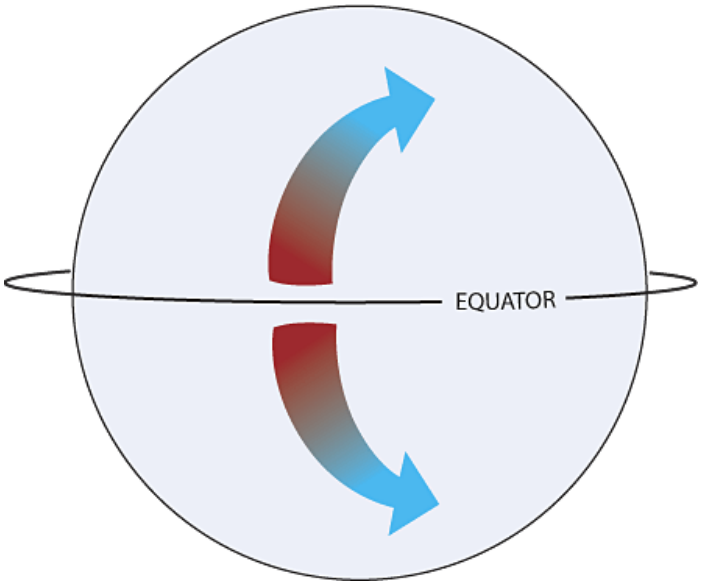


Figure 7.3.1: The rotation of the Earth on its axis deflects the atmosphere toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere, resulting in curved paths. (Public Domain; The Coriolis Effect via NOAA)

A simple demonstration of the Coriolis Effect can be conducted using two index cards. Using a pair of scissors, cut slits into each of the cards such that the two cards can fit into each other. The two fitted cards serve as our frame of reference for observing the direction of a moving object. We can draw a line from the center of the two cards, along the slit, to represent wind. By rotating one of the cards, we can simulate how wind moving in a straight line appears when the Earth's surface is rotating. The following video provides a nice demonstration of the Coriolis Effect.

Coriolis Effect

Duration of video: 2:54

Video introduction: Coriolis Effect demonstrates how the rotation of an index card can alter the path of an otherwise straight-moving particle of air. You can also try the experiment at home with a couple of index cards, a pen, two pieces of tape, and a pair of scissors.

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

13. From the video, the wind path was _____ when the index card was not being rotated.
    a. curved
    b. straight
14. On the other hand, when the index card was rotating, the path of the wind became:
    a. curved
    b. straight

The direction of rotation plays an important role. The Earth rotates from west to east. When viewed from the North Pole, the Earth appears to spin counterclockwise, while from the South Pole it appears to spin clockwise. Changing the index card's rotation from counterclockwise to clockwise reverses the direction the wind is deflected. Thus, the Coriolis force causes an apparent change in the wind's direction:

- To the right of its direction in the Northern Hemisphere
- To the left of its direction in the Southern Hemisphere

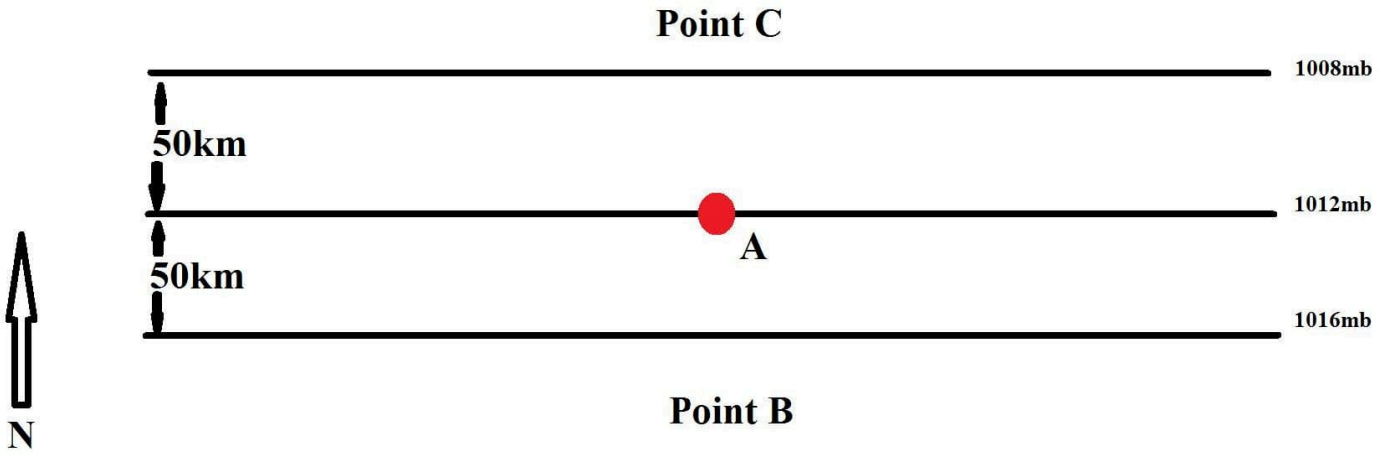


Figure 7.3.2: A simplified surface weather map shows three horizontal isobars separated by 50 km from each other. The 1008 mb pressure isobar is to the north, the 1012 mb isobar is in the middle, and the 1016 mb isobar is to the south. Point A lies on the 1012 mb isobar, Point B lies to the south of the 1016 mb isobar, while Point C lies to the north of the 1008 mb isobar. (CC BY 4.0; Alicia Mullens)

15. Returning to the simplified weather map in Figure 7.3.2, assuming we're in the Northern Hemisphere and North is at the top, West is on the left, and East is on the right. As the air particle accelerates, the Coriolis force would turn the wind:
    a. to the East
    b. to the West

Let's put into practice what we learned about the Coriolis force. Returning our attention to Boston and the printout of Figure 7.2.5. The Coriolis force would be directed at a 90° angle, to the right of the net wind force arrow or the direction of wind flow. Draw an arrow on your map that points out of Boston's station circle, and is 90° to the right of Boston's net wind arrow.

16. In Boston, the Coriolis Force would be directing the wind to the:
    a. North-Northeast
    b. North-Northwest
    c. South-Southeast
    d. South-Southwest

The magnitude of the Coriolis force is based on three key factors: size, speed, and latitude

- Size: Only large enough motions will feel a Coriolis tug. So contrary to popular belief, the water in your toilet bowl doesn't rotate due to the Coriolis force.
- Speed: The faster the wind, the stronger the Coriolis Force.
- Latitude: The further you are away from the equator, the stronger the Coriolis force. This is why cyclones or hurricanes don't form over the equator.

As the air parcel in Figure 7.3.2 accelerates, it will be tugged further and further to the right of its path (Figure 7.3.3 and Figure

7.3.4). Eventually, the direction and magnitude of the Coriolis force will become equal and opposite to the direction of the Pressure Gradient Force (PGF), causing the wind to flow parallel to adjacent isobars (Figure 7.3.5). This phenomenon is known as the Geostrophic (Earth-turning) Balance and will be investigated further later.

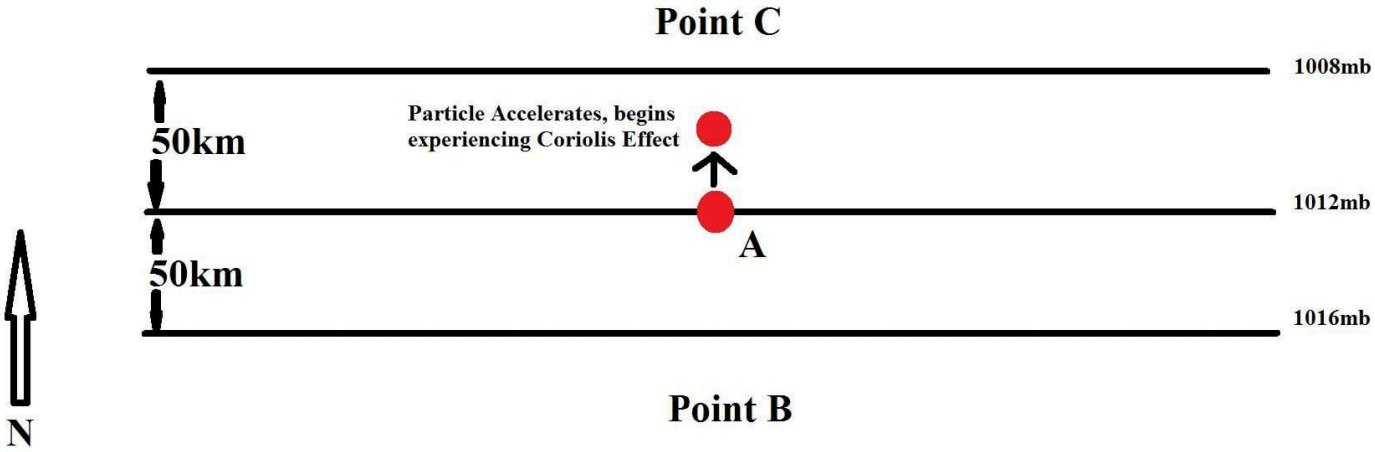


Figure 7.3.3: A parcel is located at Point A, 50 km south of Point C and 50 km north of Point B. The parcel will experience the Pressure Gradient Force (PGF) and begin moving northward toward the lower-pressure area (Point C). Once the parcel accelerates, it begins experiencing the Coriolis force, causing it to turn to the right in the Northern Hemisphere. (CC BY 4.0; Alicia Mullens)

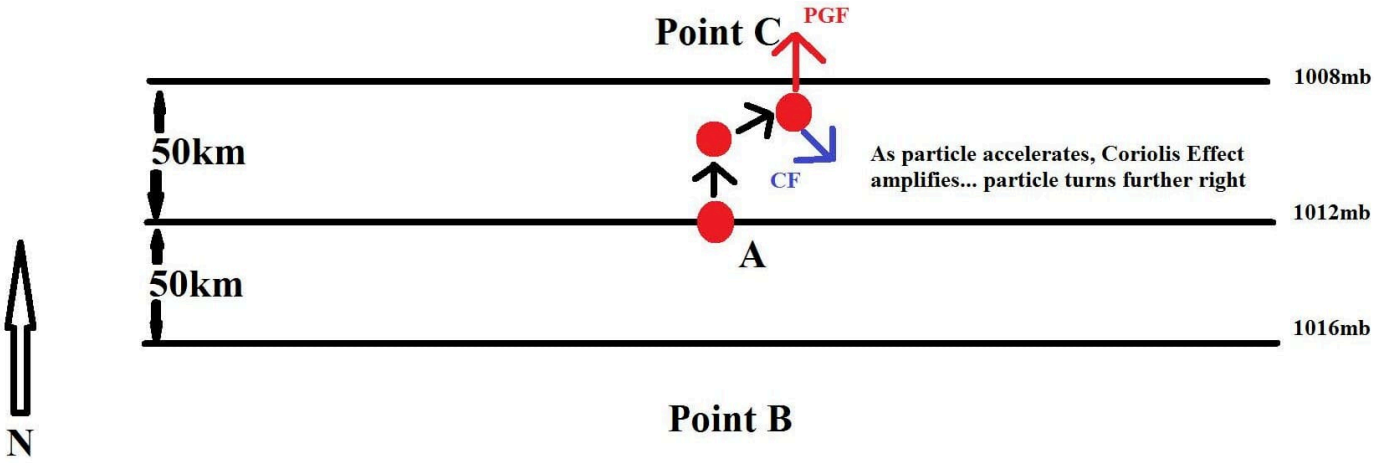


Figure 7.3.4: As the parcel accelerates from Point A, the Coriolis Force intensifies, curving the wind further to the right, while PGF continues to pull the parcel towards lower pressure (Point C). (CC BY 4.0; Alicia Mullens) Alternative description of the image.

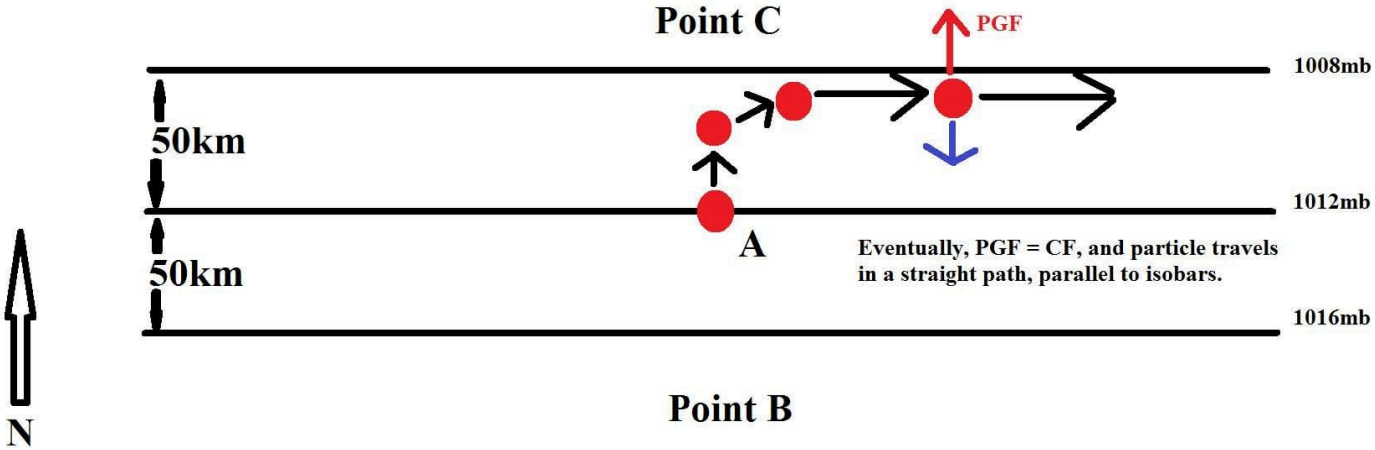


Figure 7.3.5: PGF continues to pull the parcel towards lower pressure (Point C) while CF is now directed in the opposite direction (Point B), as the parcel moves towards the right. Eventually, the Pressure Gradient Force (PGF) equals the Coriolis Force (CF) and the parcel travels in a straight path, parallel to the isobars. This is called Geostrophic flow. (CC BY 4.0; Alicia Mullens) Alternative description of the image.

17. At this point (Figure 7.3.5), the Pressure Gradient and Coriolis Forces _____ causing the wind to continue in a straight path due to inertia (Newton's first law).
    a. cancel each other out,
    b. amplify each other

Friction

The Pressure Gradient and Coriolis forces are the only forces we need to worry about in the upper atmosphere. However, near Earth's surface, trees, buildings, terrain, and other objects slow the wind. Combined, the drag caused by these objects exerts a force known as friction. Friction is always directed opposite the net wind direction. Before we jump into the effects of friction, let's do a brief review of the factors that affect the Pressure Gradient and Coriolis Forces:

- The Pressure Gradient Force is affected by differences in pressure and distance between isobars.
- The Coriolis Force is affected by Latitude, size, and speed.

18. Considering the setup in Figure 7.3.5, Friction would slow the wind down. Which force would be affected by the slowing down of the wind?
    a. Pressure Gradient Force
    b. Coriolis Force

19. As a result, which force will become stronger?
    a. Pressure Gradient Force
    b. Coriolis Force

20. This would throw the wind off from Geostrophic Balance, causing the parcel from Figure 7.3.5 to turn:
    a. Towards lower pressure
    b. Away from pressure

21. This is _____ with the Hand Twist Model we studies in Investigation 6, which suggests that winds spiral into low-pressure regions.
    a. consistent
    b. inconsistent

22. Finally, let's return to the Boston surface map. Draw an arrow pointing in the exact opposite direction of the Net Wind Force, representing Friction. In Boston, Friction is directed to the:
    a. East-Northeast
    b. West-Southwest
    c. North-Northeast
    d. South-Southeast

23. Label each of the arrows that you drew on Figure 7.2.5, and submit the figure.

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7.4: Accessible Descriptions

Figure 7.2.4 Surface Weather Conditions on October 23, 2016

This is a surface weather analysis map of the continental United States, valid at 12 Z (7:00 AM EDT) on October 23, 2016.

Key Elements:

1. Isobars:

- Shown as thin blue contour lines drawn every 4 millibars (mb).
- Pressure values range from 1000 mb to 1040 mb.
- Isobars form closed loops around high and low-pressure centers.
- Closely spaced isobars indicate stronger pressure gradients, suggesting windy conditions—especially in the northeastern U.S.

2. Pressure Centers:

- High-pressure systems (H) are centered in Southern California (1020 mb), Texas (1028 mb), and Florida and nearby Atlantic waters (1024–1028 mb).
- Low-pressure systems (L) are located in the Pacific Northwest and California coast (1008–1012 mb), the Great Plains (1004–1016 mb), and the Upper Midwest and Northeast (1004–1008 mb).

3. Frontal Boundaries:

- Cold fronts are shown as blue lines with triangles pointing in the direction of motion.
- Warm fronts are red lines with semicircles.
- Occluded fronts are purple, combining triangles and semicircles.
- Stationary fronts are alternating red/blue.

Notable features:

- A cold front extends from Nebraska to Texas.
- A stationary front lies across the central Appalachians.
- An occluded front spirals around a deep low in the far northeast U.S. near Maine and southeastern Canada.

4. Radar Reflectivity:

- Shaded regions with color scales show precipitation intensity, primarily in:
- Northeast (New York, Vermont, Maine)
- Great Lakes
- Central Plains and Rockies
- Pacific Northwest

Intensity is color-coded on the left, ranging from light (10 dBZ) to very heavy (over 70 dBZ).

5. Station Plots:

- Each station model displays:
- Temperature (°F), Dew point (°F), Wind speed and direction, Sea-level pressure, and Cloud cover.
- For example, New York reports 44°F with overcast skies and northeasterly winds.

Regional Summary:

- West Coast: Mixed precipitation in Oregon and Washington. High pressure dominates California.
- Rockies and Central Plains: Multiple low-pressure areas with frontal boundaries, widespread cloud cover, and precipitation.
- Northeast U.S.: A strong low-pressure system brings wind and rain, with closely packed isobars suggesting high wind speeds.
- Southeast and Gulf Coast: Generally clear, under high pressure with light winds.

Figure 7.2.5 A zoomed-in version of Figure 7.2.4

This is a zoomed-in portion of Figure 7.2.3, focusing on the northeastern United States and southeastern Canada at 12 Z (7:00 AM local time). The map shows isobars, surface fronts, precipitation, and weather station observations, indicating a strong low-pressure system.

Key Features:

- Low-Pressure System (L):
  - A large “L” symbol is centered over northern New England or southern Quebec.
  - Surrounding the low are tightly packed isobars (lines of constant pressure), labeled 980 mb, 984 mb, 988 mb, and so on.
  - The tight spacing indicates a strong pressure gradient, suggesting high wind speeds in the region.
- Fronts**:**
  - An occluded front (line with alternating semicircles and triangles) extends from the low eastward.
  - A cold front (triangles) and a warm front (semicircles) are attached and wrap around the low-pressure center.
  - A stationary front (alternating symbols) appears to the west.
- Precipitation**:**
  - Precipitation is mostly located in the New England states and southern Canada, extending southward through New York and into Pennsylvania.
- Weather Stations (station models):
  - Several circular plots show wind barbs, cloud cover, temperature, and pressure data.
  - Most stations report overcast conditions, temperatures in the 40s °F, and wind from the northwest or west.
  - Wind barbs indicate strong winds, consistent with the pressure gradient.

Figure 7.3.3 The Coriolis Force turns the parcel to the right

This labeled diagram illustrates how an air parcel responds to the pressure-gradient force and the Coriolis force in the Northern Hemisphere.

Diagram Structure:

- The image consists of three horizontal lines, each representing a different isobar (a line of equal atmospheric pressure):
  - Bottom Line (Point B): 1016 millibars (mb)
  - Middle Line (Point A): 1012 mb
  - Top Line (Point C): 1008 mb
- The vertical distance between each isobar is labeled as 50 kilometers.
- A northward-pointing arrow on the far left indicates directional orientation (with north at the top).

- A red circle represents an air parcel starting at Point A (1012 mb).
- The parcel initially moves northward toward lower pressure (Point C) due to the pressure gradient force, which is shown as a thick red upward arrow labeled PGF.
- As the parcel accelerates northward, the Coriolis force (CF) begins to deflect its path to the right, as shown by a blue arrow pointing eastward.
- Three red dots trace the curving path of the air parcel:
  - First directly northward.
  - Then deflected slightly northeast.
  - Finally curving more to the right as the Coriolis force increases.
- The rightward deflection continues until the Coriolis force balances the pressure-gradient force, at which point the parcel

moves in a straight line parallel to the isobars, achieving geostrophic balance (not yet fully reached in this diagram).
- A text label on the right side explains: "As the particle accelerates, the Coriolis Effect amplifies, and the particle turns further right."

Figure 7.3.4 Geostrophic Flow is achieved

This is a labeled atmospheric diagram showing the path of an air parcel under the influence of the pressure gradient force and the Coriolis effect, culminating in geostrophic balance.

Diagram Structure:

- The diagram contains three horizontal lines representing atmospheric isobars, or lines of equal pressure:
  - Bottom Line (Point B): 1016 millibars (mb)
  - Middle Line (Point A): 1012 mb
  - Top Line (Point C): 1008 mb
- Vertical spacing between isobars is labeled as 50 kilometers, showing equal pressure intervals from the surface upward.
- On the left side, an upward-pointing arrow labeled "N" denotes North, establishing that the top of the diagram is the direction toward lower pressure.

Air Parcel Motion and Forces:

- A red dot at Point A shows the initial position of the air parcel.
- The parcel moves northward from 1012 mb to 1008 mb due to the pressure gradient force (PGF), represented by a large red arrow pointing straight up.
- As the parcel moves, it is deflected to the right (eastward) by the Coriolis force (CF), shown as a blue arrow pointing rightward.
- The parcel's motion path is illustrated by several sequential red dots that curve from vertical to horizontal.
- Eventually, the parcel reaches a point where the Coriolis force exactly balances the pressure-gradient force, and it begins to move in a straight path parallel to the isobars, indicated by a horizontal black arrow.
- This final condition is labeled with the explanation: "Eventually, PGF = CF, and the particle travels in a straight path, parallel to isobars."

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8: UPPER AIR WINDS

Introduction

If you have ever flown on a cross-country flight before (Figure 8.1), you may have noticed that it's faster to travel from west to east than it is to fly from east to west. The reason is that flights fly through the upper troposphere, at about 30,000 feet, where strong winds generally blow from west to east. However, these winds are only one component of the upper troposphere's behavior, and what happens there greatly influences surface weather. We've already examined this effect when investigating stability and cloud formation. Wind direction and the general flow of the upper troposphere have significant implications for the weather we experience at the surface.



Figure 8.1: Commercial airplanes fly near the top of the tropopause, at over 30,000 feet, or 9,000 meters. (CC-BY-SA 4.0; via Wikimedia Commons)

In this investigation, we will examine upper-air weather maps and identify troughs and ridges. We will also investigate the implications of those features for surface weather.

Learning Objectives

- Investigate upper-air maps at the 500 mb and 300 mb levels.
- Distinguish surface weather conditions from upper-air conditions.
- Identify key features in the jet stream, such as troughs, ridges, and jet streaks.

Navigational Note

Investigation 8 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

8.1: Pressure Levels and Heights

8.2: Troughs and Ridges

8.3: Westerlies and the Jet Stream

8.4: Convergence, Divergence, and Jet Streaks
8.5: Accessible Descriptions

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8.1: Pressure Levels and Heights

Pressure Levels

Rather than looking at a constant elevation, Meteorologists (and aviators) focus on constant Pressure Levels – a surface in the atmosphere where air pressure remains constant. There are several pressure levels of importance, but for this investigation, we focus on two: 500 millibars (mb) and 300 millibars (mb). The 500 mb height is great at locating waves in the large-scale wind flow (such as troughs and ridges), while the 300 mb level is great at locating the jet stream. Figure 8.1.1 is a map of the 500 mb pressure level over the United States, taken at 1200 UTC on February 28, 2025.

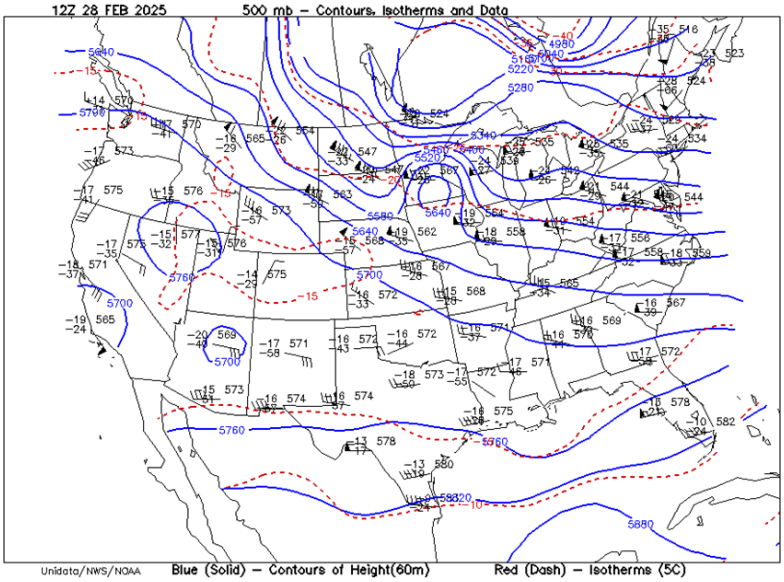


Figure 8.1.1: 500 millibar air map for 1200 UTC on February 28th, 2025. (CC BY-NC 4.0; American Meteorological Society via Unidata)
Alternative description of the image.

1. Some similar features in this map, when compared to a surface map (you could view one here: surface maps), include:
   a. Wind direction/wind speed is indicated at individual stations
   b. Air temperature is indicated at individual stations
   c. Dew point temperature is indicated at individual stations
   d. All of these are true

2. On the other hand, a few big differences between a surface map and this upper-level map include:
   a. The absence of cloud cover and precipitation information
   b. The absence of recorded pressure values (and instead, replaced with height contours)
   c. Temperature and dew point are indicated using Celsius instead of Fahrenheit (hint: Figure 8.1.2)
   d. All of these are true

If you notice, many symbols should look somewhat familiar, and others that appear quite different. One thing that should stick out to you pretty quickly is the presence of Station Models. These station models are highly similar to those observed at the surface, with only a few key differences. Figure 8.1.2 breaks down how to read these station models.

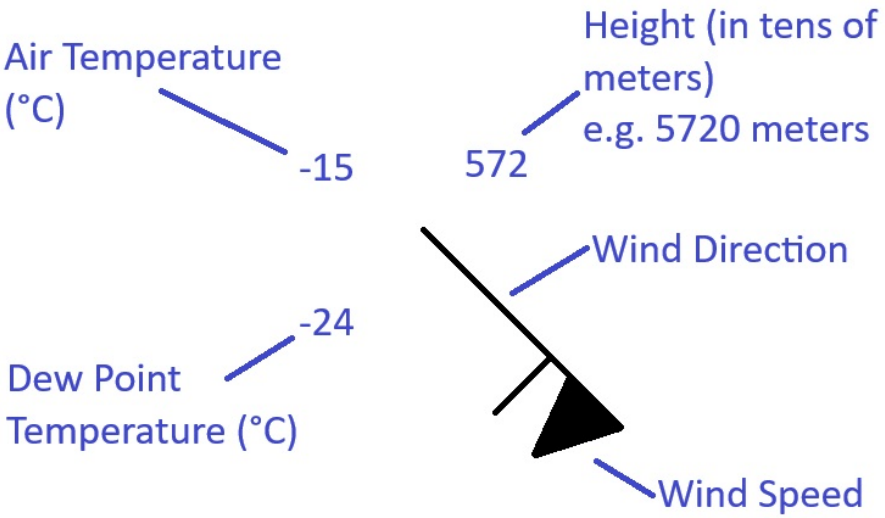


Figure 8.1.2: How to read an upper-air station model. (Public Domain; Alicia Mullens) Alternative description of image.

The main differences to note are that temperature and dew point are in °C (rather than Fahrenheit) and the three-digit number on the right now represents an altitude. Remember, everywhere on an upper air map is going to have the same air pressure, so the altitude represents at what height the pressure level is.

3. According to Figure 8.1.1, Oakland, in the San Francisco Bay Area, had an air temperature _____ at 500 mb:
   a. -37°C
   b. -18°C
   c. -571°C
   d. -65°C

4. Oakland's dew point temperature at 500 mb was:
   a. -37°C
   b. -18°C
   c. -571°C
   d. -65°C

5. The winds at Oakland were coming from the Southeast at:
   a. 10 kts
   b. 15 kts
   c. 30 kts
   d. 60 kts

6. The three-digit number in the upper-right-hand side of Oakland's station model represents altitude in tens of meters (to convert to meters, place a "0" at the right end). The three-digit number says 590, representing an altitude of:
   a. 571 m
   b. 5710 m
   c. 571,000 m
   d. 710.0 m

Height Lines

If the blue lines in Figure 8.1.1 have you thinking of isobars, you're in the right direction! However, because this map is for a 500 mb surface, all points on the map have a pressure of 500 mb. However, not everywhere will have 500 mb present at the same height. As a result, the blue lines on this map function almost like a topographic map, providing us with elevations at the 500 mb pressure level.

7. The location with the highest 500 mb height on Figure 8.1.1 is Miami, a warm city in Southern Florida, with a 500 mb height

of:
   a. 5840 m
   b. 5830 m
   c. 5850 m
   d. 5820 m

8. The location with the lowest 500 mb height on Figure 8.1.1 is Caribou, in northern Maine, with a 500 mb height of:
   a. 5120 m
   b. 5130 m
   c. 5140 m
   d. 5160 m

9. In general, the pattern of the blue height lines indicates that the highest heights are located:
   a. At lower latitudes
   b. At higher latitudes

To answer the next two questions, consider Miami and Caribou from the previous questions. At the time of Figure 8.1.1 (1200 UTC on 2/28/2025), Miami had a surface temperature of 76°F, and Caribou had a surface temperature of 14°F.

10. Higher 500 mb heights are present in the :
   a. Warmer parts of the United States
   b. Cooler parts of the United States
   c. There is no relationship between temperature and 500 mb heights

11. Lower 500 mb heights are present in the:
   a. Warmer Parts of the United States
   b. Cooler Parts of the United States
   c. There is no relationship between temperature and 500 mb heights

12. The relationship between Miami and Caribou's surface temperature and 500 mb heights, combined with the general pattern found in the previous questions, suggests:
   a. Warmer surface temperatures generally result in higher 500 mb heights
   b. Warmer surface temperatures generally result in lower 500 mb heights

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8.2: Troughs and Ridges

Waves in the Jet Stream

The collection of blue height lines on an upper-level map, such as Figure 8.2.1, is not straight as they extend across the Continental United States. Rather, they create a series of waves called troughs and ridges. Figure 8.2.1 shows an upper-level weather map with troughs and ridges.

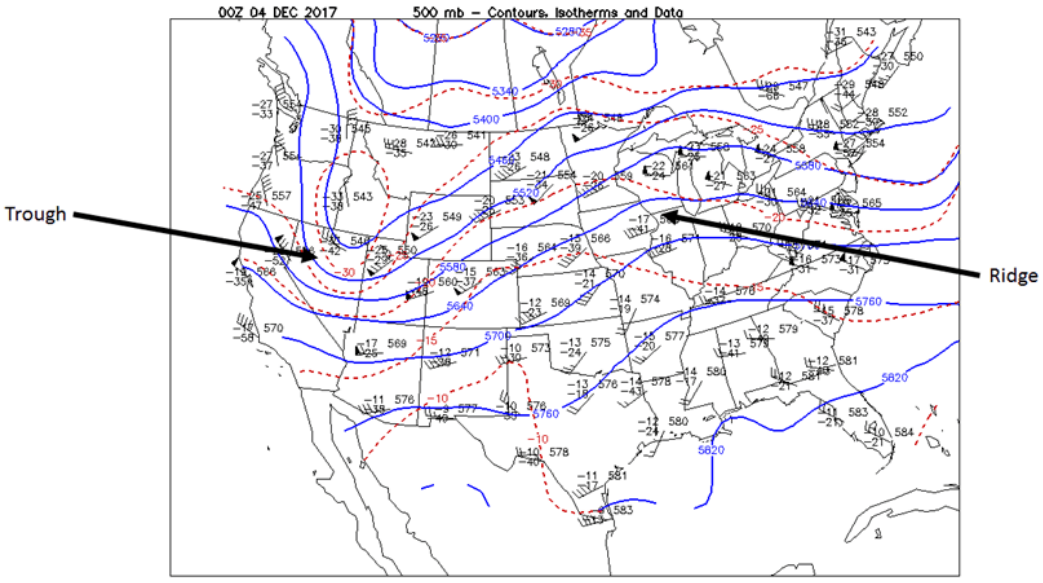


Figure 8.2.1: A 500 millibar map with a trough and ridge indicated with arrows. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

- **Ridges**: When the lines form what appears to be a hill that moves North, peaks, and then dips back South, that is called a ridge. Along the ridges, warmer air is pushed northward, creating a giant hump at the 500 millibar level.
- **Troughs**: When the lines form what appears to be a dip/depression/"u" shape that moves South, bottoms out, and then travels back North, that is called a trough. Along the troughs, cooler air is pushed south, creating what appears to be a giant valley at the 500 millibar level.

Remember, these troughs and ridges may extend over the ocean. We can assume that the height contours will eventually return to their zonal (east-west) orientation beyond the map. Let's apply this knowledge to Figure 8.2.2, which is a 500 millibar map for 1200 UTC on February 28, 2025.

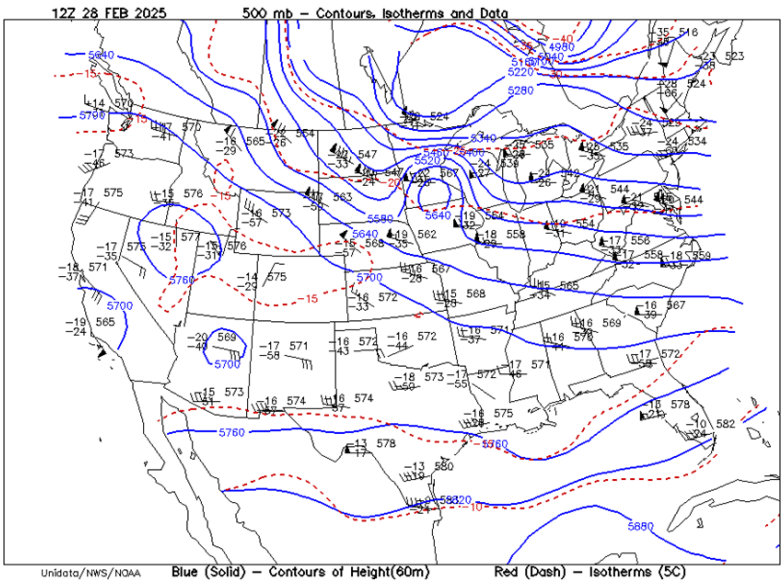


Figure 8.2.2: A 500 millibar air map for 1200 UTC on February 28th, 2025. (CC BY-NC 4.0; American Meteorological Society via Unidata) Alternative description of image.

13. The weather map in Figure 8.2.2 exhibits a pattern that features:
    a. A giant trough on the West Coast of the United States
    b. Zonal (flat) West-East flow across the entire United States
    c. A giant ridge on the West Coast and a trough in the Midwest and the East Coast

Upper-Level Winds and the Pressure Gradient Force

Let's examine the wind barbs on Figure 8.2.1. Because there is little to no friction in the upper atmosphere, winds aloft tend to be much faster than at the surface. While this isn't always true, it's a good assumption for this course and in general.

14. The wind barbs tend to _____ to the blue height lines.
    a. be parallel
    b. intersect at large angles or are nearly perpendicular

15. Winds tend to be stronger when: (Hint: Compare wind speeds over Minnesota and Michigan to wind speeds over California and Nevada)
    a. The height lines are closer together
    b. The height lines are further apart

16. Your answer to question 15 _____ with the concept that surface winds are faster when isobars are closer together (from Investigation 7), indicating that the increased speed of the wind in both situation is _____ caused by the pressure gradient force.
    a. agrees; indeed
    b. disagrees; not
    c. disagrees; indeed
    d. agrees; not

Thus, we realize that forces such as the Pressure Gradient Force and the Coriolis Force have the same impact on the wind speed and direction, regardless of elevation.

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8.3: Westerlies and the Jet Stream

Westerlies

While the 500 millibar level provides excellent insight into the specifics of upper-level wind flow, it does not reveal the overall wind pattern, notably the Jet Stream. To do that, we need to reach the 300 millibar level. Figure 8.3.1 is taken at 1200 UTC on February 28, 2025, the same time as Figure 8.1.1. It is a map of the 300 mb winds, heights, and isotachs. Isotachs are lines of constant wind speed, analogous to isobars but for wind rather than pressure. All guidelines for height lines and station models are identical to those on the 500 mb map.

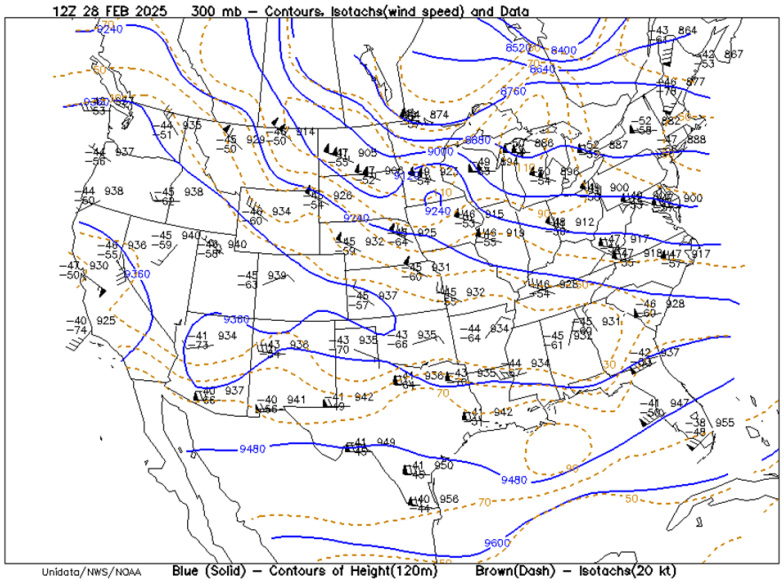


Figure 8.3.1: 300 millibar winds, heights, and isotachs for 1200 UTC on February 28, 2025. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of image.

Before we jump into the key features of the 300 mb map, let's make a few comparisons with the 500 mb map:

17. Compared to the 500 mb map (Figure 8.1.1), wind speeds at the 300 mb level are generally:
    a. Higher than the 500 mb level
    b. Lower than the 500 mb level

18. Heights in the 300 mb level are _____ than the 500 mb level. This is reasonable because air pressure decreases with altitude.
    a. higher
    b. lower

19. The relationship between latitude and height at the 300 mb level (that warmer air corresponds to higher heights) is _____ the 500 mb level.
    a. similar to
    b. different from

Let's examine a few key features of the 300 mb map.

Zonal vs. Meridional Flow

The Jet Stream is present when the blue height contours are close together, resulting in higher wind speeds. This creates a band of strong winds that travels from West to East. We can identify the presence and shape of that band by looking at the pattern

of blue lines. If the blue lines are relatively straight, traveling from West to East, we call that Zonal Flow. In this case, winds are predominantly from the West to the East (Figure 8.3.2a). On the other hand, if there are large ridges/troughs present (the jet stream is wavy), we call this Meridional Flow (Figure 8.3.2b)

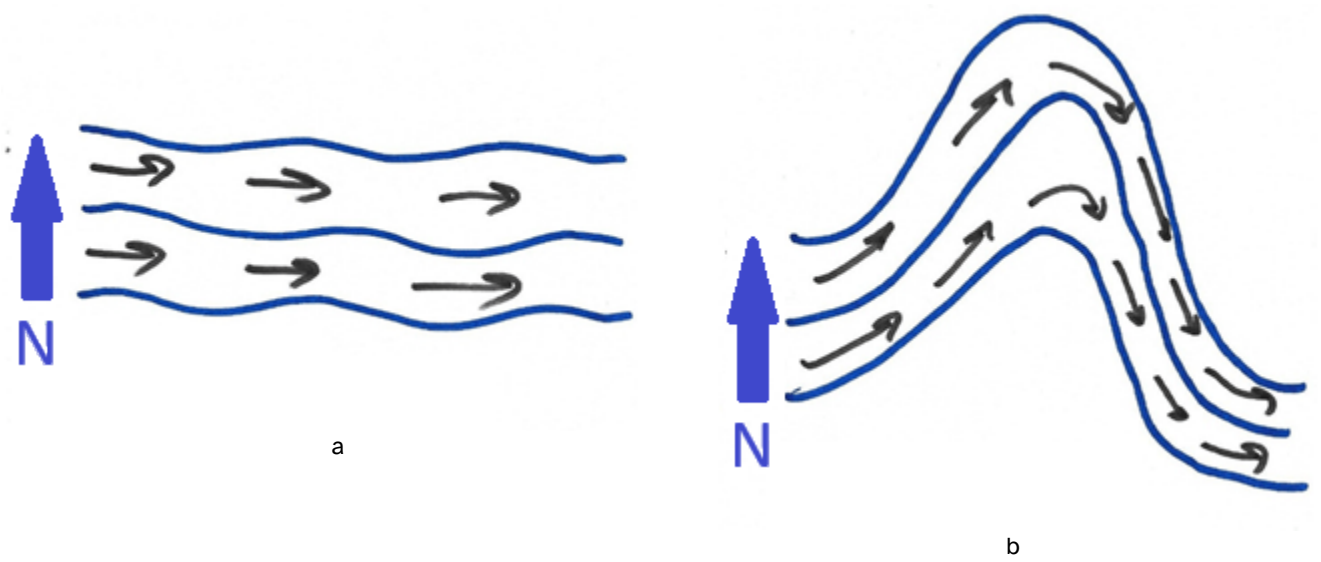


Figure 8.3.2: Zonal and Meridional Flow. (Public Domain; Alicia Mullens). Alternative description of image

20. The general wind flow present in the Jet Stream on Figure 8.3.1 is primarily:
    a. Zonal across the entire United States, with a very weak trough near North/South Dakota and Minnesota
    b. Meridional across the western 2/3 of the United States, and Zonal near the East Coast
    c. Zonal on the West Coast and Meridional across the Eastern 2/3 of the United States

21. Winds from the North/Northwest, which prevail over the eastern half of the ridges and the western half of the troughs, are likely to bring _____ advection.
    a. warm air
    b. cold air

22. Such advection is likely occurring _____.
    a. on the West Coast (California, Oregon, Washington)
    b. across the Midwest (Iowa, Wisconsin, and eastern Nebraska)
    c. along the US East Coast (New York, Massachusetts, and Pennsylvania)

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8.4: Convergence, Divergence, and Jet Streaks

Jet Streaks

The upper-level flow (in the upper troposphere) can have significant consequences for surface weather conditions. A key example of this is when Convergence and Divergence are present in the upper atmosphere. Think of the Jet Stream as a river, and the height lines on a 300 mb map are like the edges of the river. As you're flowing along the river, if the river becomes narrower (the height lines move closer together), the water has to squeeze together as it enters the narrow channel. This is called Convergence, and it occurs when air is squeezed together as shown in Figure 8.4.1. This increases wind speed. Now, suppose the channel widens again (the lines spread out), allowing water to disperse as it exits the narrow channel. This is known as Divergence (Figure 8.4.1). In a future investigation, we will examine the effects of convergence and divergence on surface weather conditions. Indeed, they are a key component of cyclogenesis, the formation and evolution of mid-latitude weather systems and cyclones.

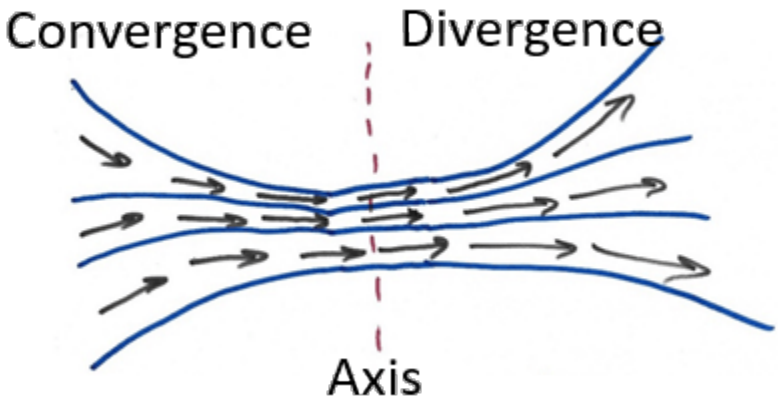


Figure 8.4.1: A diagram of Convergence/Divergence. The solid lines are height lines, similar to other upper-air maps, while the dashed line represents the axis of a trough or ridge. (Public Domain; Alicia Mullens) Alternative description of image.

When air converges, winds move faster; when air diverges, winds slow down. We can identify converging and diverging air by identifying areas of maximum wind speed, or Jet Streaks. Concentric, closed isotach contours (e.g., 70+ knots) represent the high-speed "core" of the streak, indicating the location and orientation of the strongest winds. Figure 8.4.2 shows a simplified example of isotachs and how to identify Jet Streaks.

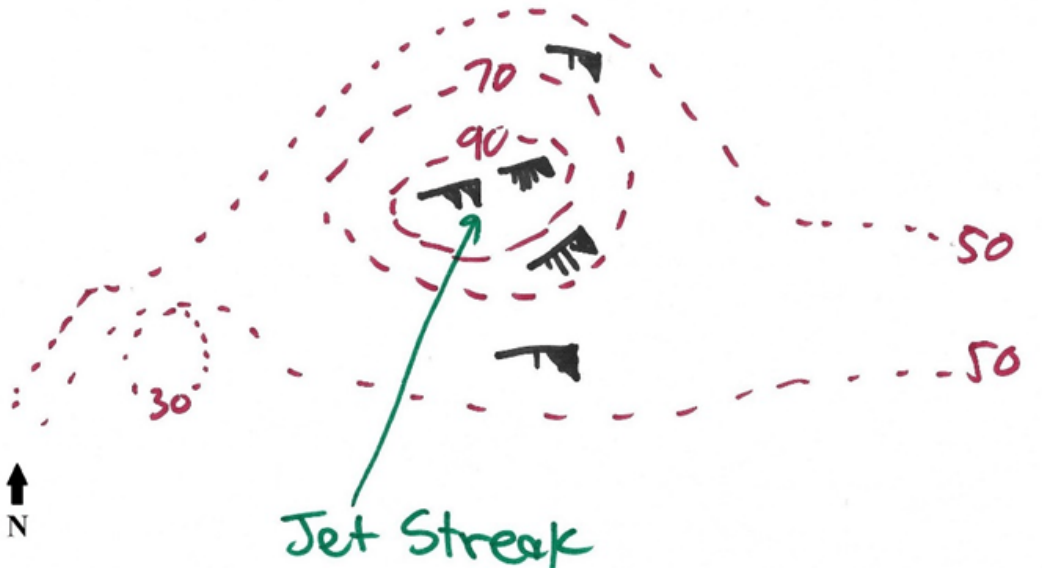


Figure 8.4.2: A Simplified Diagram of Isotachs (dashed lines), and the location of a jet streak... a bullseye where the strongest winds are present. (Public Domain; Alicia Mullens) Alternate description of image.

The last three questions for this investigation are based on Figure 8.4.3, a 300 mb map generated from weather data collected at 1200 UTC on March 13, 2018.

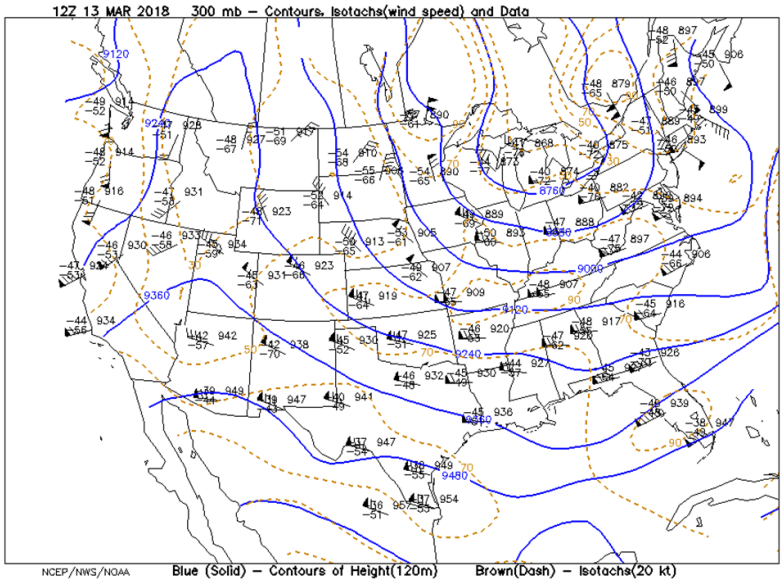


Figure 8.4.3: 300 mb map for the United States at 1200 UTC on March 13, 2018. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of image.

23. The pattern in Figure 8.4.3 is marked by:
    a. Zonal flow across the entire United States
    b. A large trough on the US East Coast
    c. A large ridge on the US West Coast
    d. All of these features except for a
24. For the Eastern Trough, a “bullseye” of higher isotach values indicates
    a. An area of calm winds
    b. A Jet Streak
25. Such areas are present:
    a. Over Northern New York and Southern Canada
    b. Over Indiana and Ohio
    c. Over Kansas and Nebraska

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8.5: Accessible Descriptions

Figure 8.1.1: 500 Millibar upper-air map for 1200 UTC on February 28, 2025

This is a weather map of the United States showing conditions in the middle of the atmosphere, at the 500 millibar pressure level. The valid time of the map is 12Z on February 28, 2025.

- 12Z means 12:00 Coordinated Universal Time, which is 7:00 a.m. Eastern Standard Time, 6:00 a.m. Central, 5:00 a.m. Mountain, and 4:00 a.m. Pacific.
- Heights are labeled in decameters, where one decameter equals 10 meters. For example, a contour labeled 570 means the height is 5,700 meters above sea level.

The map shows three main kinds of information:

1. Height contours (solid lines every 60 meters), which show the altitude where the 500 millibar pressure surface is located. Closer spacing means stronger winds and stronger weather systems.
2. Isotherms (dashed lines every 5 degrees Celsius), which show air temperature at this level of the atmosphere.
3. Wind barbs, drawn at many station points, which show wind direction and speed. Each long barb represents 10 knots, and each short barb represents 5 knots.

Regional Breakdown:

- Western United States: Heights are relatively high, around 570 to 576 decameters, which means the atmosphere is thicker here, often associated with fairer weather. Winds are generally lighter compared to the central U.S. Temperatures aloft are around minus 15 to minus 20 degrees Celsius.
- Central United States: A closed contour appears, centered over the Midwest. This indicates a trough, or low-pressure system aloft. Heights dip to around 552 to 564 decameters. The close spacing of the contours shows stronger winds. Temperatures are cold aloft, with values around minus 25 degrees Celsius. This setup supports unsettled weather, including clouds and possibly storms.
- Eastern United States: Heights range from 540 to 560 decameters, with several isotherms running through the region. Winds are stronger in the Northeast, with wind barbs indicating speeds over 50 knots. Temperatures are between minus 20 and minus 15 degrees Celsius.
- Southern United States: Heights are higher, near 576 to 582 decameters, which means a thicker atmosphere. Temperatures are warmer compared to the north, around minus 10 to minus 15 degrees Celsius. Winds are weaker in this region.

Overall Pattern:

- A trough, or dip in the flow, is centered over the Midwest, bringing stronger winds and colder air.
- Ridges, or bulges of higher heights, are located over the western and southeastern U.S., associated with calmer and warmer weather aloft.
- Wind speeds are strongest in the Midwest and Northeast, where contours are packed tightly together.

Figure 8.1.2: Upper-Air Station Model

This diagram explains the elements of a station model, which is a compact way meteorologists record and display weather data at one location in the atmosphere.

Key parts shown in this example:

1. Air Temperature: Reported as minus 15 degrees Celsius. This is the current temperature of the air.
2. Dew Point Temperature: Reported as minus 24 degrees Celsius. The dew point is the temperature at which the air becomes saturated with water vapor. A lower dew point indicates drier air.
3. Height: Reported as 572, which equals 5,720 meters above sea level. Heights are written in tens of meters to save space.

4. Wind Data:
    - Wind Direction: Shown using a standard meteorological symbol called a wind barb. The orientation of the barb encodes the direction the wind is coming from.
    - Wind Speed: The same symbol also shows speed. Each long line on the barb equals 10 knots, each short line equals 5 knots, and a filled triangle equals 50 knots. In this example, the wind speed is 10 knots.

Figure 8.2.1: 500 millibar upper-air map for 0000 UTC on December 4, 2017

This image is a weather map at the 500 millibar pressure level, valid at 00Z on December 4, 2017. The map uses solid contour lines to show geopotential height in decameters, dashed lines to show temperature in 5-degree Celsius intervals, and symbols called wind barbs to show wind speed and direction.

Two major features are labeled: a trough and a ridge.

Explanation of terms and map features:

1. Geopotential Height: Values are written in decameters, where one decameter equals 10 meters. For example, a label of 570 corresponds to 5,700 meters above sea level. These heights show where the 500 millibar pressure surface is located in the atmosphere.
2. Trough: A trough is an elongated area of lower heights, which usually represents cooler air and unsettled weather conditions aloft. On this map, the trough is indicated over the western United States.
3. Ridge: A ridge is an elongated area of higher heights, which usually represents warmer air and calmer, more stable weather conditions aloft. On this map, the ridge is indicated over the eastern United States.
4. Isotherms: Dashed lines mark temperatures in 5-degree Celsius intervals. They show how cold or warm the air is at the 500 millibar level.
5. Wind Barbs: Symbols plotted at many stations encode wind direction and speed. Each long line represents 10 knots, each short line represents 5 knots, and a filled triangle represents 50 knots.

Overall Pattern on this map:

- A trough is positioned over the western part of the country, indicating cooler and stormier weather there.
- A ridge is positioned over the eastern part of the country, indicating warmer and calmer conditions there.
- The contrast between the trough and ridge shows how the jet stream is bending across the continent, producing active weather in some regions and calmer weather in others.

Figure 8.2.2: 500 millibar upper-air map for 1200 UTC on February 28, 2025

This is a weather map of the United States showing conditions in the middle of the atmosphere, at the 500 millibar pressure level. The valid time of the map is 12Z on February 28, 2025.

- 12Z means 12:00 Coordinated Universal Time, which is 7:00 a.m. Eastern Standard Time, 6:00 a.m. Central, 5:00 a.m. Mountain, and 4:00 a.m. Pacific.
- Heights are labeled in decameters, where one decameter equals 10 meters. For example, a contour labeled 570 means the height is 5,700 meters above sea level.

The map shows three main kinds of information:

1. Height contours (solid lines every 60 meters), which show the altitude where the 500 millibar pressure surface is located. Closer spacing means stronger winds and stronger weather systems.
2. Isotherms (dashed lines every 5 degrees Celsius), which show air temperature at this level of the atmosphere.
3. Wind barbs, drawn at many station points, which show wind direction and speed. Each long barb represents 10 knots, and each short barb represents 5 knots.

Regional Breakdown:

- Western United States: Heights are relatively high, around 570 to 576 decameters, which means the atmosphere is thicker here, often associated with fairer weather. Winds are generally lighter compared to the central U.S. Temperatures aloft are around minus 15 to minus 20 degrees Celsius.
- Central United States: A closed contour appears, centered over the Midwest. This indicates a trough, or low-pressure system aloft. Heights dip to around 552 to 564 decameters. The close spacing of the contours shows stronger winds. Temperatures are cold aloft, with values around minus 25 degrees Celsius. This setup supports unsettled weather, including clouds and possibly storms.
- Eastern United States: Heights range from 540 to 560 decameters, with several isotherms running through the region. Winds are stronger in the Northeast, with wind barbs indicating speeds over 50 knots. Temperatures are between minus 20 and minus 15 degrees Celsius.
- Southern United States: Heights are higher, near 576 to 582 decameters, which means a thicker atmosphere. Temperatures are warmer compared to the north, around minus 10 to minus 15 degrees Celsius. Winds are weaker in this region.

Overall Pattern:

- A trough, or dip in the flow, is centered over the Midwest, bringing stronger winds and colder air.
- Ridges, or bulges of higher heights, are located over the western and southeastern U.S., associated with calmer and warmer weather aloft.
- Wind speeds are strongest in the Midwest and Northeast, where contours are packed tightly together.

Figure 8.3.1: 300 millibar upper air map for 1200 UTC on February 28, 2025

This is a weather map of the United States at the 300 millibar pressure level, valid 12Z on February 28, 2025. The 300 millibar level is located about 9 to 10 kilometers above sea level, where the jet stream is usually found.

The map shows three main types of information:

1. Height Contours:
   - These lines connect locations where the 300 millibar pressure surface is at the same altitude.
   - Heights are expressed in decameters, which are tens of meters. For example, a label of 936 corresponds to 9,360 meters above sea level.
   - When the contours are close together, winds are stronger.
2. Isotachs:
   - These are lines of equal wind speed, drawn in intervals of 20 knots.
   - They outline areas where winds are especially fast.
   - Tight clustering of isotachs marks the position of the jet stream.
3. Wind Barbs:
   - Plotted at many locations to show wind data.
   - The barb indicates wind direction and speed. Each long line equals 10 knots, each short line equals 5 knots, and each filled triangle equals 50 knots.

Overall Pattern on this map:

- A strong jet stream is shown across the central United States, where isotachs are close together and wind speeds exceed 100 knots.
- Heights are lower in the northern part of the map and higher in the southern part, which is typical at this level of the atmosphere.
- This pattern indicates that weather systems below are being influenced by the fast-moving jet stream overhead.

Figure 8.3.2: Zonal vs. Meridional

This diagram compares two different patterns of atmospheric winds in the upper atmosphere. Both panels show airflow represented by arrows, with one side displaying a straighter pattern and the other side displaying a wavier pattern.

First Panel – Zonal Flow:

- The airflow is relatively straight, following a smooth path across the map.
- This is called zonal flow, meaning the jet stream has little waviness.
- Zonal flow is generally linked to more stable and consistent weather patterns.

Second Panel – Meridional Flow:

- The airflow curves into large waves, with alternating peaks and dips.
- This is called meridional flow, meaning the jet stream has significant waviness.
- Meridional flow is generally linked to more variable weather, with stronger contrasts between calm and stormy conditions.

Figure 8.4.1: Convergence/Divergence

This diagram illustrates the concepts of convergence and divergence in atmospheric winds. Arrows are used to represent airflow, and a dashed line labeled “axis” separates the two regions.

Convergence:

- Airflow is shown moving closer together, with streamlines narrowing toward the axis.
- This represents convergence, which means air is crowding together in one location.
- When this happens in the upper atmosphere, the air often has no choice but to sink, which can lead to calm, clear weather.

Divergence:

- Airflow is shown spreading apart, with streamlines moving away from the axis.
- This represents divergence, which means air is thinning out in one location.
- When this happens in the atmosphere, air from lower levels tends to rise, which is often linked with cloud formation and precipitation.

Axis:

- The dashed line marks the dividing boundary between the converging air and the diverging air.

Figure 8.4.2: Jet Streaks

This diagram illustrates a jet streak, which is a localized region of especially fast winds within the jet stream.

Features shown in the diagram:

1. Wind Speed Contours:
   - Dashed lines mark isotachs, or lines of equal wind speed, labeled 30, 50, 70, and 90 knots.
   - These values increase toward the center, showing where the fastest winds are located.
2. Wind Barbs:
   - Symbols are plotted within and around the isotachs to indicate actual measured winds.
   - Each long line represents 10 knots, each short line represents 5 knots, and each filled triangle represents 50 knots.
   - Several of these wind barbs confirm that the highest speeds are concentrated near the center.
3. Jet Streak Label:
   - An arrow highlights the area inside the 90-knot isotach, identifying it as the jet streak.
4. Summary:
   - A jet streak with a maximum wind speed above 90 knots, indicated by a 90 knot isotach with wind barbs higher than 90 knots inside of the jet streak. A wind barb of 75 knots is located between the 70 and 90 knot isotach indicating winds between 70 and 90 knots, while two wind barbs of 60 knots are located between the 50 knot and 70 knot isotach, indicating winds between 50 knots and 70 knots. There is also a 30 knot circle indicating an area of weaker winds.

Figure 8.4.3: 300 millibar upper air map for 1200 UTC on March 13, 2018

This map shows conditions in the upper atmosphere at the 300 millibar pressure level, valid at 12Z on March 13, 2018. The 300 millibar level is typically located around 9 to 10 kilometers above sea level and is where the jet stream is usually found.

Information displayed on the map:

1. Height Contours:
    - Solid lines connect points where the 300 millibar pressure surface is at the same altitude.
    - Heights are written in decameters, which are tens of meters. For example, a value of 930 means 9,300 meters above sea level.
    - Closer spacing of these contours indicates stronger winds and more dynamic weather patterns.
2. Isotachs (Wind Speed Lines):
    - Dashed lines show areas of equal wind speed, drawn at 20-knot intervals.
    - Stronger wind speeds are clustered where these isotachs are tightly grouped.
    - Maximum wind speeds on this map exceed 90 knots in parts of the flow, marking the location of a jet streak within the jet stream.
3. Wind Barbs:
    - Symbols plotted across the map show both wind direction and wind speed.
    - Each long line equals 10 knots, each short line equals 5 knots, and each filled triangle equals 50 knots.
    - Many plotted barbs confirm wind speeds over 100 knots in certain regions.

Overall pattern on this map:

- A strong jet stream arcs across the northern United States, with concentrated regions of faster winds above 90 knots.
- Lower heights appear in the northern portion of the map, while higher heights appear farther south, consistent with the usual slope of the 300 millibar surface.
- The presence of a jet streak suggests areas of enhanced upper-level convergence and divergence, which can influence rising or sinking motion and surface weather systems below.

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9: EL NIÑO AND LA NIÑA

Introduction

The Atacama Desert, located along the Pacific coast of Chile in South America, is known as one of the driest non-polar deserts in the world (Figure 9.1). The cool Humboldt ocean current sweeps northward along the coast, resulting in less than 15 millimeters (0.6 inches) of rainfall per year in the Atacama Desert. Southerly winds along the coast also promote the upwelling of cold, nutrient-rich waters, which attract large populations of fish, such as anchovies. Thus, fishing is a major source of food and income for the Peruvians who live just north of this region. However, every few years, something changes. Rainfall increases in the desert, the fish vanish, and the arid desert landscape begins to bloom with a vibrant display of flowers (Figure 9.2). Because this always happens around Christmas in those years, the residents began calling it "El Niño", which in Spanish means "the boy", but in this context, refers to the Christ child.



Figure 9.1: The arid landscape of the Atacama Desert. (CC BY-SA 2.0; Valerio Pillar via Wikimedia Commons).



Figure 9.2: The Atacama Desert after heavy rains. (CC BY-SA 2.0; Javier Rubilar via Wikimedia Commons).

Whenever it occurs, weather extremes such as droughts, floods, and heatwaves affect people across different continents. While

South American countries like Chile and Peru face flooding, Australia and East Asia suffer from droughts and Heatwaves. In Africa, eastern countries like Kenya suffer from increased rainfall and deadly diseases, while southern countries, such as South Africa, face drought. Even Europe is not spared, with northern countries facing colder-than-average winters and southern countries experiencing heavier-than-average rainfall and flooding. Here in the United States, El Niño typically brings warmer, drier winters to the northern U.S. and wetter conditions to the southern U.S., including increased rainfall and flooding in Central and Southern California. Thus, it is commonly discussed in the news and during weather reports. So we've all heard about it from somewhere, but how many of us know what El Niño really is? Answer the following question before we investigate this global-scale phenomenon that affects the weather worldwide.

1. What do you think El Niño is?

Learning Objectives

By the end of this investigation, you should be able to:

- Describe the El Niño Southern Oscillation
- Identify the 3 phases of the Walker circulation
- Distinguish between the Pacific surface conditions during El Niño, La Niña, and Neutral phases.

Navigational Note

Investigation 9 has 24 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

9.1: The Walker Circulation
9.2: El Niño and La Niña Phases
9.3: Accessible Descriptions

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9.1: The Walker Circulation

Neutral Conditions

El Niño is a phase in the Walker Circulation. La Niña is another phase in the same circulation, and the state of the circulation between El Niño and La Niña is referred to as the Neutral phase. To understand El Niño and La Niña, we must first understand the Walker Circulation. The Walker Circulation occurs in the equatorial eastern Pacific and begins with the trade winds, which commonly blow from East to West. As the winds blow along the ocean surface, they push warm surface waters to the west as well. As a result, warm surface waters accumulate in the Western Pacific, near Asia, Indonesia, and Australia, while cooler surface waters upwell (rise from below) in the Eastern Pacific, along the coast of Peru. Figure 9.1.1 shows the Walker Circulation during such neutral conditions.

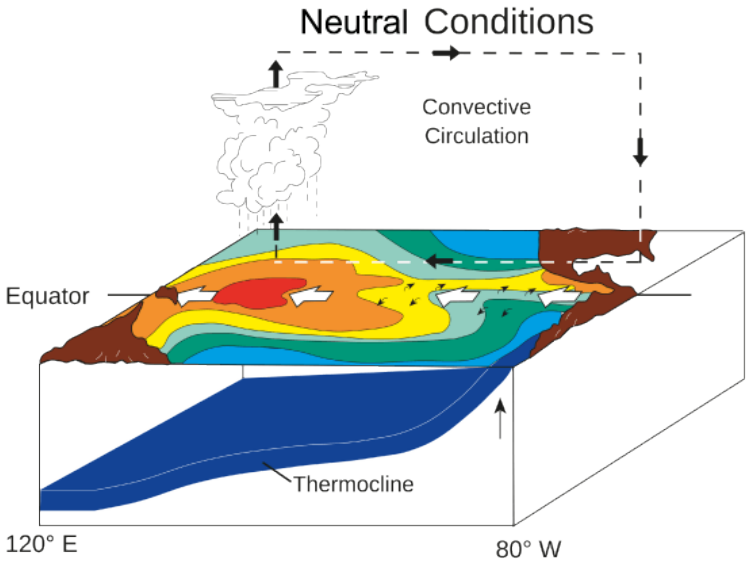


Figure 9.1.1: The Walker Circulation during Neutral Conditions. (Public Domain; Schematic Diagrams via NOAA/PMEL). Alternative description of the image.

Using this information, let's understand the atmospheric dynamics of the Neutral Phase of the Walker Circulation.

2. Warmer sea surface temperatures in the western Pacific create warm, rising air, and thus _____ pressure conditions near east Asia.
   a. high
   b. low

3. Cooler sea-surface temperatures in the eastern Pacific produce cooler, sinking air, and thus _____ pressure conditions near South America.
   a. high
   b. low

Let's confirm our understanding using Figure 9.1.2, which shows typical surface air pressure and winds, centered over the equatorial Pacific.

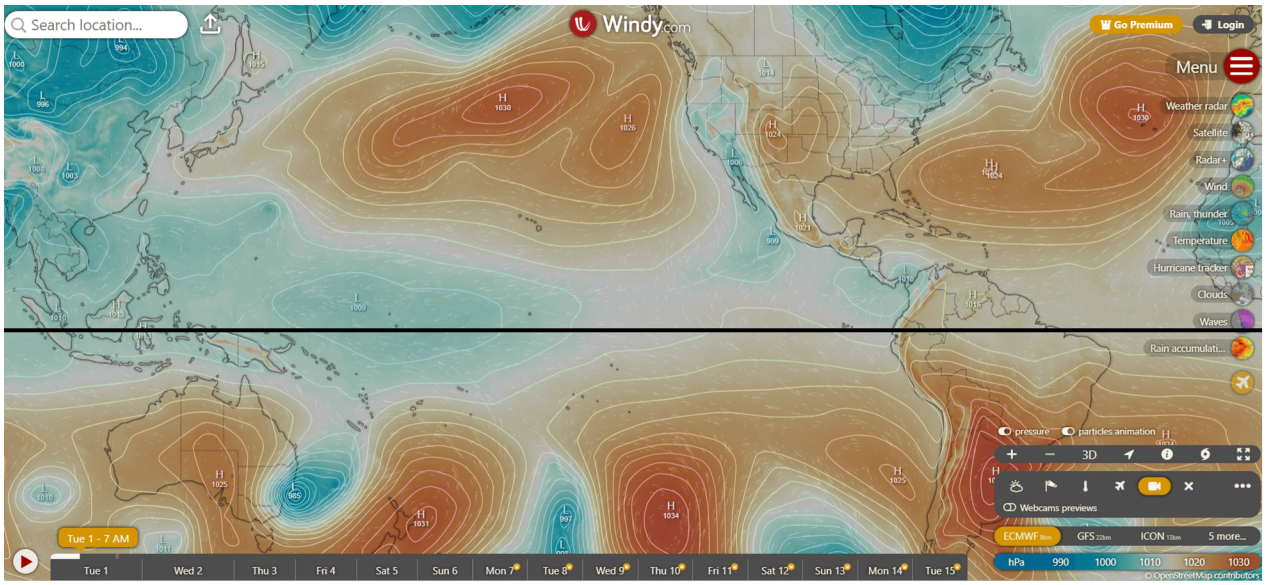


Figure 9.1.2: Surface Air Pressure and Wind centered over the Equator (black line). (CC BY 4.0; Pressure Contours via Windy.com) Alternative description of image.

While it's very tempting to focus on the longitude coordinates and believe that the left side of Figure 9.1.2 is the "eastern" Pacific, while the right side is the "western" Pacific. This is not true. The reason the coordinates switch from west to east while traveling west on the map is that you cross the International Date Line and enter the Eastern Hemisphere. The west remains on the left, and the east remains on the right. Thus, the eastern Pacific refers to the Pacific Ocean along the coasts of North and South America, whereas the western Pacific refers to the Pacific Ocean along the coasts of East Asia and Australia.

4. In general, there is _____, which is consistent with the Walker circulation during a Neutral Phase. (Hint: Blue indicates low pressure and red indicates high pressure).
   a. lower pressure in the eastern equatorial Pacific and higher pressure in the western equatorial Pacific
   b. higher pressure in the eastern equatorial Pacific and lower pressure in the western equatorial Pacific

5. This inequality in pressure between the eastern and western Pacific creates a pressure gradient force, which pushes additional air:
   a. From west to east
   b. From east to west

The surface air rises to higher altitudes over Indonesia, moves back toward Central and South America, and descends to the surface due to the region's high pressure. This circulation of air in the equatorial Pacific has significant implications for the local climate.

6. The western Pacific has warm, rising air and more moisture, which allows for the formation of:
   a. Stormy weather
   b. Calm clear weather

7. On the other hand, the eastern Pacific has cooler sinking air and less moisture, which makes it:
   a. Stormier
   b. Drier

Following the 1982-1983 El Niño event, which led to numerous extreme weather events worldwide, a series of buoys jointly operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) and the Japanese Meteorological Agency (JMA) were deployed along the Equatorial Pacific. This array is called the TAO/Triton Array, and the locations of the buoys are shown in Figure 9.1.3.

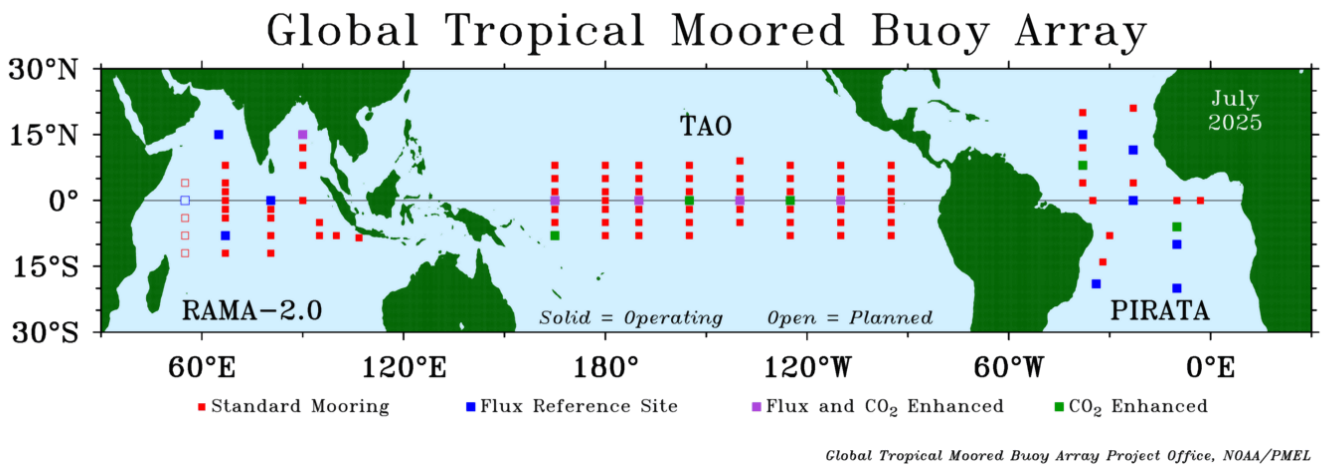


Figure 9.1.3: Positions of the Global Tropical Moored (TAO/Triton) Buoy Array across the Equatorial Pacific (Public Domain; Global Tropical Moored Buoy Array via NOAA/PMEL). Alternative description of the image.

Sensors on the buoys measure various oceanographic and meteorological parameters, such as sea surface temperature (SST), wind speed and direction, air temperature, and humidity. The data is then transmitted in near-real time via NOAA's polar-orbiting satellites to NOAA's Pacific Marine Environmental Laboratory (PMEL). The data is then plotted on maps, such as Figure 9.1.4 , which shows 5-day SST and wind speed means as well as anomalies for the period ending July 2, 2018. These maps enable oceanographers and meteorologists to closely examine the behavior of the Walker Circulation.

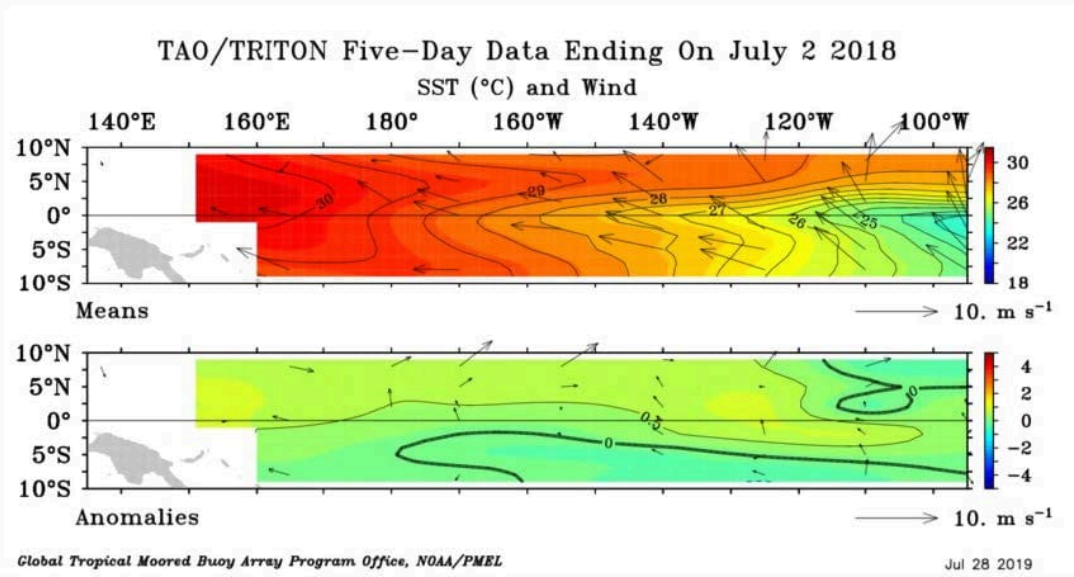


Figure 9.1.4: TAO/Triton measured Sea Surface Temperature (SST) and wind speed mean values (top) and anomalies (bottom) for the 5-day period ending July 2, 2018. (Public Domain; Monthly Mean SST and Winds via NOAA/PMEL). Alternative description of the image.

There are two panels on Figure 9.1.4. The top panel shows 5-day mean observed sea surface temperatures and wind vectors. Here's how to read these:

- Temperature: Blues are cold, greens are mild, yellows are warm, reds are hot.
- Wind Vectors: The arrow points in the direction the wind is blowing towards, and the length of the arrow indicates how fast the wind is moving.

8. According to Figure 9.1.4, the hottest sea surface temperatures (top panel) are located:
   a. In the western Pacific
   b. In the central Pacific
   c. In the eastern Pacific

9. The coldest sea surface temperatures are located:

a. In the western Pacific
b. In the central Pacific
c. In the eastern Pacific

10. Except for the eastern third of the map, the winds in the top panel were generally blowing:
    a. From west to east
    b. From east to west

The bottom panel in Figure 9.1.4 indicates anomalies in SST and winds, which are differences from the average. For example, if the class average on a test was 80% and someone earned 85%, that would be 5% above average, hence a 5% positive anomaly. Anomalies are shaded in the same manner as the mean SST. Colder waters are represented by dark blue and purple; near-average temperatures are shaded in green; hot anomalies are depicted in orange and red. There are also isolines (lines of constant value) to help detect the pattern of anomalies.

11. The anomalies in Figure 9.1.4, indicate that the sea surface temperatures were:
    a. Much hotter (more than +3°C) than normal
    b. Much colder (less than -3°C) than normal
    c. Almost completely normal

12. Trade wind anomalies, indicated by the wind arrows, are:
    a. Very strong and directed eastward
    b. Light and varying in direction

These conditions represent the “neutral condition" of the Walker circulation.

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9.2: El Niño and La Niña Phases

El Niño

However, every few years, key components of the Walker Circulation shift, thereby triggering an El Niño event. Figure 9.2.1 shows the Walker Circulation during the El Niño phase.

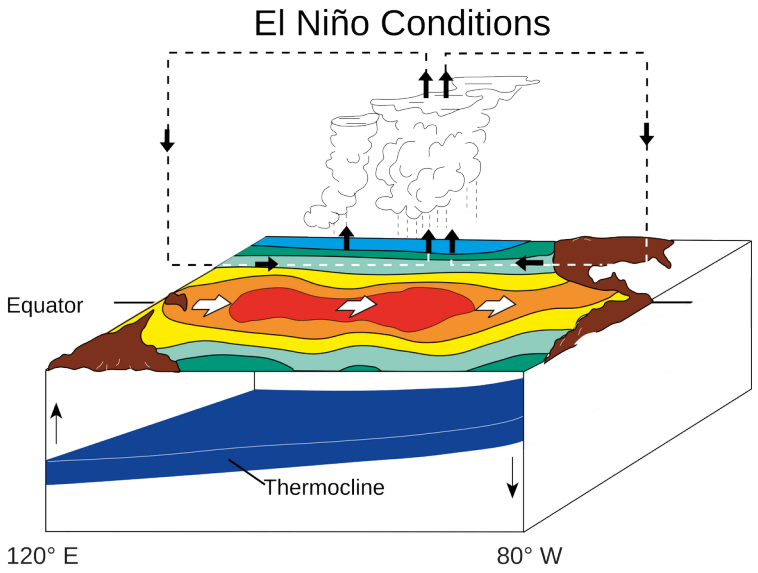


Figure 9.2.1: The Walker Circulation in an El Niño phase. (Public Domain; Schematic Diagrams via NOAA/PMEL) Alternative description of image.

13. The trade winds, which usually carry warm water to the western Pacific, either slow down or reverse completely, allowing for:
    a. Warm water to collect in the eastern Pacific
    b. More cold water to collect in the eastern Pacific

14. In turn, this allows the collection of warmer, rising air, thereby allowing a _____ pressure system to build over the eastern Pacific.
    a. low
    b. high

15. On the other hand, because the trade winds weaken, there is _____ warm water present in the western Pacific.
    a. more
    b. less

16. Therefore, there is less warm air over the western Pacific, resulting in _____ pressure and _____ weather.
    a. lower; wetter
    b. higher; wetter
    c. higher; drier
    d. lower; drier

17. Thus, we can conclude that the Walker Circulation _____ during an El Niño.
    a. strengthens
    b. reverses
    c. does not change

La Niña

La Niña is the opposite of El Niño. During this phase of the Walker Circulation, rather than weakening or reversing from the Neutral Phase, the trade winds intensify. Figure 9.2.2 shows Walker Circulation during the La Niña Phase.

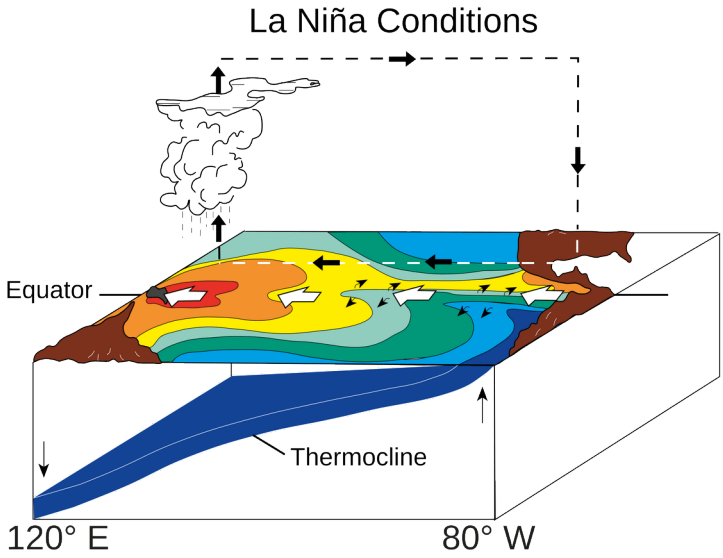


Figure 9.2.2: The Walker Circulation during La Niña. (Public Domain; Schematic Diagrams via NOAA/PMEL) Alternative description of image.

18. This intensification of the east-to-west trade winds results in _____ warm water collecting over the western Pacific, resulting in _____ warm, rising air.
    a. more; less
    b. more; more
    c. less; more
    d. less; less

19. On the other hand, the eastern Pacific experiences _____ sea surface temperatures and _____ air.
    a. even cooler; cooler, sinking
    b. warmer; warmer, rising

Let us assess whether we can identify these changing sea-surface temperature patterns and wind directions using the TAO/Triton buoy array in the equatorial Pacific. Figure 9.2.3 shows the TAO/Triton measured mean sea surface temperature, winds, and anomalies for December 2015.

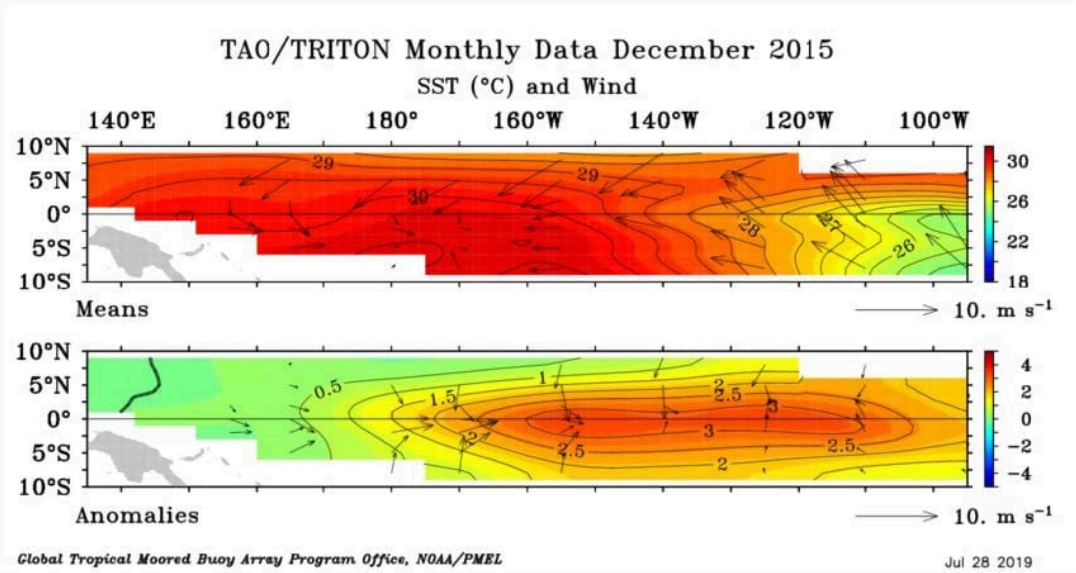


Figure 9.2.3: Sea-surface temperatures and anomalies for December 2015. (Public Domain; Monthly mean SST and Winds via NOAA/PMEL)
Alternative description of image.

20. According to the lower panel in Figure 9.2.3, during December 2015, the most significant temperature anomalies were:
    a. Very cold (colder than -2°C below normal)
    b. Closer to average
    c. Very hot (hotter than +2°C above normal)

21. The largest anomalies were located:
    a. In the western Pacific
    b. In the central and eastern Pacific

22. Trade wind anomalies, especially in the middle and western half of the map, were:
    a. Mainly west-to-east and towards the Equator
    b. Mainly east-to-west and away from the Equator
    c. Light and varying in direction

23. These conditions indicate that the Walker Circulation was in a(n) _____ phase.
    a. La Niña
    b. El Niño
    c. Neutral

Figure 9.2.4 shows data from the TAO/Triton array during December 2010. You'll notice that the sea-surface temperatures and wind speed anomalies are different from Figure 9.2.3. Sea-surface temperatures are much cooler in the eastern Pacific, and the trade winds are blowing stronger from east to west.

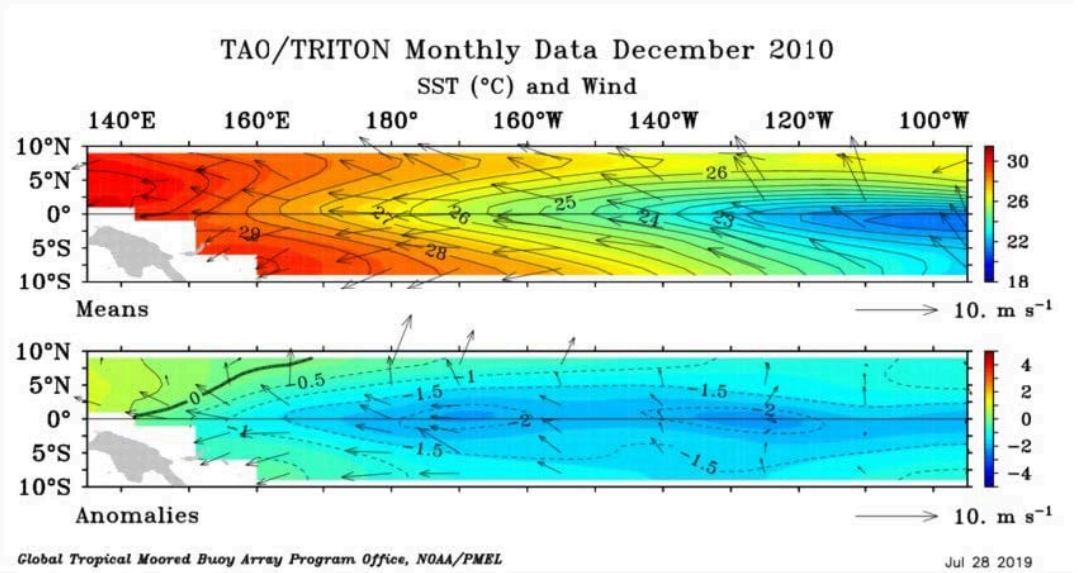


Figure 9.2.4: TAO/Triton sea-surface temperatures and wind anomalies for December 2010. (Public Domain; Monthly mean SST and Winds via NOAA/PMEL) Alternative description of image.

24. Considering mean temperatures, trade winds and anomalies in Figure 9.2.4, we can confidently say that during December 2010, the Walker Circulation was in a(n) _____ phase.
    a. Neutral
    b. El Niño
    c. La Niña

Additional Reading

In this investigation, we didn't cover the impacts of El Niño and La Niña because the focus was on identifying the signatures and detecting their presence. If you want to learn more about the effects of El Niño and La Niña on our weather, check out the following links.

- How El Niño and La Niña Affect California Weather - El Niño often brings wetter, cooler conditions and increased rainfall to Central and Southern California. At the same time, La Niña typically leads to drier, warmer conditions, increasing drought and wildfire risks in the south.
- El Niño and La Niña Affect Weather in the U.S. and Worldwide: El Niño suppresses Atlantic hurricane activity by increasing vertical wind shear. La Niña, by contrast, reduces vertical wind shear, leading to stronger and more frequent Atlantic hurricanes.

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9.3: Accessible Descriptions

Figure 9.1.1 The Walker Circulation during Neutral Conditions

This figure illustrates normal atmospheric and oceanic circulation patterns across the tropical Pacific Ocean under non-El Niño conditions.

Layout:

- This is a 3D cross-section of the equatorial Pacific Ocean, oriented with:
  - Australia and Southeast Asia (west) on the left side (labeled ~120°E longitude)
  - South America (east) on the right side (labeled ~80°W longitude)
  - The Equator runs horizontally across the center.
- Ocean and Atmosphere Features:
  - Warm ocean surface waters are piled up in the western Pacific due to easterly trade winds.
  - Cooler ocean water dominates the eastern Pacific, near the coast of South America.
  - A sloping thermocline—the boundary between warm surface water and cold deep water—is shown dipping deeper in the west and rising toward the surface in the east.
  - Upwelling is occurring along the South American coast, where cold water is rising to the surface.
  - White arrows near the ocean surface indicate the direction of surface winds (easterlies)—from east to west.
  - Convective clouds and rising air are located over the warm waters of the western Pacific, indicating strong convection and thunderstorm activity.
  - Dashed arrows indicate the atmospheric return flow aloft, moving from west to east and completing the Walker convective circulation loop.

Annotations:

- Labeled “Neutral Conditions” at the top, this configuration shows typical Walker Cell circulation:
  - Surface winds blow from east to west (trade winds).
  - Warm water and rising air in the western Pacific support deep convection and rainfall.
  - Cooler water and sinking air in the eastern Pacific result in dry conditions.

Figure 9.1.2 Surface Air Pressure and Wind over the Equator.

This is a global weather visualization map from Windy.com, showing atmospheric surface pressure patterns across much of Earth, including North and South America, the Pacific Ocean, Australia, and parts of Asia. The image is divided into a Northern Hemisphere (top) and Southern Hemisphere (bottom) view.

Key Features:

- Color Shading and Isobars:
  - Areas of high pressure (H) are labeled with values (e.g., 1030 hPa, 1026 hPa).
  - Areas of low pressure (L) are labeled with values (e.g., 999 hPa, 985 hPa).
  - White contour lines (isobars) connect areas of equal pressure, illustrating the shape and gradient of pressure systems.
- Notable Pressure Systems:
  - Strong high-pressure systems exist:
  - Over the eastern Pacific Ocean (~1030 hPa),
  - North of Hawaii and east of Japan,
  - Over Australia and parts of South America.
- Low-pressure systems appear:
  - Off the west coast of the U.S. (~999 hPa),
  - Near the Philippines, the South Pacific, and eastern South America.

- Wind Flow Visualization:
  - Particle animation (visible as fine streaks) illustrates the direction of surface winds, which generally flow:
  - Clockwise around high-pressure systems in the Southern Hemisphere,
  - Counterclockwise around lows in the Northern Hemisphere.
- Wind patterns are tightly packed near strong pressure gradients, such as around tropical lows.

Figure 9.1.3 Positions of TAO/Triton Array Buoys

This map displays the Global Tropical Moored Buoy Array, which consists of oceanographic buoys distributed across the tropical Pacific, Indian, and Atlantic Oceans as of July 2025. These buoys cover vast regions across the respective oceans and are part of three regional networks used for long-term climate and ocean monitoring.

- RAMA-2.0 (Indian Ocean, left side of map)
- TAO (Pacific Ocean, center of map)
- PIRATA (Atlantic Ocean, right side of map)

Map Layout:

- The map spans latitudes from 30°N to 30°S and longitudes from 60°E to 0°E, wrapping around the globe from the Indian Ocean to the Atlantic.
- Landmasses include Africa, South America, Southeast Asia, and Australia.
- Buoy positions are marked across the ocean basins with various colored squares, each color representing a different type of mooring instrumentation.

Buoy Types and Symbols:

Each square represents a buoy site.

- Solid squares = currently operating
- Open squares = planned deployment
- Colored coding represents standard mooring (red), flux reference sites (blue), flux and CO_2 enhanced (purple), and CO_2 enhanced (green) buoy locations.

Figure 9.1.4 Sea Surface Temperatures for July 2018

This figure contains two horizontal panels representing TAO/TRITON ocean monitoring data for the equatorial Pacific Ocean, covering the five-day period ending July 2, 2018. The panels display sea surface temperature (SST) and surface wind vectors, with the lower panel also showing anomalies relative to climatological averages.

Top Panel – “Means” (Sea Surface Temperature and Wind):

- The top panel shows SST in degrees Celsius (°C) across a horizontal section of the equatorial Pacific, from 140°E to 100°W longitude, and 10°S to 10°N latitude.
- A gradient ranges from:
  - 30°C in the western Pacific near 140°E,
  - 20–26°C as it moves eastward toward South America.
  - Contour lines labeled (e.g., 30, 29, 28...) indicate lines of equal SST (isotherms).
  - Wind vectors (arrows) represent average surface winds, generally showing easterly trade winds blowing from east to west across the central Pacific.

Bottom Panel – “Anomalies” (SST and Wind Deviations from Normal):

- This panel shows SST anomalies (differences from long-term averages) for the same region and time period.
- The color gradient ranges from:

    - +2 to +4°C for positive anomalies (warmer than normal),
    - -2 to -4°C for negative anomalies (cooler than normal).
- Overall, the anomalies are mostly near zero, indicating neutral ENSO conditions (neither El Niño nor La Niña).
- Contour lines labeled with numbers (e.g., 0, +1, -1) delineate SST anomaly values.
- Wind anomaly vectors (arrows) show small deviations in direction and magnitude, indicating slight variations from typical trade wind patterns.

Figure 9.2.1 The Walker Circulation during El Niño

This is a 3D schematic cross-section of the equatorial Pacific Ocean, illustrating El Niño conditions within the El Niño–Southern Oscillation (ENSO) cycle.

Layout:

- The diagram spans from 120°E (left) to 80°W (right) along the equator, depicting ocean and atmospheric patterns across the tropical Pacific.
- The left side represents the western Pacific (near Indonesia and Australia).
- The right side represents the eastern Pacific (near South America).

Key Features:

Ocean Structure:

- Warm surface water stretches uniformly across the Pacific, from west to east.
- Cooler water is confined to deeper layers and pushed downward throughout the entire basin.
- The thermocline, the boundary between warm surface water and cooler deep water, is shown as flat and deep, unlike in normal conditions when it is tilted.
- Upwelling of cold water is suppressed near South America.

Surface Winds:

- The usual trade winds (from east to west) are weakened or reversed.
- Black arrows along the ocean surface indicate weakened or reversed wind direction, blowing from west to east across the equator.

Atmosphere:

- Rising air and deep convection (clouds and upward arrows) are now centered in the central and eastern Pacific, rather than over the western Pacific.
- Dashed white arrows show upper-level atmospheric return flow, completing a disrupted Walker circulation loop.
- Rainfall and thunderstorm activity are displaced eastward, toward the central Pacific.

Figure 9.2.2 The Walker Circulation during La Niña.

This is a 3D schematic cross-section of the equatorial Pacific Ocean, illustrating La Niña conditions, a component of the El Niño–Southern Oscillation (ENSO) climate pattern.

Layout:

- The cross-section extends from 120°E (left) to 80°W (right) along the equator.
- Western Pacific (left side) represents the region near Australia and Southeast Asia.
- Eastern Pacific (right side) represents the region near South America.

Ocean Features:

- Warm surface waters are pushed farther west than normal, accumulating in the western Pacific.
- The eastern Pacific is dominated by cooler waters.
- The thermocline, the boundary between warm and cold water, is steeper than normal, being much shallower near South America and deeper in the western Pacific.
- Strong upwelling of cold, nutrient-rich water is shown off the coast of South America.

Atmospheric Circulation:

- Surface trade winds (arrows along the surface) are stronger than normal, blowing east to west across the Pacific.
- These winds drive warm surface water westward and enhance upwelling in the east.
- Rising air and deep convection (indicated by black upward arrows and clouds) are concentrated over the western Pacific, where the water is warmest.
- A dashed white arrow above the surface indicates upper-level atmospheric return flow moving west to east, completing the Walker circulation.
- Sinking air and dry conditions are shown over the eastern Pacific, near South America.

Figure 9.2.3 Sea Surface Temperatures and Anomalies for December 2015

This figure shows sea surface temperature (SST) and wind data across the equatorial Pacific Ocean during December 2015, based on measurements from the TAO/TRITON buoy array. The data is presented in two horizontal panels:

Top Panel – "Means" (Sea Surface Temperature and Wind):

- This panel shows average SSTs (in °C) and surface winds between 10°N and 10°S latitude, from 140°E to 100°W longitude.
- The SSTs are displayed using a color gradient from:
  - 30°C in the western and central Pacific,
  - 26–28°C in the east,
  - 18–22°C near South America.
  - Isotherms (contour lines) mark temperatures at 1°C intervals (e.g., 30°C, 29°C, 28°C).
  - Wind vectors (arrows) show the direction and magnitude of surface winds:
- Arrows mostly point from west to east across the central and eastern Pacific,
- Indicating weakened or reversed trade winds, which are typical of El Niño events.

Bottom Panel – "Anomalies" (SST and Wind):

- This panel shows deviations from the average (climatological) conditions.
- Color shading indicates SST anomalies (in °C), with:
  - Positive anomalies (+2 to +3.5°C) in the central and eastern equatorial Pacific.
  - The strongest warming occurs between 160°W and 100°W, peaking at about +3.5°C.
  - Areas with cooler-than-normal SSTs (very limited in this case).
- Contour lines trace SST anomaly values (e.g., 1.5, 2.0, 3.0).
- Wind anomaly vectors display eastward-pointing arrows, indicating weakened or reversed easterly winds, consistent with El Niño.

Figure 9.2.4 Sea Surface Observations and Anomalies for December 2010

This figure presents monthly sea surface temperature (SST) and wind data from the TAO/TRITON buoy array for the equatorial Pacific Ocean during December 2010. It includes two horizontal panels:

Top Panel – "Means" (Sea Surface Temperature and Wind):

- The panel displays average SSTs and wind vectors between 10°N and 10°S latitude, from 140°E to 100°W longitude.

- A gradient represents SSTs from:
  - 30°C in the western Pacific,
  - 18–24°C as it moves eastward toward South America.
  - Contour lines (isotherms) labeled at 1°C intervals (e.g., 29, 28, 26°C) trace regions of equal temperature.
  - Arrows show surface wind direction and speed:
- Arrows point strongly from east to west, indicating intensified easterly trade winds typical of La Niña.

Bottom Panel – “Anomalies” (SST and Wind):

- This panel shows anomalies (differences from the long-term average).
- SST anomalies from -1°C to -3°C dominate the central and eastern Pacific, showing cooler-than-average water.
- Contour lines labeled -1.5, -2.0, etc., trace the extent of cold anomalies.
- Wind anomaly vectors show stronger-than-normal easterlies, reinforcing the cooling effect.

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10: MID-LATITUDE CYCLONES

Introduction

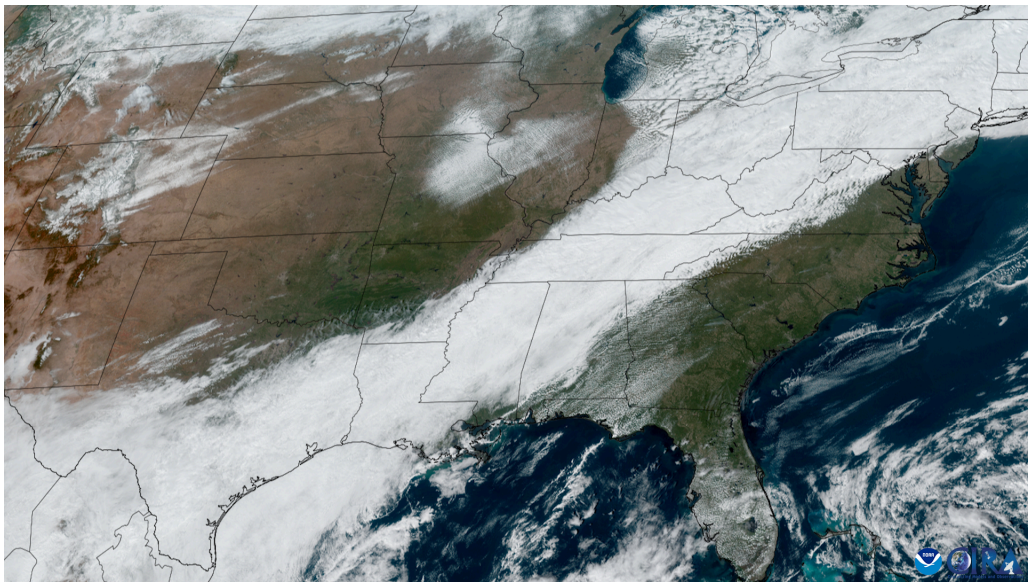


Figure 10.1: Satellite view of a mid-latitude cyclone in the central and eastern United States. This weather system is similar to the one responsible for the sudden change in weather described in the introduction to this investigation. (Public Domain; CSU/CIRA & NOAA via Wikimedia Commons)

This investigation starts off with a story from Alicia Mullens, one of the authors of this lab manual:

> "It was 12:30 am on a warm, humid Saturday night in central Texas. A major blizzard had been tearing through western Texas and was forecast to reach our region by dawn the next morning. Being the weather enthusiast I am, I wanted to go outside and watch the thunderstorms that were on the leading edge of the blizzard. So after my wife went to bed, I went out into the back yard and sat down with a couple of drinks, waiting for the storm to arrive. When I went outside, it was warm, windy, and humid... it felt more like a summer night than a late-December evening. And it remained that way for a long time... 1 am... still warm... 2 am... still warm... 2:30 am... still warm... and then suddenly, an ICY wind blew in from the North... within minutes I was running for my jacket. The next weather observation showed a 25°F temperature drop in 20 minutes!!! It was snowing the next morning!
>
> I had just experienced something that I've taught about, and read in books, and heard others talk about... but had never experienced myself... I had experienced a frontal passage!"

Indeed, many weather systems, such as thunderstorms and mid-latitude cyclones, can cause sudden, almost violent changes in weather conditions (Figure 10.1). We'll cover thunderstorms in more depth in Investigation 11, but this investigation focuses on the presence, movement, and conditions of mid-latitude cyclones.

Learning Objectives

- Identify weather conditions before, during, and after a frontal passage.
- Determine, using a set of weather observations, when a cold front passed a region.
- Observe the movement of a well-defined mid-latitude cyclone.

Navigational Note

Investigation 10 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

10.1: Fronts
10.2: Air Pressure Changes in Frontal Passages
10.3: Tracking Mid-Latitude Cyclones
10.4: Accessible Descriptions

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10.1: Fronts

Frontal Boundaries

A front is a boundary between two air masses, which are large bodies of air with similar temperatures. These air masses originate either near the poles (cold air masses) or near the tropics (warm air masses), and interact with each other. The United States, located in the mid-latitudes, is an excellent battleground for different air masses because it lies approximately halfway between the equator and the poles (hence it's located in the mid-latitudes). Along a warm front, cold air is retreating, making room for warm, often moist air to take its place. Figure 10.1.1 is a 3-dimensional cross-section of a warm front, including the location of both warm and cold air along it.

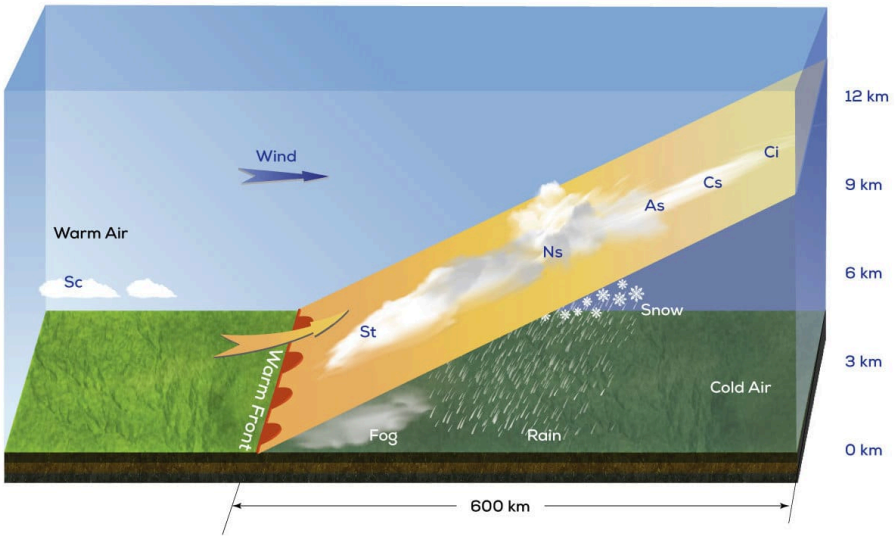


Figure 10.1.1: A warm front is moving with the wind. Along the front, warm air gently overrides cold air, producing fog, stratus, and nimbostratus clouds. (CC-BY-SA 4.0; Kh1604 via Wikimedia Commons). Alternative description of the image.

Weather conditions ahead of a warm front are typically cold and unsettled, while those behind it are warm and clear as the warm air mass moves over. Because warm air only rises gently, at a small angle over the cold air mass, clouds that form are typically shallow, and precipitation, if any, is typically light. Because warm air is generally lighter, it travels more slowly than cold air, and warm fronts generally travel more slowly than cold fronts.

On the other hand, cold fronts are more abrupt. Along a cold front, a cold, dense air mass rapidly pushes warm air away, leading to more abrupt cooling. Furthermore, as shown in the cross-section of a cold front in Figure 10.1.2, cold air forces warm air up at a large angle (almost straight up), generating tall cumulus and cumulonimbus clouds, often leading to severe weather (such as the severe weather the author of this investigation was hoping to experience in the introduction).

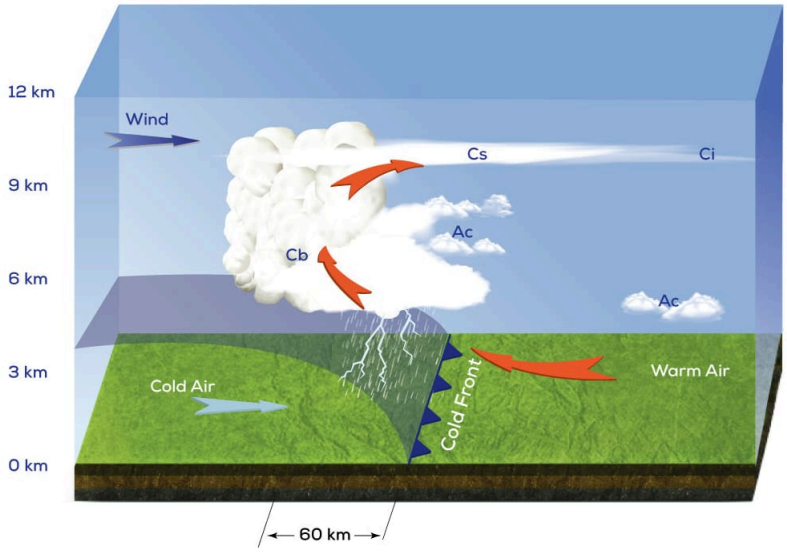


Figure 10.1.2: A cold front is moving with the wind. Along the front, warm air is forced up at a high angle over cold air, producing tall cumulonimbus clouds and stormy weather. (CC-BY-SA 4.0; Kh1604 via Wikimedia Commons). Alternative description of the image.

Weather conditions ahead of a cold front are typically warm, with increasing cloudiness. Rapidly cooling and stormy conditions immediately follow the cold front, and cool, generally clearing conditions prevail after the front passes. Cold fronts produce some of the stormiest and most unsettled weather in the United States. Now we are going to delve deeper into the conditions before, during, and after a cold frontal passage. Figure 10.1.3 is a Meteogram showing 24-hour weather conditions taken at Kerrville-Schriener Municipal Airport for the 24 hours beginning at 0000 UTC on December 27th (6 pm local time on 12/26) and ending at 0000 UTC on December 28th (6 pm local time on 12/27). The numbers on the x-axis of the bottom panel represent time in UTC.

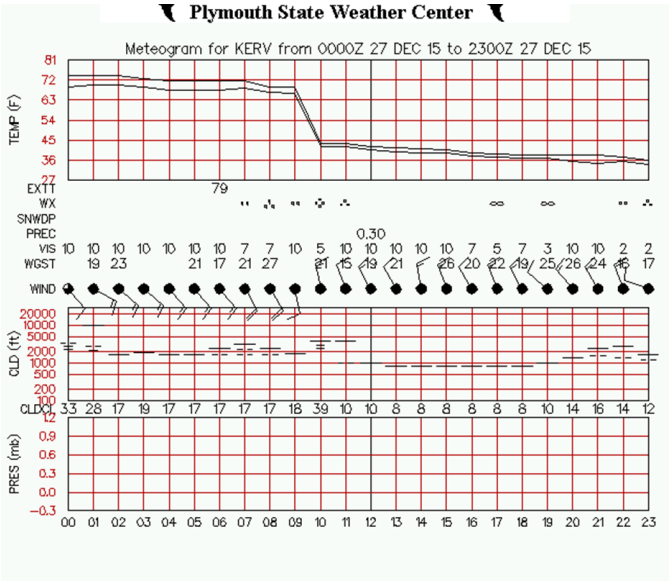


Figure 10.1.3: A meteogram showing temperature and dew point (first panel), precipitation, visibility, and wind barbs (second panel), cloud height (third panel), and air pressure tendency (fourth panel) for Kerrville-Schriener Municipal Airport for 24 hours beginning at 6 pm on 12/26/2015 and ending at 6 pm on 12/27/2015. (CC-BY-NC 4.0; Meteograms via Plymouth State). Alternative description of the image.

For this investigation, we will focus on air temperature (the warmer line in the first panel), dew point temperature (the cooler line in the first panel), and wind direction/speed (in the second panel).

1. Air temperature (the warmer of the two black lines on the first panel) was approximately _____ at the beginning of the period.
   a. 73°F
   b. 60°F

   c. 54°F
   d. 35°F
2. The biggest drop in both air temperature (the top black line) and dew point temperature (the bottom of the two black lines) occurred between ____ on December 27th.
   a. 0100 and 0200 UTC
   b. 0900 and 1000 UTC
   c. 1200 and 1300 UTC
   d. 1500 and 1600 UTC.
3. After the sudden drop in air temperature, both temperature and dew point _____ until the end of the period.
   a. recovered substantially
   b. leveled off
   c. continued to decline steadily
   d. began rising steadily
4. Other conditions also experienced substantial changes. Before the temperature drop from question 2, winds were primarily coming from the:
   a. North-northwest
   b. North-northeast
   c. South-southeast
   d. South-southwest
5. After the temperature drop, winds shifted to the:
   a. North-northwest
   b. North-northeast
   c. South-southeast
   d. South-southwest

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10.2: Air Pressure Changes in Frontal Passages

Air Pressure and Fronts

Not shown on the meteogram for Kerrville, but also of importance, is air pressure. Air Pressure Data was not available for this particular day in Kerrville. Both warm and cold fronts behave like areas of low pressure, with air pressure steadily declining as the front approaches and increasing once the front passes. In fact, especially in summer months when differences between warm and cold air masses are small (hence frontal conditions are not as well pronounced), the decreasing air pressure followed by a recovery in air pressure is a telltale sign of a frontal passage. Let's investigate a more detailed example of this. Figure 10.2.1 is a map of surface conditions across the United States at 1200 UTC (7 am Central Daylight Time) on July 28, 2019, focusing on a cold front stretching from central Canada through western North Dakota, down to a low-pressure system in Wyoming.

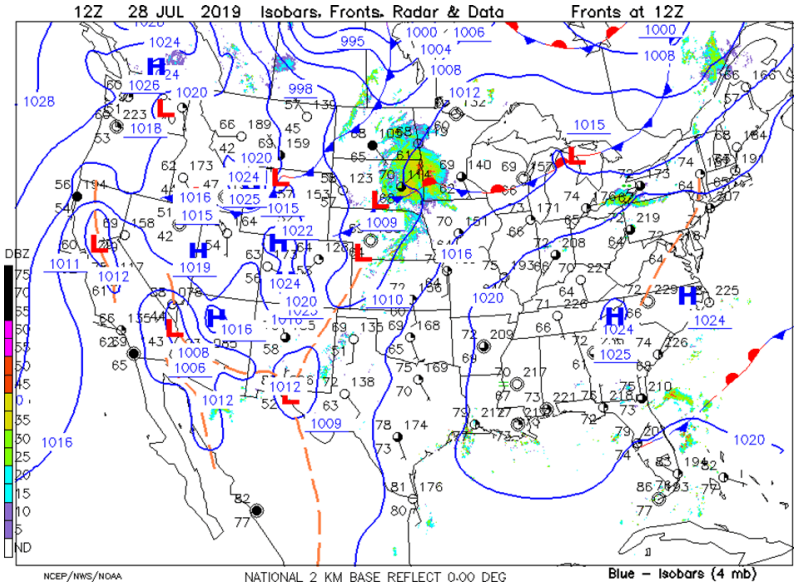


Figure 10.2.1: Surface Weather Conditions for the United States at 1200 UTC on July 28, 2019. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

6. Based on the direction the 'spikes' on the cold front are pointing towards, this front is traveling:
   a. Towards the north
   b. Towards the east-southeast
   c. Towards the west
7. At 1200 UTC, Bismarck, in central North Dakota, is reporting a temperature 68°F, a dew point of 65°F, and winds coming from the _____ at 5 knots.
   a. north
   b. southeast
   c. southwest
   d. west

Figure 10.2.2 is a map of surface conditions across the United States at 0000 UTC on July 29, 2019, 12 hours after Figure 10.2.1.

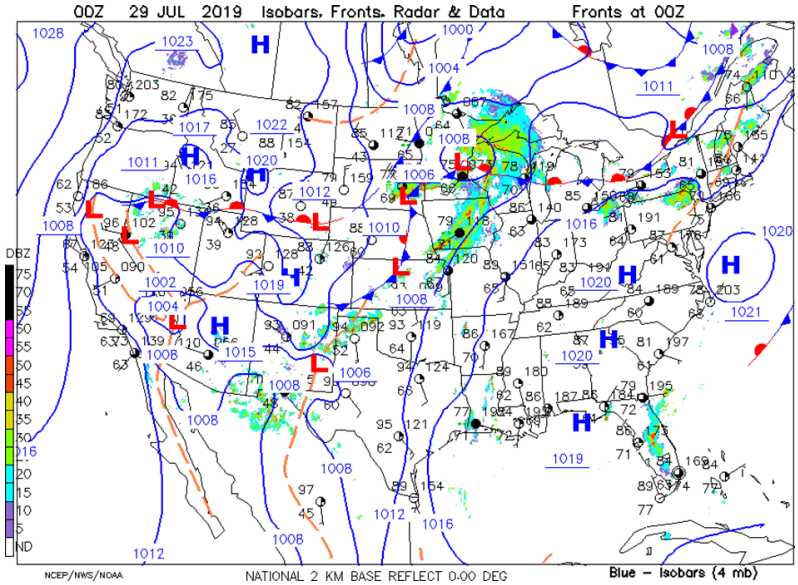


Figure \(\PageIndex{2}\): Surface Weather Conditions for the United States at 0000 UTC on July 29, 2019. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of image.

8. By 0000 UTC on July 29th, the front _____ passed Bismarck.
   a. had
   b. had not yet
9. Bismarck's wind direction:
   a. Shifted to the northwest
   b. Remained similar to 1200 UTC
   c. Shifted to the east

Figure 10.2.3 is a Meteogram for Bismarck International Airport during the 24 hours between 0700 UTC (12 am Central Daylight Time) on July 28th and 0700 UTC (12 am Central Daylight Time) on July 29th.

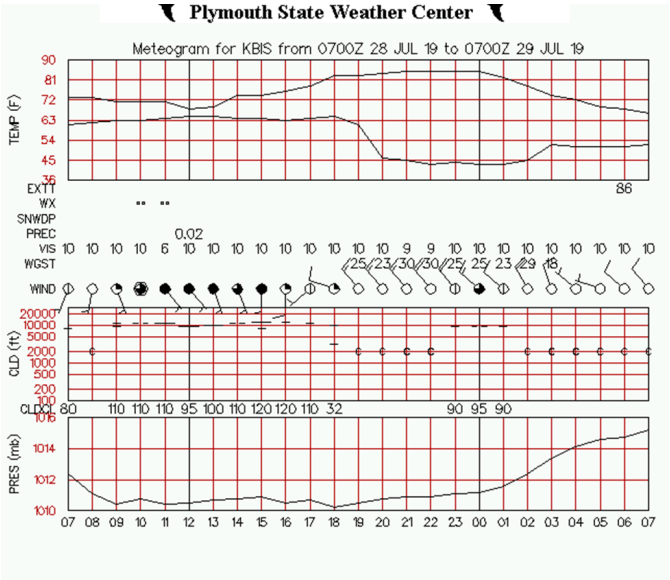


Figure 10.2.3: Meteogram of Surface Weather Data for Bismarck International Airport for the period between 0700 UTC on July 28th and 0700 UTC on July 29th. (CC-BY-NC 4.0; Meteograms via Plymouth State). Alternative description of the image.

10. Bismark's air temperature was _____ at the end of the period in Figure Figure 10.2.3 than the beginning of the period.
    a. higher
    b. the same
    c. lower

11. Between 0700 UTC and 0900 UTC on July 28th, air pressure:
    a. Increased
    b. Decreased
    c. Remained steady

After the shift in pressure mentioned above, air pressure stabilized until approximately 1800 UTC.

12. After 1800 UTC, the air pressure
    a. Began rising
    b. Began dropping
13. A significant change in wind direction, from south-southwest to northwest occurred _____ air pressure began rising.
    a. at the same time as
    b. a few hours before
    c. a few hours after
14. The dew point began decreasing _____ air pressure began rising.
    a. at the same time as
    b. a few hours before
    c. a few hours after

Therefore, despite little change in air temperature, changes in air pressure, dew point, and wind direction confirm the passage of a cold front during the period between 1200 UTC and 0000 UTC, as suggested by Figures 10.2.1 and 10.2.2.

Detection of warm and occluded frontal passages is also possible using surface observations. However, changes in conditions tend to be much subtler and more gradual than those associated with cold frontal passages. A few things to note is that in every frontal passage, changes in air pressure are similar, while changes in wind direction, dew point and air temperature are very different, while this may sound counterintuitive, the passage of a cold front does not necessarily mean that it's going to get colder suddenly, so it's necessary to look at all of the factors at play when analyzing the presence and movement of a frontal boundary.

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10.3: Tracking Mid-Latitude Cyclones

What are Mid-Latitude Cyclones?

Often, when people think of “cyclones,” Tornadoes, Hurricanes, and Typhoons come to mind. However, cyclones are common almost anywhere on Earth and impact large swaths of land on a near-daily basis. The rainfall that occurs across California in wintertime is caused by a type of cyclone called a “Mid-Latitude” cyclone (also known as an "Extratropical cyclone"), which lies beyond the tropics. These cyclones then travel across the United States and Canada, giving rain, snow, ice, and even thunderstorms to most of the region.

What are the Mid-Latitudes?

When we discussed El Niño in Investigation 9, we focused on the planet's Equatorial region, often referred to as the Tropics. The mid-latitudes, on the other hand, are further North (or South in the southern hemisphere) of the tropics. There are various definitions of the Mid-Latitude, but for this class, we'll describe them as the region of the world between latitudes 30° North/South and 60° North/South. The mid-latitude region is prone to severe storms because it serves as a battleground for warm tropical air from the equator and cold polar air from the poles. These regions are highlighted in Figure 10.3.1.

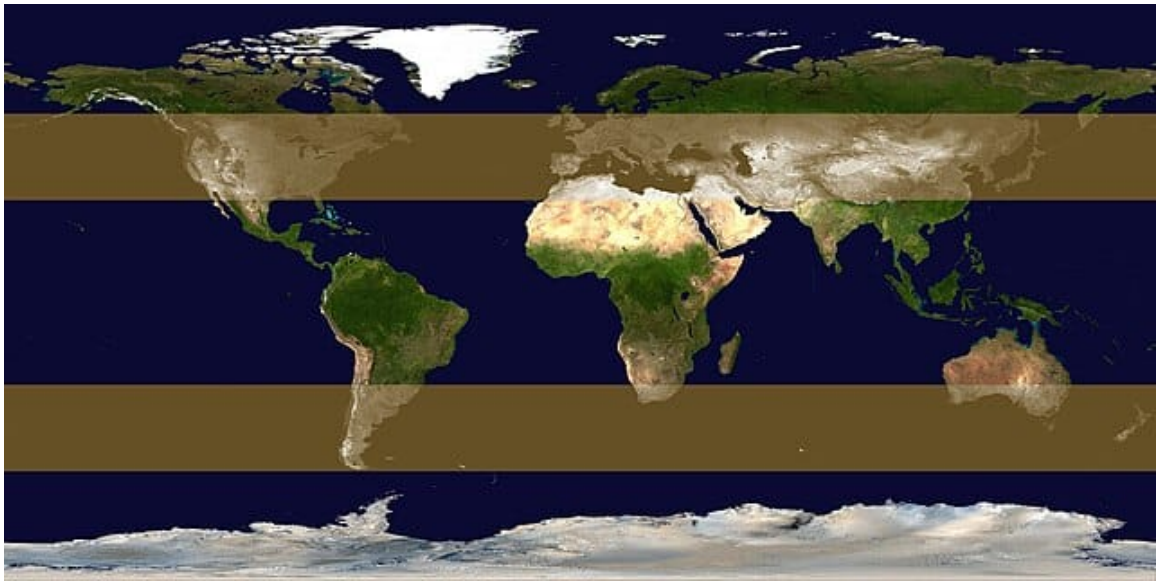


Figure 10.3.1: General location of the mid-latitudes on Earth. (Public Domain; Titoxd via Wikimedia Commons). Alternative description of the image.

What is a Mid-Latitude Cyclone?

The definition of a Mid-Latitude Cyclone sounds just like the name, a cyclone (low pressure), in the mid-latitudes. The big deal with them, however, is that cyclonic motion pulls warm air up from the tropics and pushes cold air down from the polar regions. These movements of air create fronts, and a set-up similar to that shown in Figure 10.3.2



Figure 10.3.2: The United States with a mid-latitude cyclone over Iowa. (CC-BY-SA 3.0; Phoenix2 via Wikimedia Commons). Alternative description of the image.

15. From the hand-twist model for cyclonic flow, we know that winds will travel _____ around the low pressure system over Iowa.
    a. clockwise and out of
    b. counterclockwise and into

You can print out or download and open Figure 10.3.2. Draw arrows on the map indicating how air is flowing around the low-pressure system. This will help you answer the following questions.

16. Warm air from the south is being pushed northward along which side of the mid-latitude cyclone? (Hint: where are the winds primarily coming from the south)
    a. The northwest
    b. The southwest
    c. The southeast
    d. The northeast

The region from question 16 is called the "Warm Sector" of the mid-latitude cyclone, and is responsible for bringing warm, moist air into the storm. This acts as the storm's fuel.

17. Because much of the warm air is coming from the humid Gulf of Mexico, dew point temperatures in the warm sector should be relatively _____.
    a. high
    b. low
18. Cold air from the north is wrapping around the _____ side of the cyclone:
    a. the east-southeastern
    b. the western
    c. the southern
    d. the northern

The two black lines represent fronts. which act as boundaries between the warm sector and cold air wrapping around the back of the cyclone. The cold front, where cold air is moving in and warm air is moving out, extends southwest from the low-pressure system through Kansas, Oklahoma, and Texas. In contrast, the warm front, where warm air is moving in and pushing cold air away, extends East from the low pressure through Illinois, Michigan, and Pennsylvania.

Now, let's assume the low-pressure cyclone is traveling due east, which is common for mid-latitude cyclones following the Jet Stream. As the storm travels east, the two fronts spin counter-clockwise like a pinwheel (or a propeller) with the low pressure at the center. As the fronts rotate around the low-pressure system, the warm front will likely be traveling north of its current position. As a result, Michigan and Wisconsin can expect warming over the next few hours as the warm front passes, while Colorado and

Wyoming can expect cooling as the cold front passes. As the cold front advances, it forces warm, moist air from the warm sector to rise, producing tall storm clouds and precipitation.

19. While both the cold and warm fronts spin around the low-pressure system, the cold front actually moves faster than the warm front. As a result, the warm sector of the storm will _____ overtime.
    a. grow
    b. shrinks
20. Eventually, the cold front catches up to the warm front, a process known as occlusion. This cuts the storm off from warm, moist air, causing the storm to:
    a. Become stronger
    b. Weaken and eventually dissipate.

Figure 10.3.3 is a satellite image of the Continental United States, taken at 1651 UTC (9:51 am Pacific Time, 12:51 pm Eastern Time) on July 29, 2019. Notice the long white band of clouds draping across the Upper and Middle Mississippi valleys, with a comma-shaped spiral over the Wisconsin-Minnesota border.

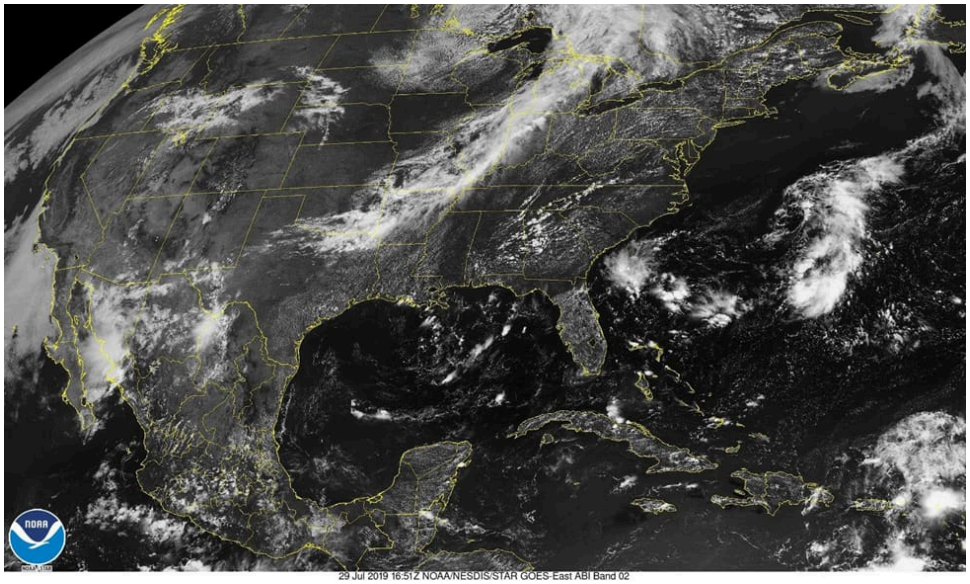


Figure 10.3.3: GOES-East Visible Satellite for the Continental United States, taken at 1651 UTC on July 29, 2019. (Public Domain; GOES-East). Alternative description of the image.

An animation of the storm's movement can be found here. An animation zoomed in over the Great Lakes can be found here: Close-up of animation

21. The cold front, or the long line of clouds extending from Michigan down to Oklahoma was mainly moving _____ during the time of the animation.
    a. east
    b. west

Figure 10.3.4 is a map of surface observations taken at 1200 UTC on July 29, several hours before the satellite picture and animations from Figure 10.3.3.

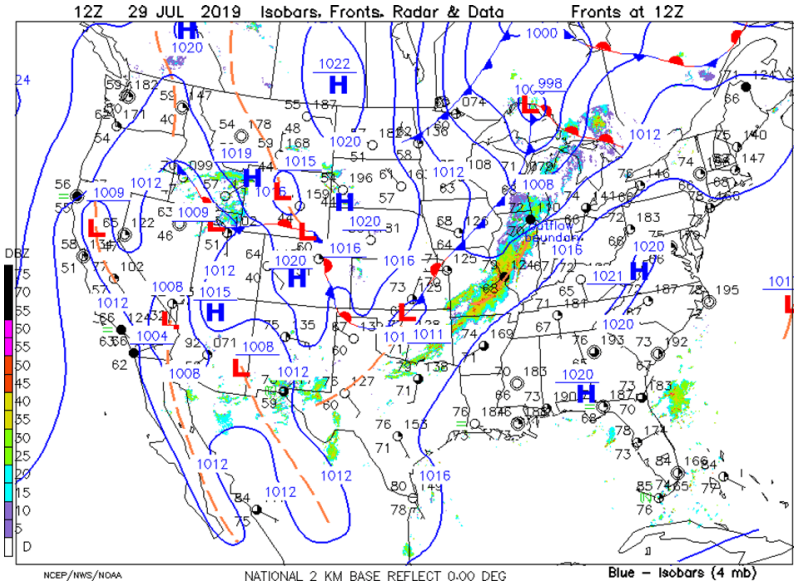


Figure 10.3.4: Surface Weather Conditions for the United States at 1200 UTC on July 29, 2019. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

While the mid-latitude cyclone being investigated will not have major impacts on St. Louis' temperatures, it should be noted that this cyclone is present during summertime, when the difference between the warm air ahead of a cold front and the cold air behind one isn't large.

22. At 1200 UTC, the low-pressure center of the mid-latitude cyclone we are investigating was over:
    a. Southern Texas
    b. Southern Canada and Lake Superior
    c. The southeastern United States
23. The bulk of the precipitation associated with this cyclone was located:
    a. Ahead of the warm front
    b. In the warm sector
    c. Behind the cold front

Saint Louis, in Eastern Missouri, directly under the large swath of rain, has an air temperature of 79°F and a dew point of 68°F. While it's hard to read, at 1200 UTC, winds out of St. Louis were blowing from the Southwest at 10kts. Because these storms bring heavy rainfall and sudden temperature changes, weather forecasters want to predict their movement. Figure 10.3.5 is a map of the 500 mb winds and contour lines, derived from radiosonde (weather balloon) launches at the same time as Figure 10.3.4 (1200 UTC on July 29, 2019), with a red "L" superimposed to indicate the location of the mid-latitude cyclone. Think of the solid blue lines as the edges of a river, and the wind barbs as a guide to where the current is coming from.

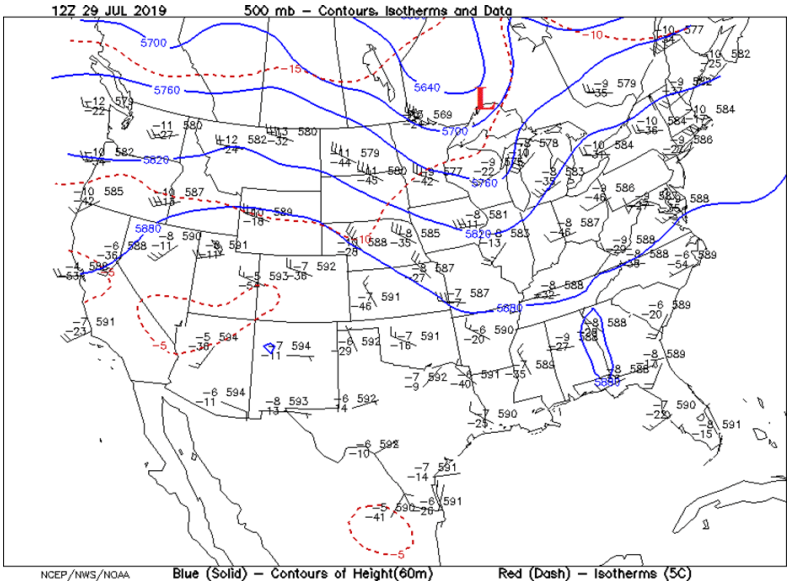


Figure 10.3.5: 500 mb Winds, isotherms, and height contours taken at 1200 UTC on July 29, 2019. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

24. The approximate surface location of the center of the mid-latitude cyclone has been indicated by a red 'L'. Based on the stream's flow around the cyclone, and by the wind barb direction over northern Michigan, the storm is likely to travel _____ over the next 12 hours.
    a. northeast
    b. southwest
    c. southeast
    d. northwest

Figure 10.3.6 is a map of surface weather conditions taken at 0000 UTC, 12 hours after Figures 10.3.4 and 10.3.5.

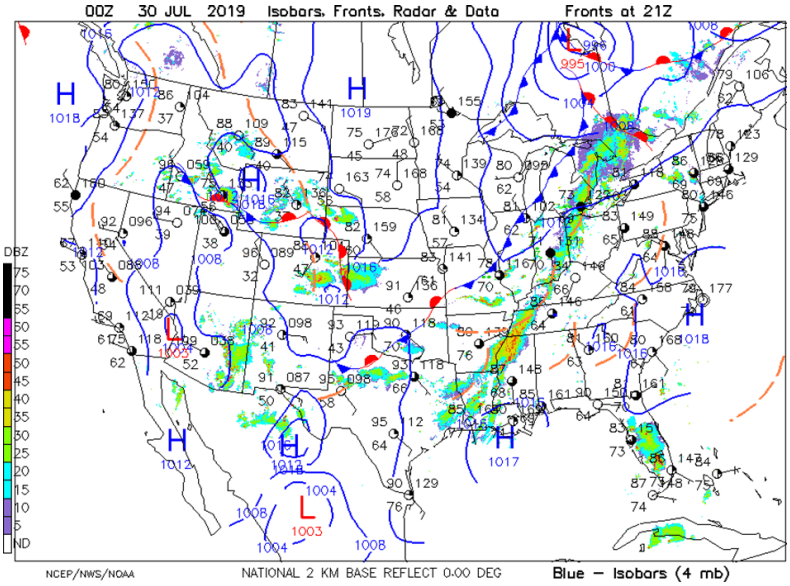


Figure 10.3.6: Surface Weather conditions at 0000 UTC on July 30, 2019. (CC BY-NC 4.0; American Meteorological Society via Unidata). Alternative description of the image.

25. Over the past 12 hours, the center of the mid-latitude cyclone _____ move in the direction predicted in question 24.
    a. did not
    b. did

While the mid-latitude cyclone being investigated did not have major impacts on St. Louis' temperatures, it should be noted that

this cyclone is present during summertime, when the difference between the warm air ahead of a cold front and the cold air behind one isn't large.

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10.4: Accessible Descriptions

Figure 10.1.1: Cross-section of a warm front

A warm front where warm air gradually rises above cold air. The slope of warm air over cold air extends for hundreds of kilometers. Different cloud types form along the slope, including stratocumulus near the surface, stratus, nimbostratus producing rain, altostratus, cirrostratus, and cirrus at higher altitudes. Fog occurs near the ground ahead of the front, rain falls closer to the boundary, and snow occurs farther into the cold air mass.

Figure 10.1.2: Cross-section of a cold front

A cold front where dense cold air pushes beneath warm air, forcing it upward rapidly. The rising warm air forms large cumulonimbus clouds producing thunderstorms and heavy rain. Other clouds shown include altocumulus, cirrostratus, and cirrus at higher altitudes.

Figure 10.1.3: Meteogram for Kerrville, Texas

A meteogram from the Plymouth State Weather Center for KERV covering 0000Z to 2300Z on December 27, 2015.

- Temperature and Dew Point: Values begin near 70 degrees Fahrenheit and remain steady during the early hours. Around 0900-1000 UTC, the temperature decreases quickly to the mid-40s and then continues a gradual decline into the upper 30s by late in the period.
- Reported weather: Periods of light precipitation occur in the morning and around midday.
- Precipitation amount: Accumulated precipitation reaches three-tenths of an inch by midday.
- Visibility: Mostly 10 miles, with reductions to 7 miles in the morning and briefly to 5 miles near the time of peak precipitation.
- Wind: Sustained winds generally between 10 and 20 knots. Gusts occur frequently, reaching as high as 27 knots.
- Cloud cover: Conditions vary between broken and overcast. Cloud bases are reported mainly between one thousand and five thousand feet, with some higher layers.

Overall, the meteogram indicates a frontal passage with a sharp temperature decrease, measurable precipitation, reduced visibility, gusty winds, and persistent cloud cover.

Figure 10.2.1: Weather Map at 1200 UTC on July 28, 2019

A surface weather analysis valid at 12Z on July 28, 2019, displaying isobars, pressure systems, frontal boundaries, precipitation radar, and surface station data across the contiguous United States.

- Pressure systems
  - Multiple low-pressure centers are charted: one in the central Plains around 1009 millibars, another in the northern Plains near 1008 millibars, and several in the western U.S. ranging from 1006 to 1012 millibars.
- High-pressure centers are located in the Southeast (around 1024–1025 millibars), the central Rockies (1020–1022 millibars), and the Northwest (1026–1028 millibars).
- Isobars: Contours drawn every 4 millibars outline pressure fields, with tighter spacing near the northern Plains indicating stronger gradients.
- Frontal boundaries:
  - Cold fronts extend through parts of the Midwest, the Plains, and the Southeast. A cold front extends from central Canada, through the state of North Dakota, to Wyoming and Idaho. Spikes on the frontal symbol indicate that the front is moving towards the east-southeast.
  - Warm fronts are present in the Northeast and northern Plains.
  - Stationary fronts are indicated in the central Rockies and along portions of the eastern U.S.
  - Several trough lines extend across the West and Southwest.
- Precipitation (radar reflectivity):

    - Moderate to heavy precipitation is concentrated in the northern Plains and Upper Midwest.
    - Lighter precipitation areas appear in the Southeast, Ohio Valley, and Gulf Coast.
    - Small scattered areas of precipitation are also shown in the Rockies and Southwest deserts.
- Station observations:
    - Each station model provides temperature, dew point, wind, sea-level pressure, pressure trend, and present weather.
    - Temperatures range mostly from the 60s to 80s Fahrenheit, with higher humidity in the central and eastern regions, as indicated by higher dew points.
    - Wind barbs show variable flow: southerly winds in the central U.S. around 15–25 knots near the low-pressure system, lighter winds elsewhere.

Overall interpretation:
The map depicts a broad low-pressure system dominating the central U.S., associated with fronts and widespread precipitation in the northern Plains. High-pressure systems in the Southeast and Northwest provide more stable conditions there. Tight pressure gradients in the Midwest suggest stronger winds and unsettled weather.

Figure 10.2.2: Weather Map at 0000 UTC on July 29, 2019

A surface weather analysis valid at 00Z on July 29, 2019, showing isobars, pressure systems, frontal boundaries, radar-based precipitation, and surface station reports across the contiguous United States.

- Pressure systems:
    - Multiple low-pressure centers are charted across the central U.S. and the West, with values near 1006 to 1009 millibars in the Plains and Midwest, and around 1008 to 1010 millibars in the Southwest.
    - High-pressure centers are located in the Southeast, Mid-Atlantic, and portions of the interior West, with pressures from 1015 to 1021 millibars.
- Isobars: Contours drawn every 4 millibars depict the pressure field, showing gradients around the central Plains low and the high-pressure ridge across the East.
- Frontal boundaries:
    - A cold front extends from the Minnesota southward into the central Plains.
    - Stationary fronts run across the central Rockies, Southwest, and southern Plains.
    - Warm fronts are indicated in parts of the Midwest and Northeast.
    - Trough lines extend through the West and the Gulf Coast.
- Precipitation (radar reflectivity):
    - Moderate to heavy precipitation is concentrated over the central and northern Plains and the Midwest, linked to low-pressure systems and frontal zones.
    - Scattered areas of lighter precipitation are noted in the Southeast, Gulf Coast, and parts of the Rockies and Southwest.
- Station data:
    - Observations include temperature, dew point, wind, pressure trends, and weather conditions.
    - Temperatures are generally in the 70s and 80s Fahrenheit across much of the country, with dew points showing high humidity in the central and eastern states.
    - Wind reports show stronger flow near the central low-pressure system, with gusts and sustained winds in the 15–25 knot range, lighter elsewhere.

Overall interpretation:
The map depicts a central U.S. low-pressure system driving unsettled weather, including widespread precipitation and stronger winds in the Midwest and Plains. High pressure over the East provides relatively more stable conditions, while scattered showers continue across the Gulf Coast and Southwest.

Figure 10.2.3: Meteogram for Bismarck, North Dakota.

A meteogram from the Plymouth State Weather Center for KBIS (Bismarck, North Dakota), valid from 0700Z on July 28, 2019, to 0700Z on July 29, 2019.

- Temperature: Air temperature begins near the upper 60s Fahrenheit in the early period, increases steadily through the afternoon to around the upper 80s, then decreases overnight to the mid-60s. Dew point temperatures begin near the mid-60s, decrease through the day into the mid-40s, then rise slightly late in the period.
- Weather reports: Symbols indicate light precipitation or weather activity between 0800Z and 1000Z.

- Precipitation amount: A small total accumulation of 0.02 inches occurs during the morning.
- Visibility: Generally 10 miles, reduced briefly to 6 miles in the morning, returning to 9–10 miles for the remainder of the period.
- Wind: Sustained winds shift during the day, with speeds varying around 10 to 20 knots. Gusts are stronger in the afternoon and evening, peaking between 25 and 30 knots.
- Cloud cover: Reported as variable. Cloud base heights range between 1,000 and 5,000 feet, with occasional mid-level layers up to around 10,000 feet.
- Pressure: Surface pressure starts near 1013 millibars early in the day, falls steadily to around 1010 millibars by evening, and then rises overnight back toward 1015 millibars.

Overall interpretation:
The meteogram shows a warm daytime period with decreasing humidity, gusty winds, and a brief episode of light precipitation in the morning. Conditions stabilize overnight with rising pressure and cooler temperatures.

Figure 10.3.1: Earth's Climate Zones.

World map of Earth labeling major climate zones by latitude, with tropical regions near the equator, polar regions near the poles, and middle latitudes between them in both hemispheres, where many temperate climates are found.

Figure 10.3.2: Cyclone over Iowa

Outline map of the United States with state boundaries shown. A low-pressure center marked “L” is located over the central Plains near the Missouri–Kansas area. Two thick solid lines extend toward this center: one curves northeastward from the southern Plains, and another stretches westward from the Mid-Atlantic and Ohio Valley region, both converging at the low-pressure system.

Figure 10.3.3: Satellite image of the Eastern United States.

A satellite image from July 29, 2019, at 16:51 UTC, showing the continental United States, Mexico, Central America, the Caribbean, and part of the Atlantic Ocean.

- Cloud cover:
  - Widespread cloud systems extend across the central U.S., with organized bands stretching over the Midwest and Plains.
  - Additional cloud clusters are present along the Gulf Coast, across Florida, and offshore in the Atlantic.
  - Dense cloud areas are visible over Mexico and parts of Central America, associated with convection and storms.
  - Scattered tropical systems are developing in the western Atlantic near the Bahamas and north of the Caribbean islands.
- Geographic coverage:
  - The image outlines state and national borders for the U.S., Mexico, and Caribbean islands.
  - The Gulf of Mexico, Atlantic Ocean, and eastern Pacific are included within the frame.

Overall interpretation:
The image depicts multiple weather systems, including frontal cloud bands across the U.S., convection over Mexico, and tropical disturbances in the Atlantic basin.

Figure 10.3.4: Weather Map at 1200 UTC on July 29, 2019

This map shows surface weather conditions for the United States, valid at 12Z on July 29, 2019.

Information displayed on the map:

1. Isobars (lines of pressure):
   - Solid lines connect points of equal atmospheric pressure, drawn every 4 millibars.
   - Lower pressures are marked with “L,” and higher pressures are marked with “H.”
   - Tighter spacing of isobars indicates stronger surface winds.
2. Fronts:
   - Symbols show the positions of surface weather fronts.

- A cold front marks the leading edge of advancing cooler air.
- A warm front marks the leading edge of advancing warmer air.
- A stationary front marks where warm and cold air masses meet but neither is advancing.
- An occluded front marks where a cold front has overtaken a warm front.
- Boundaries can also include outflow boundaries from thunderstorms.

3. Radar data (precipitation):
   - Shaded areas represent radar reflectivity, showing where rain and storms are occurring.
   - Stronger shading indicates heavier precipitation.
   - On this map, a line of thunderstorms extends across parts of the central United States.
4. Station models:
   - Plotted at many locations, providing surface observations.
   - Each includes temperature, dew point, pressure, wind speed, wind direction, and current weather.
   - These observations help confirm the position of fronts and precipitation areas.

Overall pattern on this map:

- Multiple high and low pressure systems are spread across the country, with a low pressure center over Southern Canada and Lake Superior.
- A line of thunderstorms is associated with a cold frontal boundary in the central United States.
- High pressure areas are generally linked with calmer and clearer weather, while low pressure areas and fronts are linked with unsettled weather.

Figure 10.3.5: Upper-Air map at 1200 UTC on July 29, 2019

This map shows conditions at the 500 millibar pressure level, valid at 12Z on July 29, 2019. The 500 millibar level is located about 5 to 6 kilometers above sea level, often referred to as the “mid-levels” of the atmosphere.

Information displayed on the map:

1. Height Contours:
   - Solid lines connect points where the 500 millibar pressure surface is at the same altitude.
   - Values are written in decameters, or tens of meters. For example, a value of 588 means 5,880 meters above sea level.
   - When contours are close together, winds are stronger at this level.
2. Isotherms (Temperature Lines):
   - Dashed lines mark equal temperatures, drawn every 5 degrees Celsius.
   - Temperatures are written near plotted stations, mostly ranging from about minus 5 to minus 15 degrees Celsius across the U.S.
3. Station Plots:
   - Symbols show observed data at 500 millibars for specific locations.
   - Each includes temperature, dew point, wind speed, and wind direction.

Overall pattern on this map:

- A broad ridge of higher heights is present across much of the southern United States, suggesting warmer and more stable mid-level conditions.
- Lower heights are located across the northern U.S., consistent with cooler mid-level air.
- The temperature field shows relatively warmer air in the south and cooler air in the north, typical for summer.
- Winds are stronger where the contours are closer together, such as near the northern portion of the map.

Figure 10.3.6: Weather Map at 0000 UTC on July 30, 2019.

This is a surface weather analysis map valid at 00Z on July 30, 2019. The map displays isobars, pressure systems, fronts, radar data, and station observations for the United States.

- Isobars: Solid lines connect locations of equal surface pressure, drawn every 4 millibars. Closer spacing indicates stronger winds.
- Pressure Systems: High pressure centers are marked with an “H,” indicating more stable surface conditions. Low pressure

centers are marked with an “L,” indicating more unsettled surface conditions. Several high and low centers are spread across the country.
- Fronts: Symbols show surface boundaries between different air masses. Cold fronts, warm fronts, stationary fronts, and occluded fronts are indicated. Boundaries separate regions of contrasting temperature and humidity, where precipitation is more likely.
- Radar Data: Shaded areas represent radar reflectivity, identifying where precipitation is occurring. Higher reflectivity suggests heavier precipitation or thunderstorms. A broad band of precipitation stretches across the central and eastern United States, with localized clusters of storms in the Plains, Rockies, and Southeast.
- Station Models: Weather stations across the map display temperature, dew point, wind speed, wind direction, and current weather. These observations help confirm the location of fronts and precipitation.

Overall Pattern:

- High pressure systems are located over parts of the western and southeastern United States.
- Multiple low pressure systems and associated frontal boundaries are located across the central and northern United States, including a mid-latitude cyclone over Northern Ontario, Canada with a cold front extending from Northern Ontario, through Michigan and Illinois, and into Arkansas.
- Radar shows precipitation bands and clusters of thunderstorms aligned with these frontal zones.

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11: THUNDERSTORMS AND TORNADOES

Introduction

Mark Twain once said, "*Thunder is good, thunder is impressive; but it is lightning that does the work.*" While he was talking about pompous bluster versus quiet, efficient action, little did he know that by 2024, lightning strikes would cause 55-60 fatalities and over 400 injuries every year in the United States. Severe weather events, such as tornadoes and thunderstorm-related flooding, cause multiple deaths and between USD 200 billion and USD 500 billion in damage each year, according to NOAA. A thunderstorm is a type of rain shower that typically includes thunder and lightning. They are very common across the continental United States and worldwide, where they account for most summertime rainfall and are often considered a normal part of life. Some people even claim they can determine the time of day simply by knowing whether a thunderstorm is present in their area. Figure 11.1 shows a thunderstorm approaching a small farmhouse in Mendoza, Argentina.



Figure 11.1: A Thunderstorm in Malargüe County, Mendoza Province, Argentina. (CC BY-SA 2.0; XXXX via Flickr)

We'll begin this investigation by examining the general ingredients of ordinary air-mass thunderstorms, then delve deeper into the conditions that enable them to become truly destructive weather events. We'll wrap up this investigation by examining the scariest hazard produced by some thunderstorms – the tornado.

Learning Objectives

By the end of this investigation, you should be able to:

- Identify the atmospheric ingredients that allow ordinary thunderstorms to form
- Identify the atmospheric ingredients that allow thunderstorms to become severe
- Rank the intensity of a Tornado by its wind speed and destruction

Navigational Note

Investigation 11 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

11.1: Ingredients for Thunderstorms
11.2: Types of Thunderstorms
11.3: Tornadoes
11.4: Accessible Descriptions

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11.1: Ingredients for Thunderstorms

Thunderstorm Formation

Thunderstorms form when sufficient heat and moisture are present in the air. Heat causes the warm, moist air near the surface to rise, forming an updraft. Moist air cools and condenses, forming clouds. Latent heat is released during this process, thereby sustaining the upward movement of air. As this air continues to rise, the process creates strong upward and downward winds, leading to a mature cloud stage characterized by heavy precipitation, lightning, and thunder. Such clouds are composed of liquid droplets, ice crystals, hail, and graupel, which can be detected clearly by weather radars. Figure 11.1.1 is a weather map of surface weather conditions, fronts, and precipitation across the United States at 2100 UTC (4 pm Central Daylight Time) on May 28, 2019.

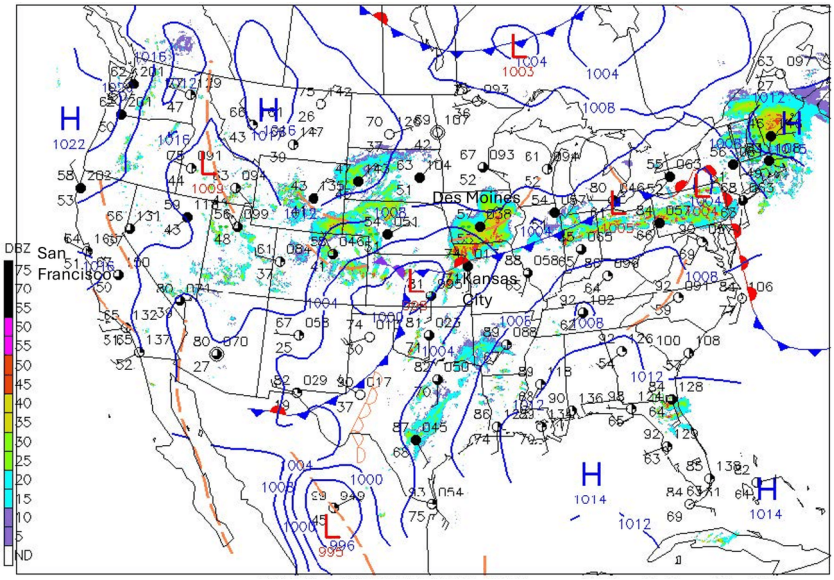


Figure 11.1.1: Surface Weather Conditions at 2100 UTC on May 28, 2019. (Public Domain; American Meteorological Society via NCEP/NWS) Alternative description of image.

1. According to Figure 11.1.1, Kansas City, in western Missouri, was reporting a temperature of 74°F and a dew point of 71°F. Except for locations along the US Gulf Coast, Kansas City's dew point was ____ than most of the locations in the Continental United States.
   a. higher
   b. within a degree or two
   c. lower

Remember, the dew point is the temperature to which air must be cooled at constant pressure for it to become saturated. It is a good indicator of the amount of moisture in the air. When the air's temperature drops to its dew point, the air becomes saturated (100% relative humidity).

2. Kansas City's dew point was only a few degrees different from its air temperature. This indicates that the air was _____.
   a. close to saturation
   b. very dry

Areas of heavy rainfall and thunderstorms are indicated on weather maps such as Figure 11.1.1 as a series of orange/red shadings embedded in larger areas of precipitation. Irregularly shaped blue/green/yellow blobs indicate different intensities of reflected radar echoes.

3. The presence/lack of such shading indicate that there _____ thunderstorms in Kansas City at 2100 UTC.
   a. were
   b. were not

4. On the other hand, consider San Francisco, California, which at 2100 UTC has an air temperature of 64°F, and a dew point of:
    a. 66°F
    b. 57°F
    c. 51°F
    d. 48°F

5. Therefore, San Francisco's air is _____ than Kansas City's.
    a. more humid
    b. drier

6. The appearance/lack of orange/red shadings embedded in radar echoes near San Francisco indicate that thunderstorms _____ occurring in the area.
    a. were
    b. were not

While heat and moisture are key ingredients for Thunderstorm formation, other dynamics in the atmosphere can also aid in the formation of thunderstorms. For example, consider Des Moines, in Central Iowa, with an air temperature of 57°F and a dew point of 54°F.

7. Des Moines, in central Iowa is _____ than Kansas City.
    a. much warmer/wetter
    b. much cooler/wetter
    c. much warmer/drier
    d. much cooler/drier

8. However, there _____ thunderstorms near Des Moines.
    a. are
    b. are not

This suggests that some other dynamics are in play. Other elements that can allow thunderstorms to form include frontal lifting: a meteorological process where warm air is forced to rise over a colder air mass at a weather front, upper-level divergence: the spreading out of air in the upper levels of the atmosphere, and vertical wind shear: a change in wind direction/speed with height. The presence of Convective Available Potential Energy (CAPE) can also greatly influence thunderstorm formation.

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11.2: Types of Thunderstorms

Severe Thunderstorms

As previously mentioned, thunderstorms are part of everyday life for many people, especially in the summer, and are classified as "air mass" or "ordinary" thunderstorms. However, many of the thunderstorms that were occurring in the United States at the time of Figure 11.1.1 were severe thunderstorms. Severe thunderstorms generally last longer than ordinary thunderstorms and can produce very strong winds, flooding, hail, and/or tornadoes. Ordinary thunderstorms are generally short-lived and do not produce very strong winds or large hail. For severe thunderstorms to develop, the following things are necessary:

- Fuel: The previously mentioned ingredients — heat and moisture — are fuel for thunderstorms.
- A layer of Convective Inhibition (CIN) near the surface of the earth, and Convective Available Potential Energy (CAPE) higher up in the atmosphere.
- A lifting mechanism, like a front, low-pressure system, or a mountain range. This "triggers" the lifting of air above the CIN layer near the surface.
- Vertical wind shear: A change in the wind direction and wind speed with height prevents the fuel from running out, and can also provide rotation for thunderstorms.

Vertical wind shear can be of two types:

- Speed Wind Shear: Winds become faster as you rise in the atmosphere.
- Directional Wind Shear: Winds change directions as you rise in the atmosphere.
  - Near the surface, winds typically blow from the south, allowing warm, moist air from the Gulf of Mexico to feed into the storms.
  - A few thousand feet up (about 850 mb), winds begin to shift from south to southwest.
  - By about 500 mb, winds shift from southwest to west.

Before continuing, you may want to review the definitions of fuel (Section 11.1), CAPE and CIN (Investigation 5), Fronts (Investigation 10), and Upper-Level Maps (Investigation 8). Figure 11.2.1 shows upper-air data from a Radiosonde Launch at Topeka, Kansas, about 100 miles West of Kansas City, at 1200 UTC (7 am Central Daylight Time) on May 28, 2019.

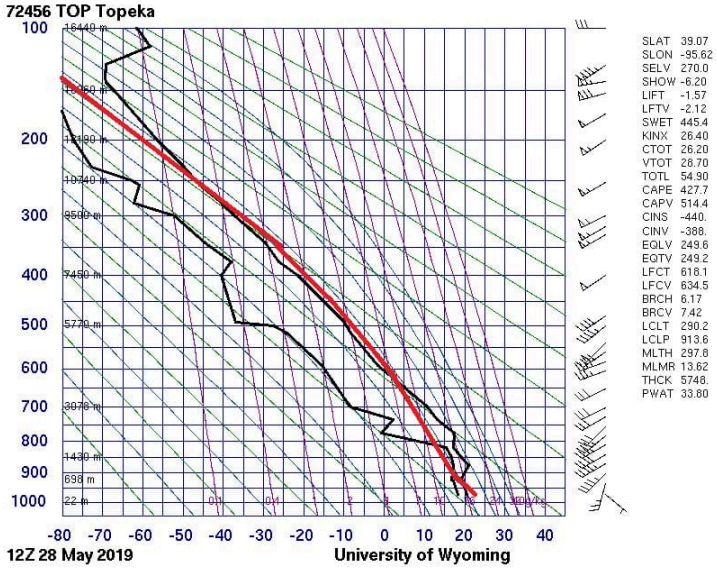


Figure 11.2.1: A Stüve Diagram displaying data from a Radiosonde Launch at 1200 UTC on May 28, 2019, over Topeka, Kansas. Parcel temperature is overlaid on the chart. (CC BY-NC 4.0; Larry Oolman via University of Wyoming) Alternative description of the image.

The following are some True/False questions based on Figure 11.2.1.

9. There is a layer of CIN near the surface of the Earth.
    a. True
    b. False

10. Higher up, a layer of CAPE is present.
    a. True
    b. False

11. Winds shift from south/southeast to southwest/west as you rise from the surface in the atmosphere. Hint: Check the wind barbs.
    a. True
    b. False

12. Wind speed does not generally increase from the surface to about 150 mb.
    a. True
    b. False

13. Based on questions 11 and 12, there was adequate wind shear to support severe thunderstorm development.
    a. True
    b. False

14. Based on Figure 11.1.1, there was no "trigger" present near the Kansas City/Topeka region.
    a. True
    b. False

15. Putting all of this together, it was likely that at least some of the thunderstorms over the Kansas City region were severe thunderstorms.
    a. False
    b. True

Let's verify this. Whenever conditions are favorable for severe thunderstorm formation, the National Weather Service will issue an outlook indicating how likely severe thunderstorms are for a particular region. Table 11.2.1 is the guide to how to interpret this information, and Figure \(\PageIndex{2}\) is the Severe Thunderstorm Outlook for the United States, Valid at 2000 UTC on May 28, 2019.

Table 11.2.1: A Guide to Severe Thunderstorm Categories from the National Weather Service.

Risk Category	Description	Threat Details
Thunderstorms (no label)	No severe thunderstorms expected	Lightning and/or flooding threats may exist with all thunderstorms.
1 - Marginal (MRGL)	Isolated severe thunderstorms possible	Limited in duration, coverage, and/or intensity.
2 - Slight (SLGT)	Scattered severe storms possible	Short-lived and/or not widespread. Isolated intense storms are possible.
3 - Enhanced (ENH)	Numerous severe storms possible	More persistent and/or widespread. A few storms may be intense.
4 - Moderate (MDT)	Widespread severe storms likely	Long-lived, widespread, and intense.
5 - High (HIGH)	Widespread severe storms expected	Long-lived, very widespread, and particularly intense.

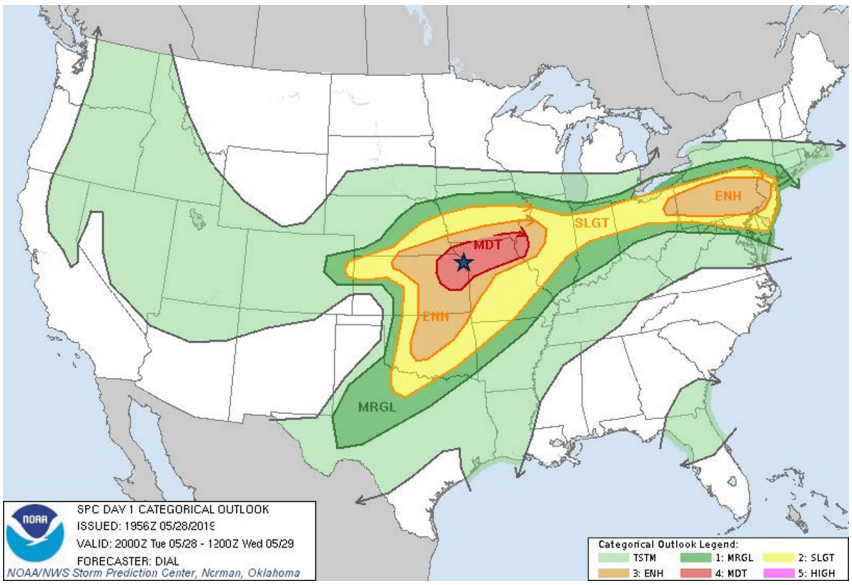


Figure 11.2.2: Severe Thunderstorm Categorical Outlook valid at 2000 UTC on May 28, 2019, with Kansas City's location displayed. (Public Domain; Severe Weather Outlook via NOAA/SPC) Alternative description of the image.

16. Based on Table 11.2.1 and Figure 11.2.2, severe storms were _____ at and near Kansas City during this time.
    a. isolated
    b. possible
    c. widespread and likely
    d. not expected
17. This _____ that conditions over Kansas City were favorable for severe thunderstorms to form.
    a. cannot confirm
    b. confirms

The conditions appear suitable for severe thunderstorms, and the forecast calls for them, but did they actually occur? The Storm Prediction Center (SPC) in Norman, Oklahoma, a branch of the National Weather Service, also produces maps showing storm reports for specific days. Figure \(\PageIndex{3}\) shows Storm Reports over the United States for May 28, 2019. Severe Thunderstorms produce Tornadoes (red), High Winds (blue), and large hail (green).

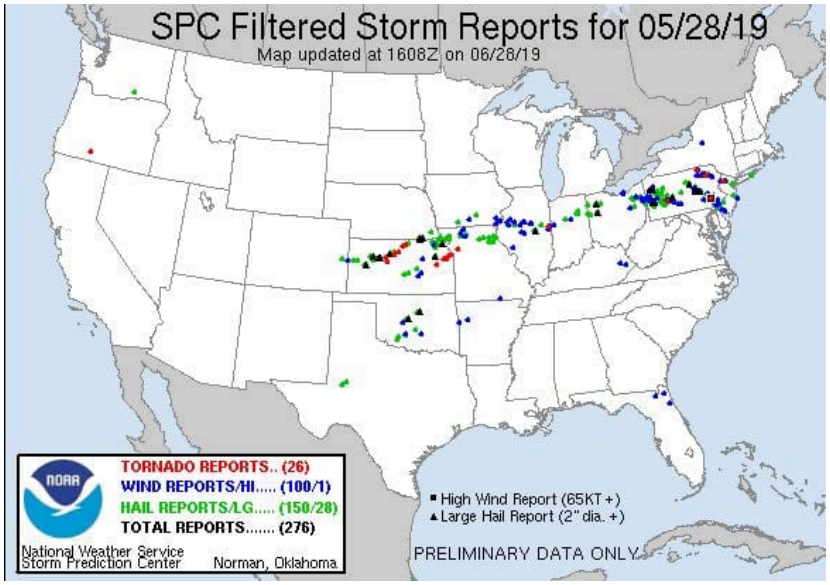


Figure 11.2.3: Severe Weather Reports for May 28, 2019. (Public Domain; Storm Reports via NOAA/SPC) Alternative description of the image.

18. According to Figure 11.2.3, there _____ reports of severe thunderstorms produced events (such as tornadoes and hail) near Kansas City Area on May 28, 2019.

a. were not
b. were

19. This _____ that conditions needed for severe thunderstorms were present, and that the weather forecasters accurately predicted severe thunderstorms for Kansas City on May 28, 2019.
    a. confirms
    b. disproves

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11.3: Tornadoes

Tornado Occurrence

Several of the severe weather reports mapped on May 28, 2019, were triangles, which indicate tornadoes. A tornado is a narrow, violently rotating column of air that extends from a thunderstorm to the ground. They are among the most violent phenomena of all atmospheric storms we experience. They pose a major threat when severe weather is present; therefore, meteorologists must track their location and intensity to warn people in their path. It's also important to analyze tornadoes post-event to learn more about them. Figure 11.3.1 shows tornado occurrences in 2019 compared to the average.

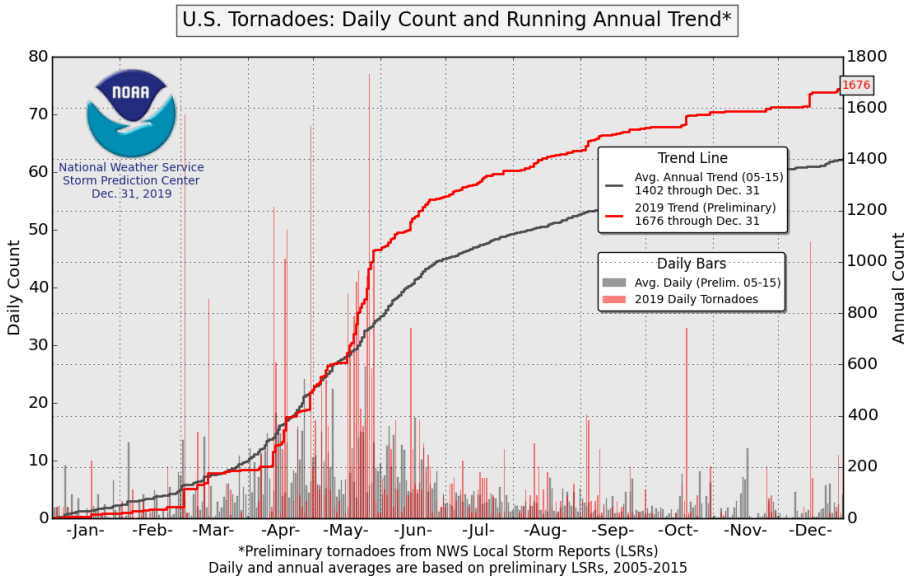


Figure 11.3.1: Tornado Occurrence in 2019 versus the daily average from 2005-2015, for the United States. (Public Domain; Tornado Reports via NOAA/SPC) Alternative description of the image.

20. Based on the average daily tornado occurrences in Figure 11.3.1: the time of year, on average, with the largest number of tornadoes is:
    a. Jan-Mar
    b. Apr-Jun
    c. Jul-Sep
    d. Oct-Dec

This is called Tornado Season, when tornadoes are most common in the continental U.S. The 2019 Eastern Kansas outbreak in Figure 11.2.3 is included and noticeable in Figure 11.3.1.

21. The day with the most number of tornadoes is approximately ___. Hint: Tallest red bar.
    a. Feb 22nd
    b. Oct 31st
    c. May 28th
    d. Dec 15th

The strongest storm during this outbreak developed a tornado south of Clinton Lake in southwestern Douglas County, KS (NWS Topeka). It continued through southeastern Lawrence, KS (NWS Topeka) before crossing into Leavenworth County, KS, moving through the town of Linwood, KS, and the area west of Bonner Springs, KS. You can read more about this tornado outbreak on the National Weather Service report.

Tornado Alley is a region in the central United States where most tornadoes occur. It includes parts of Texas, Oklahoma, Kansas, Nebraska, Missouri, and Iowa. However, that doesn't mean tornadoes do not occur outside this region. Figure 11.3.2 is the map of

storm reports for the 2018 Halloween Outbreak.

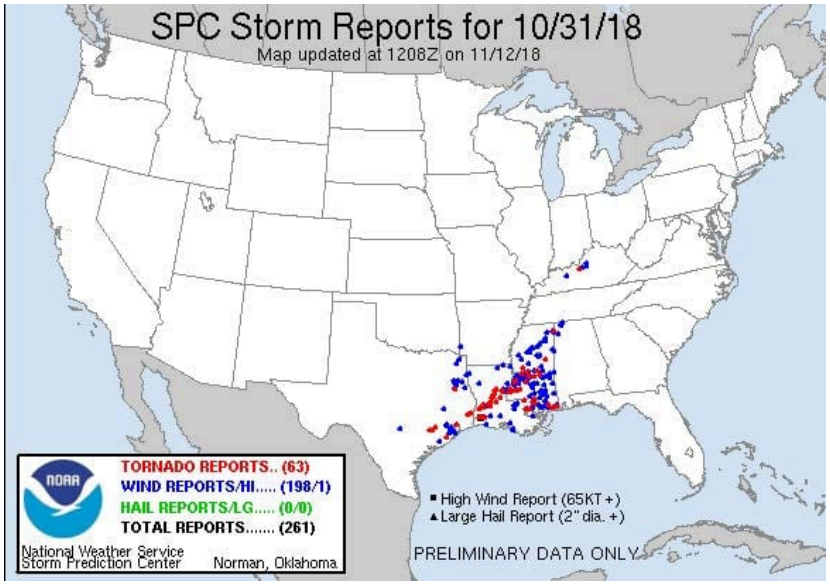


Figure 11.3.2: Map of Severe Weather Reports for October 31, 2018. (Public Domain; Storm Reports via NOAA/SPC) Alternative description of the image.

22. The majority of tornado reports (in red) happened in which of the following states?
    a. Texas
    b. Louisiana/Mississippi
    c. Kentucky/Alabama

The most intense tornado of the day occurred near Fishville, in Central Louisiana. Information on this tornado can be found on the NOAA website.

The Enhanced Fujita Scale

What makes certain tornadoes more intense compared to others? How do we determine that the Fishville tornado was the most intense among the Central Louisiana Halloween outbreak? In 1971, Ted Fujita, a Japanese American meteorologist who studied severe weather at the University of Chicago, collaborated with Allen Pearson, head of the National Severe Storms Forecast Center (SPC), to develop the Fujita Scale to measure tornado intensity. In 2007, the Fujita Scale was replaced by the Enhanced Fujita Scale, which is more accurate and is currently used to rank tornadoes in the United States. Because it is difficult and, not to mention, extremely dangerous to try to measure the rotational wind speeds inside an active tornado, the Enhanced Fujita Scale ranks the intensity of a tornado based on the amount of damage caused. The damage, combined with prior research, is then used to determine the tornado's maximum rotational wind speed. Table 11.3.1 below shows the Enhanced Fujita Scale and the six categories used to rank tornado intensity.

Table 11.3.1: The Enhanced Fujita Scale for ranking tornadoes.

Enhanced Fujita Scale	Wind speed
EF-0	65-85 mph
EF-1	86-110 mph
EF-2	111-135 mph
EF-3	136-165 mph
EF-4	166-200 mph
EF-5	> 200 mph

The Fishville Tornado lasted 8 minutes, traveled 7.21 miles, and was categorized as an EF-2 tornado.

23. This would give it a ground speed of _____ mph. Hint: mph = length in miles*60/time in minutes
    a. 45
    b. 37
    c. 7
    d. 54
24. Based on the storm's rating on the EF scale, the storm likely had winds between:
    a. 86 - 110 mph
    b. 111-135 mph
    c. 136 - 165 mph
    d. 166 - 200 mph

The Fishville tornado resulted in no fatalities, two injuries, and about $200,000 in property damage. While this is just one example of a less-dramatic tornado, other tornado outbreaks were responsible for significant deaths and destruction. Let's examine the devastation caused by the Joplin Tornado. It occurred on 22 May 2011, near Joplin, Missouri, lasted 20 minutes, and traveled 8.8 miles. This would give it a ground speed of 26.4 mph, which is slower than the Fishville tornado, but the Joplin tornado was categorized as an EF-5.

25. Based on the Joplin tornado's rating on the EF scale, the tornado likely had winds around:
    a. 111-135 mph
    b. 136 - 165 mph
    c. 166 - 200 mph
    d. > 200 mph

The storm events database recorded that the Joplin tornado resulted in the death of 158 people, 1150 injuries, and nearly $2.8 billion in property damage. This suggests that it is the rotational wind speed, rather than the tornado's straight-line ground speed, that accounts for most of the fatalities and property damage during a tornado event.

Additional Reading

During the investigation, we explored the Fishville tornado and some details of the Joplin tornado. You can explore detailed occurrence and damage reports from other tornadoes, outbreaks, and more information on the Joplin tornado using the following links:

- El Reno tornado of 2013 - An EF3 tornado in Oklahoma.
- 2011 Alabama outbreak - An outbreak of multiple EF4 and EF5 tornadoes.
- 2011 Joplin tornado - More details on the Joplin tornado

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11.4: Accessible Descriptions

Figure 11.1.1: Surface Weather Conditions

Overview of Map Features:

The map includes:

- Surface observations using standard station models (showing temperature, dew point, wind, pressure trend, and sky cover).
- Radar reflectivity data overlaid using color-coded shading for areas of precipitation.
- Isobars drawn every 4 millibars
- Fronts include cold fronts, warm fronts, stationary fronts, and occluded fronts.
- High (H) and low (L) pressure centers are marked.

Weather Highlights:

1. Precipitation and Radar Reflectivity:

- A band of moderate to heavy precipitation stretches from the central Plains through the Midwest and into the Northeast.
- The highest radar reflectivity values, indicating the most intense rainfall or storms, are located over parts of Illinois, Indiana, and the Northeast U.S.
- Additional scattered showers and thunderstorms are seen across the Southwest, southern Plains, and Gulf Coast.

2. Frontal Systems:

- A cold front extends from the Great Lakes southwestward into Oklahoma and Texas.
- A warm front is draped across the Mid-Atlantic region.
- Several stationary and occluded fronts are positioned in the Midwest and South.

3. Pressure Systems:

- Multiple low-pressure centers are located across the Midwest, Northeast, and southern U.S., with central pressures ranging from 1004 to 1008 millibars.
- High-pressure systems are centered over the western U.S. (1022 mb), the Gulf of Mexico (1014 mb), and the Atlantic Ocean.

4. Surface Observations:

- Station models report temperatures ranging from the 40s in the northern Rockies to the 90s in the southern Plains and Southeast.
- Wind barbs indicate wind direction and speed at each station; stronger winds are observed near frontal boundaries.
- Many stations show overcast or cloudy skies, particularly in areas with precipitation.

Figure 11.2.1: A Stüve Diagram over Topeka, Kansas.

This image shows a Skew-T log-P thermodynamic diagram generated by the University of Wyoming for Topeka, Kansas (station 72456), valid at 12Z (7:00 AM Central Daylight Time) on May 28, 2019. The diagram presents a vertical profile of atmospheric temperature, humidity, and stability indicators used to evaluate the potential for cloud formation, convection, and severe weather.

Axes and Scales:

- Vertical axis (left): Pressure in millibars (mb), decreasing logarithmically from 1000 mb at the bottom to 100 mb at the top.
  - Corresponding altitudes (right axis): Range from approximately sea level (~0 km) to ~16 km (~52,000 ft).
- Horizontal axis (bottom): Temperature in degrees Celsius, skewed diagonally from lower left to upper right.

Key Plot Features:

1. Temperature (Red Line):

- Represents the environmental temperature profile from the surface upward.
- Starts near +20°C at the surface (~1000 mb), decreases with height in a mostly linear fashion, reaching around -60°C near 100 mb (around 16 km).

2. Dew Point (Black Line):

- Indicates moisture content at each level.
- Close to the temperature line in the lower levels (indicating saturated or moist air), then diverges significantly higher up, suggesting drier air aloft.

3. Wind Barbs (Right side):

- Show wind speed and direction at each pressure level.
- Barbs point toward the direction from which the wind is coming.
- Wind speeds increase with height, as indicated by several barbs showing stronger upper-level flow.

Key Thermodynamic Values (shown at top right):

- CAPE (Convective Available Potential Energy): 427.7 J/kg. Indicates moderate instability and potential for convection (thunderstorms).
- CIN (Convective Inhibition): -440.0 J/kg. Represents a strong cap or lid on convection, likely suppressing thunderstorm initiation unless lifted.
- LCL (Lifted Condensation Level): 913.6 mb (~800 m altitude). The height at which a lifted air parcel becomes saturated.
- LFC (Level of Free Convection): 634.5 mb (~3.7 km altitude). The level at which an air parcel becomes warmer than its environment and rises freely.
- EL (Equilibrium Level): 249.6 mb (~10.6 km altitude). The top of the buoyant layer; storm tops may reach this level.
- PWAT (Precipitable Water): 33.80 mm. Total water vapor in the atmospheric column; a relatively moist profile.

Figure 11.2.2: Severe Thunderstorm Categorical Outlook

The map shows forecasted areas of thunderstorm activity and severe weather risk across the contiguous United States. Risk categories range from general (non-severe) thunderstorms to high-end severe thunderstorm outbreaks.

Geographic Scope:

The map includes all 48 contiguous U.S. states. Individual states are outlined, and risk areas are superimposed as enclosed shapes. A star symbol marks a specific location within a region of elevated severe risk, centered in eastern Nebraska and western Iowa.

Severe Weather Risk Categories, from lowest to highest risk, the outlook areas include:

1. TSTM (Thunderstorms):

- Broad, lightly shaded area covering much of the western U.S., parts of the Southeast, and southern Texas.
- Represents areas where general thunderstorms are expected, but no severe weather is forecast.

2. MRGL (Marginal Risk):

- A larger area inside the thunderstorm region covers parts of the Southwest, Southern Plains, and Midwest.
- Indicates isolated severe thunderstorms are possible but limited in duration and/or intensity.

3. SLGT (Slight Risk):

- Covers an arc from eastern Oklahoma and Texas northeast through the Ohio Valley and into the Mid-Atlantic.
- Indicates scattered severe storms possible, with isolated intense storms.

4. ENH (Enhanced Risk):

- Located in the central parts of Kansas, Missouri, and Illinois.
- Indicates numerous severe storms possible, some of which may be intense.

5. MDT (Moderate Risk):

- A smaller, more focused region inside the Enhanced Risk area, located in southeastern Nebraska and southwestern Iowa.
- Suggests widespread severe storms are likely, including long-lived and intense storms.

Figure 11.2.3: Severe Weather Reports

- The map outlines the United States with state boundaries shown.
- Severe weather reports are plotted as symbols across multiple states.
- A few symbols are marked with centers indicating particularly intense events:
- A center on a wind report symbol means wind gusts of 65 knots or higher
- A center on a hail symbol indicates hail 2 inches in diameter or greater

Report Summary:

- Total reports: 276
- Tornado reports: 26
- Wind reports: 100 (including 1 significant wind event)
- Hail reports: 150 (including 28 significant hail events)

Geographic Distribution:

- Tornado and large hail reports are heavily clustered in parts of the central U.S., especially across eastern Kansas, Missouri, and western Illinois.
- Wind damage reports are more widespread, extending from the southern Plains through the Midwest and into the Northeast.
- Additional scattered reports appear in the Mid-Atlantic, Southeast, and southern Great Plains, with isolated events reaching into Oklahoma, Texas, and Virginia.

Figure 11.3.1: Tornado Occurrence

This image is a dual-axis line-and-bar graph from the National Weather Service Storm Prediction Center, showing the daily and cumulative counts of U.S. tornadoes reported in 2019, compared with the historical average for 2005 through 2015.

Axes and Labels:

- The horizontal axis at the bottom represents the calendar year from January through December.
- The left vertical axis shows the daily tornado count, ranging from 0 to 80.
- The right vertical axis shows the running total of tornadoes (annual count), ranging from 0 to 1800.

Lines and Bars:

- A line shows the average annual trend in tornado counts from 2005 to 2015. This line gradually increases throughout the year, ending at 1402 tornadoes on December 31.
- Another line shows the 2019 cumulative tornado count, which rises more steeply than the average and ends at 1676 tornadoes, surpassing the historical trend by over 270 tornadoes.

- Vertical bars represent the average number of tornadoes per day (from 2005 to 2015).
- Other vertical bars show the actual number of tornadoes reported per day in 2019. These vary widely, with significant spikes in April, May, and early June, with some days reaching 50 to 70 tornadoes.

Figure 11.3.2: Severe Weather Reports

This map shows filtered storm reports received on October 31, 2018, across the southeastern United States. It includes preliminary data for tornadoes, damaging wind events, and large hail.

Geographic Coverage:

- The map shows the contiguous United States with state borders outlined.
- Most storm reports are concentrated along the Gulf Coast, particularly in Louisiana, Mississippi, and Alabama, with scattered reports extending into Georgia and parts of Florida.

Storm Report Totals:

- Tornado reports: 63
- Symbol: Red triangles
- Wind reports: 198 total, including 1 high wind report (65 knots or greater)
- Hail reports: 0
- Total storm reports: 261
- A small asterisk on any dot indicates a significant event:
- For wind, that means gusts of 65 knots (75 mph) or greater.
- For hail, that would mean 2 inches in diameter or larger.

Clustering and Patterns:

- A notable concentration of dots is visible across southern Mississippi and Alabama, where multiple tornadoes and reports of wind damage have been filed.
- A dense cluster of wind reports is present along the central Gulf Coast, likely due to a line of severe thunderstorms.
- No hail reports are shown for this day.

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12: HURRICANES

Introduction

Hurricanes and tropical cyclones are the largest-scale single extreme weather events on Earth. A single hurricane can range in size from 50 to 1000 miles in width. Typhoon Tip, the largest tropical cyclone in history, had a wind diameter of 1,380 miles. It can also have wind speeds exceeding 200 miles per hour. Hurricane Patricia was the strongest tropical cyclone on record with maximum sustained winds of 215 mph! In a single 20-minute time period, a hurricane can release the same amount of energy as a 10-megaton nuclear bomb (about 700 times the amount of the bomb dropped on Hiroshima - NOAA). Unlike the comparatively smaller tornadoes, Hurricanes can affect large areas of land in a short amount of time, prompting large-scale evacuations in the most extreme cases. If you're a traveler, you want to know what parts of the world are prone to hurricanes, and when. If you live in a hurricane-prone area, you want to keep an eye on any storms present near your area, and if you're an insurance broker, you want to know what locations are prone to the worst damage caused by a hurricane. Because of this, accurate understanding and forecasting of hurricanes is a significant business in the United States and worldwide.

In 2018, Hurricane Michael underwent rapid intensification, transitioning from a relatively minor storm to a Category 5 hurricane—the highest level on the Saffir-Simpson hurricane intensity scale —in just a few hours (Figure 12.1). In this investigation, we will track and forecast Michael's path as it approaches the Florida Panhandle region.

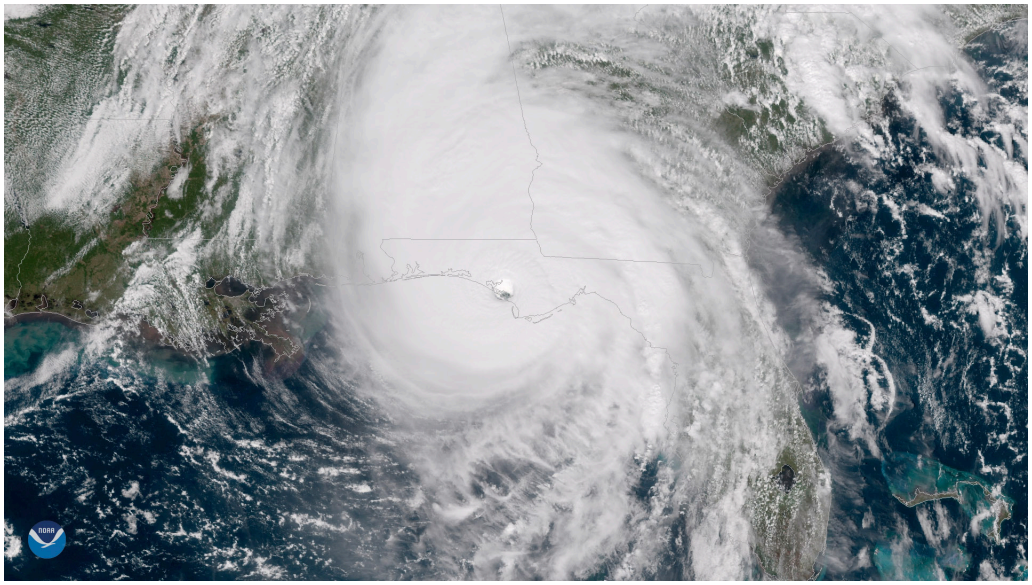


Figure 12.1: Hurricane Michael as it makes landfall in the Florida Panhandle. (Public Domain; Hurricane Michael via NOAA)

Learning Objectives

- Explain the different stages of tropical cyclone development, and discern the difference between a tropical depression, tropical storm, and hurricane.
- Determine the location, intensity, and forecast for a tropical cyclone using a National Hurricane Center tropical cyclone advisory product.
- Using the wind field of a tropical cyclone, determine where the strongest winds are located and how they relate to the cyclone's forward motion.

Navigational Note

Investigation 12 has 25 questions in total, and the list is continuous, carrying over from the first to the last subpages of the investigation.

12.1: Where and how do hurricanes form?
12.2: Tracking and forecasting hurricanes
12.3: Air pressure vs. intensity for Hurricane Michael
12.4: Accessible Descriptions

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12.1: Where and how do hurricanes form?

Hurricane tracks and intensities

Figure 12.1.1 shows the tracks and intensities of all tropical cyclones on record. While the map may seem overwhelming, the main focus is on identifying the areas where colored lines, indicating the presence of a tropical cyclone at one time, are present. Therefore, focus on the areas where these colored lines are present.

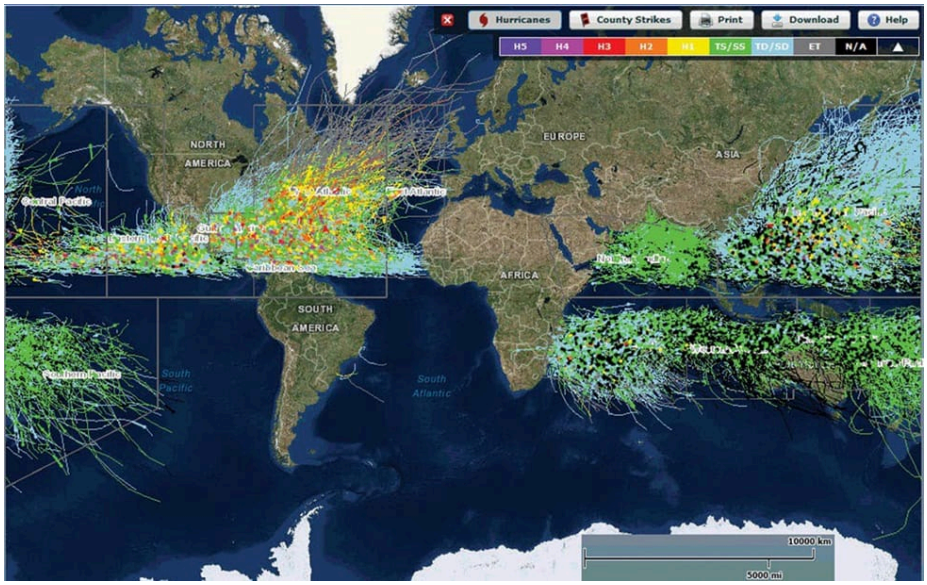


Figure 12.1.1: Map of Tropical Cyclone Paths and Occurrences. (Public Domain; via NOAA Coastal Services). Alternative description of the image.

Tropical cyclones have historically formed across multiple ocean basins, with the highest concentration in the Atlantic, Caribbean, Gulf of Mexico, and western Pacific. The tracks illustrate how storms often cluster in warm, tropical regions and can travel across large portions of the ocean. Figure 12.1.1 also shows fewer storms in the South Atlantic and eastern South Pacific, highlighting that those areas rarely experience cyclones.

1. Most tropical cyclones form in and near the tropics (near the equator), where there is plenty of _____.
   a. dry air
   b. cold air
   c. heat and moisture
2. Tropical cyclones are common in almost every ocean basin, except for
   a. The North Atlantic Ocean
   b. The South Atlantic Ocean
   c. The Eastern South Pacific Ocean (near South America)
   d. b & c only.
3. While many of these storms form in the tropics they _____ cross the equator and into the other hemisphere.
   a. always
   b. never
4. This is because on the equator the _____ becomes zero, preventing air from “spinning” in cyclonic motion.
   a. Frictional Force
   b. Coriolis Force
   c. Gravitational Force

In addition to the ingredients mentioned in question 1, hurricanes need two more key ingredients in order to form:

- **Warm Ocean Waters (80°F or higher):** These are found along the east coasts of continents like North America, where warm

ocean waters are carried from the equator towards the poles. On the west coasts of continents, cold ocean waters travel from the poles to the equator.
- **Low Vertical Wind Shear:** This occurs when winds change direction or speed with height. Vertical wind shear helps create tornadoes, but it shears off hurricanes, weakening them.

5. Notice from Figure 12.1.1 that California, on the west coast of North America, gets very few hurricanes. This is likely because:
   a. California is too far away from the equator
   b. California has too much wind shear (which forms tornadoes)
   c. The North Pacific Ocean along the California coastline is too cold to support hurricanes

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12.2: Tracking and forecasting hurricanes

Tracking hurricanes

Because of its cold ocean waters and the typical east-to-west tracks of tropical cyclones, California is spared most of the hazards produced by Hurricanes. This isn't the case across the entire East and Gulf Coasts of the United States. In early October 2018, the Florida Panhandle experienced the wrath of Hurricane Michael, which intensified rapidly prior to landfall. Figure 12.2.1 is an advisory map for Michael that includes its location, intensity, wind speed, and direction of travel, projected path and intensity, and any watches or warnings issued for the storm. This advisory was issued at 7 pm Central Daylight Time on Sunday, October 7, 2018.

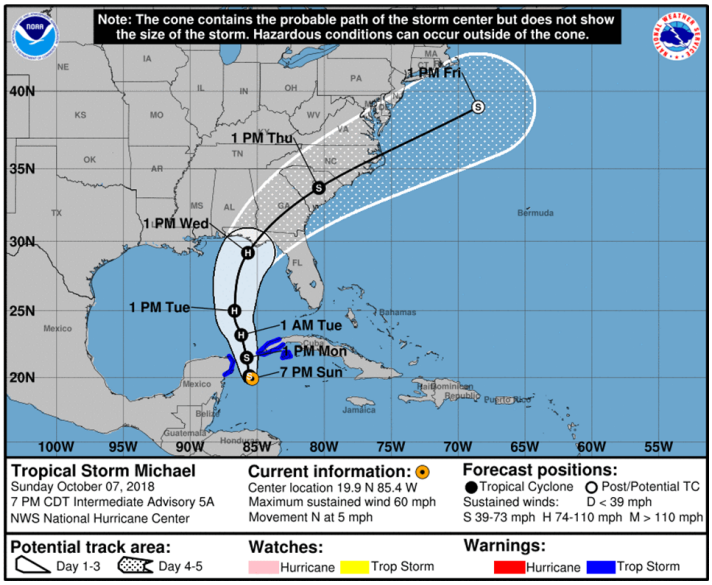


Figure 12.2.1: Advisory Map of Michael issued at 7 pm CDT on Sunday, October 7, 2018. (Public Domain; Hurricane Michael Archive via National Hurricane Center). Alternative description of the image.

6. At the time of this advisory (Figure 12.2.1), Michael was a:
   a. Tropical Depression (D)
   b. Tropical Storm (S)
   c. Hurricane (H)
   d. Major Hurricane (M)

The scale used to rate tropical cyclones is the Saffir-Simpson scale, which classifies storms by current wind speed. The list of classifications are provided in Table 12.2.1.

Table 12.2.1: Tropical cyclone intensities according to the Saffir-Simpson hurricane scale.

Classification	Wind Speed
Tropical Depression	Below 39 mph
Tropical Storm	39-73 mph
Category 1 Hurricane	74-95 mph

Category 2 Hurricane	96-110 mph
Category 3 Major Hurricane	111-129 mph
Category 4 Major Hurricane	130-156 mph
Category 5 Major Hurricane	Above 156 mph

7. The storm was located (the orange circle with the black dot in the middle):
   a. In the Western Gulf of Mexico
   b. Just off the coast of Florida
   c. Between the Yucatan Peninsula and Cuba
   d. Near Antarctica
8. The blue outlining on the coastlines mentioned in Figure 12.2.1 indicates that those regions were under a _____ .
   a. Tropical Storm Watch
   b. Tropical Storm Warning
   c. Hurricane Watch
   d. Hurricane Warning

Watches and Warnings are issued by local governments (in the United States, the National Hurricane Center is responsible for issuing watches) based on the following criteria in Table 12.2.2.

Table 12.2.2: Different tropical cyclone advisories and what they mean.

Advisory Type	**What it means**
Tropical Storm Watch	Tropical Storm Conditions Possible within 48 hours
Tropical Storm Warning	Tropical Storm Conditions Expected within 36 hours
Hurricane Watch	Hurricane Conditions Possible within 48 hours
Hurricane Warning	Hurricane Conditions Expected within 36 hours

9. At 7 pm CDT on Sunday, October 7, 2019 (Figure 12.2.1), the storm was _____ from striking the U.S. Gulf Coast. Therefore, watches and warnings could not yet be issued.
   a. Less than 36 hours away
   b. Between 36 and 48 hours away
   c. More than 48 hours away
10. At 7 pm CDT on Sunday, October 7, 2019, Michael was forecast to ___ on Wednesday:
   a. Hit Texas as a Tropical Storm
   b. Hit Florida as a Hurricane
   c. Completely dissipate (die off)
   d. Hit Florida as a Major Hurricane

Let's move forward in time to Michael's forecast position and intensity at 1 am on Tuesday, as shown in Figure 12.2.1. The location is shown by a big black dot with an "H" in the middle. Figure 12.2.2 is the advisory issued at 1 am on Tuesday, October 9, 2018.

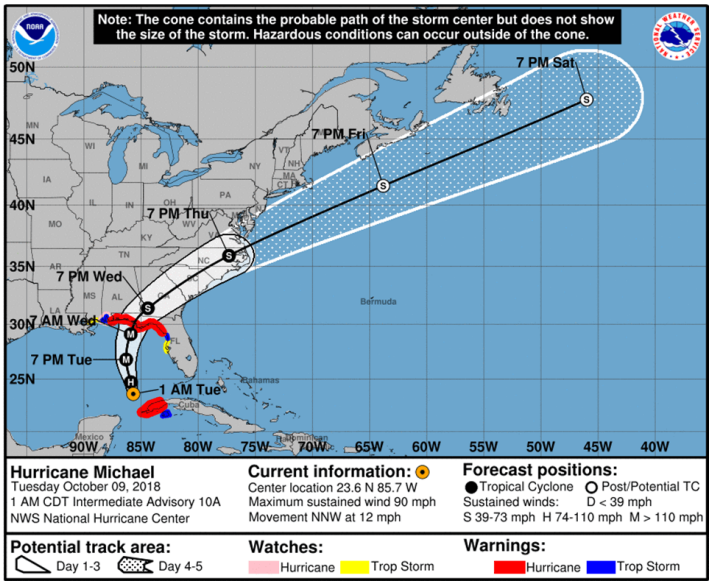


Figure 12.2.2: 1 am CDT Advisory for Michael on October 9, 2018. (Public Domain; Hurricane Michael Archive via National Hurricane Center). Alternative description of image.

11. By the time of Figure 12.2.2, Michael had:
    a. Weakened into a Tropical Depression
    b. Remained a Tropical Storm
    c. Strengthened into a Hurricane
    d. Strengthened into a Major Hurricane (to check, look at the wind speed).
12. It's location at the time of Figure 12.2.2 was _____ from the forecast location at 7pm on Sunday, October 7, 2018 (Figure 12.2.1).
    a. Within a few degrees of longitude and latitude
    b. Many degrees of longitude and latitude
13. At this point, ____ have been issued for parts of the United States, particularly Florida and Alabama.
    a. Hurricane Warnings
    b. Tropical Storm Warnings
    c. Tropical Storm Watches
    d. All of these
14. As of this time, Michael was expected to strike the Florida Panhandle as a:
    a. Tropical Storm
    b. Hurricane
    c. Major Hurricane

Let's move on to Figure 12.2.3, the 7 am CDT Advisory for Wednesday, October 10, 2018, issued just hours before Michael made landfall.

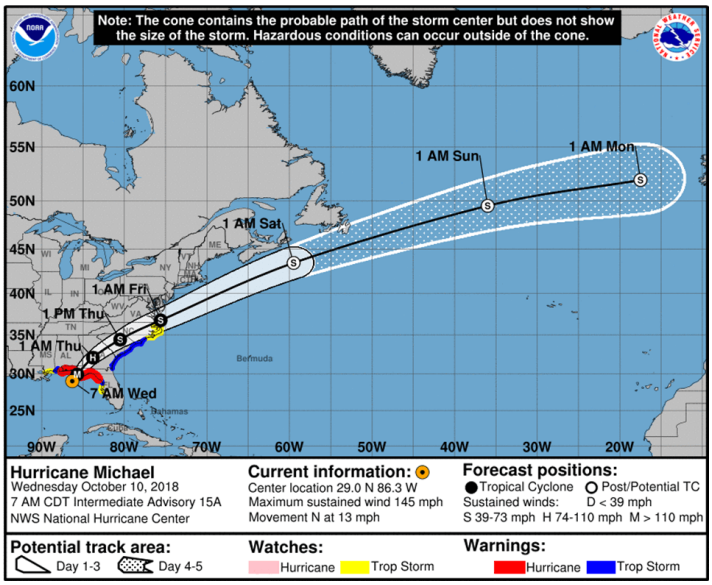


Figure 12.2.3: 7 am CDT Advisory map for Michael on Wednesday, October 10, 2018. (Public Domain; Hurricane Michael Archives via National Hurricane Center). Alternative description of image.

15. At the time of Figure 12.2.3, Michael _____ intensify into a Major Hurricane, as was forecasted in Figure 12.2.2 (Hint: Check the current wind speed.)
    a. did
    b. did not
16. At the time, Michael was a _____ hurricane (refer to table 12.2.1 for classification).
    a. Category 1
    b. Category 2
    c. Category 3
    d. Category 4
17. After making landfall, Michael was forecast to:
    a. Travel west and strike Texas as a Major Hurricane
    b. Travel northeast and gradually weaken
    c. Remain stationary near the Florida Coastline as a Major Hurricane

Any time an active storm is present, you can visit the National Weather Service's National Hurricane Center (NHC) webpage, which provides a map of current storms and a plethora of information about the current and forecast position and intensity of hurricanes. Hurricane outlooks from prior storms can be retrieved from the archive page, accessible via the Archive link on the NHC homepage.

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12.3: Air pressure vs. intensity for Hurricane Michael

Winds and air pressure in a hurricane

The primary cause of a hurricane's intense winds is changes in the minimum surface air pressure in the eye of the storm. As the minimum surface pressure declines, the pressure difference between the hurricane's center and its periphery increases. Recall from Investigation 7 that a bigger difference in pressure results in a stronger pressure gradient force, hence a stronger wind. As the minimum central pressure within Hurricane Michael decreases, wind speeds should naturally increase. We can investigate both Michael's minimum central pressure and wind speed to highlight this. Figure 12.3.1 shows maximum sustained wind speeds (blue line, left Y axis) and air pressure (orange line, right Y axis) vs. time (UTC).

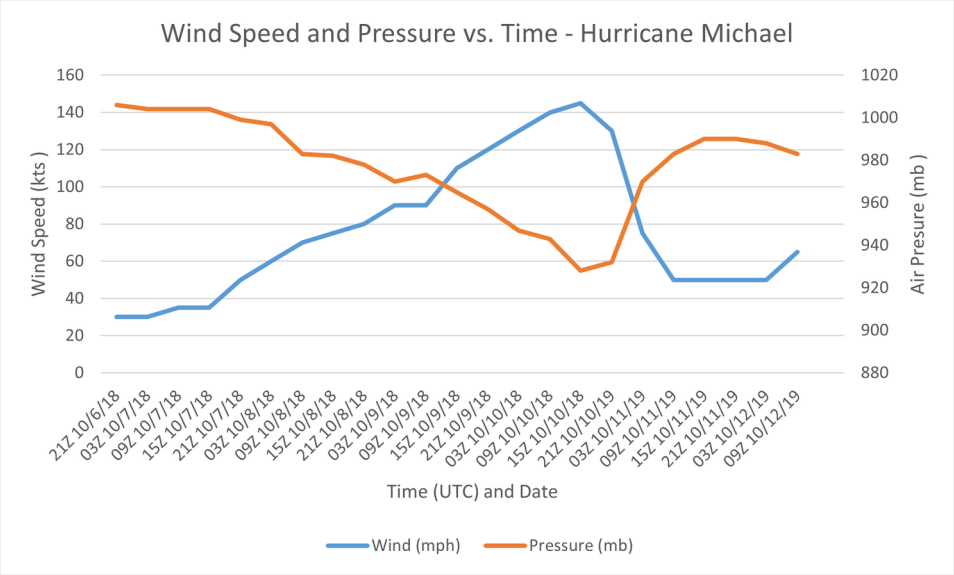


Figure 12.3.1: Plot of air pressure and wind versus time for Hurricane Michael. (Public Domain; Alicia Mullens). Alternative description of the image.

18. Between 21Z on October 6th and 15Z on October 10th, the minimum air pressure of Michael (the orange line) generally:
    a. Increased
    b. Declined
19. On the other hand, during the same time period, maximum wind speeds in the storm generally:
    a. Increased
    b. Declined
20. After 15Z on October 10th, the air pressure:
    a. Increased
    b. Stayed the same
    c. Decreased
21. During the same period, the maximum wind speeds in the storm:
    a. Increased
    b. Stayed the same
    c. Decreased
22. Based on this information, we can say that, in general, as air pressure declines
    a. Wind speed increases
    b. Wind speed also decreases
23. The time (15Z on October 10th) from the previous three questions is approximately 10 am on October 10th, which _____ with the time that Michael was forecast to make landfall in Florida.
    a. coincides
    b. does not coincide
24. Thus, the weakening of Hurricane Michael was likely caused by:

a. Making landfall and losing access to warm ocean waters
b. A sudden increase in wind shear
c. Neither of these

25. The weakening was:
a. Faster than the strengthening
b. Slower than the strengthening.

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12.4: Accessible Descriptions

Figure 12.1.1: Tracks of all tropical cyclones on record.

Map-based tool showing that tropical cyclones have historically formed across multiple ocean basins, with the highest concentration in the Atlantic, Caribbean, Gulf of Mexico, and western Pacific. The tracks illustrate how storms often cluster in warm, tropical regions and can travel across large portions of the ocean. The map also shows fewer storms in the South Atlantic and eastern South Pacific, highlighting that those areas rarely experience cyclones. The tool includes filters for storm categories, options for printing and downloading, and labels for major ocean basins and continents.

Figure 12.2.1: Michael advisory at 7pm CDT on October 7, 2018.

This forecast product was issued by the National Hurricane Center on Sunday, October 7, 2018, at 7 PM CDT for Tropical Storm Michael.

- Current storm details: At issuance, the center of Michael was located at 19.9°N, 85.4°W with maximum sustained winds of 60 miles per hour. The storm was moving north at 5 miles per hour.
- Forecast track and timing:
  - By late Sunday night and Monday, the system was expected to move northward over the northwestern Caribbean and strengthen.
  - By Tuesday afternoon, Michael was forecast to approach the Gulf Coast as a hurricane.
  - By Wednesday and Thursday, the storm was predicted to track inland across parts of the southeastern United States.
  - By Friday, the system was expected to move off the U.S. East Coast and into the Atlantic Ocean.
- Intensity forecast: The advisory indicated that Michael would strengthen from a tropical storm into a hurricane before reaching land, with sustained winds projected to exceed 74 miles per hour.
- Hazard notes: The forecast emphasized that the cone represents the probable path of the storm's center but does not account for the full size of the system. Hazardous conditions such as wind, rain, and storm surge could extend beyond the cone.
- Watches and warnings: At the time of the forecast, both tropical storm and hurricane watches and warnings had been issued for parts of the affected region, alerting coastal and nearby inland areas to prepare for possible impacts.

Figure 12.2.2: Michael advisory at 1am CDT on October 9, 2018.

This advisory was issued by the National Hurricane Center early on Tuesday, October 9, 2018, for Hurricane Michael.

- Current storm details: At the time of issuance, the storm center was located at 23.6°N, 85.7°W with maximum sustained winds of 90 miles per hour. Michael was moving north-northwest at 12 miles per hour.
- Forecast track and timing:
  - By Tuesday evening, Michael was predicted to intensify into a hurricane with maximum winds exceeding 110 miles per hour as it continued toward the Gulf Coast.
  - By Wednesday morning, the storm was expected to make landfall along the Gulf Coast as a major hurricane.
  - By Wednesday evening and Thursday, the storm center was projected to move inland across the southeastern United States, weakening but still bringing strong winds and heavy rainfall.
  - By Friday and Saturday, the system was forecast to move off the U.S. East Coast into the Atlantic Ocean.
- Intensity forecast: Michael was expected to strengthen from a hurricane into a major hurricane before landfall, producing winds well above 110 miles per hour.
- Hazard notes: The cone of uncertainty depicts the probable path of the storm's center, not its full size. Impacts such as wind, rainfall, and storm surge could extend beyond the cone.
- Watches and warnings: Hurricane and tropical storm watches and warnings were in effect for portions of the Gulf Coast at the time of this advisory, highlighting the potential for life-threatening conditions.

Figure 12.2.3: Michael advisory at 7am CDT on October 10, 2018.

This is an official forecast graphic for Hurricane Michael, issued by the National Hurricane Center at 7 AM Central Daylight Time on Wednesday, October 10, 2018 (Advisory 15A). The map outlines the projected path and intensity forecast for the storm, along with watch and warning areas and a shaded region known as the “cone of uncertainty.” A note clarifies that the cone shows only the probable track of the storm center, and hazardous weather can occur outside the cone.

Current Storm Information:

- Storm Name: Hurricane Michael
- Storm Type: Major Hurricane
- Advisory Time: 7 AM CDT
- Center Location: Latitude 29.0° North, Longitude 86.3° West
- Maximum Sustained Winds: 145 miles per hour
- Movement: North at 13 miles per hour

Watches and Warnings:

- Hurricane warnings are in effect for parts of the Gulf Coast, including areas near where landfall is expected.
- Tropical storm warnings extend inland and along portions of the southeastern U.S. coastline.
- These designations indicate where hurricane- and tropical-storm-force winds and storm surge are expected or possible within the next 12–48 hours.

Forecast Path and Timing:

- Landfall is expected later on Wednesday, with Michael still at major hurricane strength (wind speeds greater than 110 mph).
- By 1 AM Thursday, the storm is forecast to weaken slightly but remain a hurricane as it moves inland.
- By 1 PM Thursday, the system is expected to weaken to a tropical storm as it progresses further across the southeastern U.S.
- By 1 AM Friday, the storm is forecast to move off the East Coast, continuing as a tropical storm.
- Between Saturday and Monday, the system is forecast to transition to a post-tropical cyclone as it moves over the open Atlantic Ocean, away from North America.

Each forecast position along the track includes a symbol to indicate the predicted intensity of the storm at that point:

- M = Major hurricane (>110 mph winds)
- H = Hurricane (74–110 mph winds)
- S = Tropical Storm (39–73 mph winds)
- D = Tropical Depression (<39 mph winds)
- O = Potential or post-tropical cyclone

The forecast cone expands over time, indicating increased uncertainty in the storm’s future position beyond the first 72 hours. Forecast points are labeled at 24-hour intervals up through 1 AM Monday, five days after the advisory issuance.

Figure 12.3.1: Air Pressure and Wind Speed graph for Hurricane Michael

This image is a time series graph showing how Hurricane Michael’s maximum sustained wind speed and minimum central pressure changed over time. The graph covers the period from October 6 to October 12, 2018, with time shown in Coordinated Universal Time (UTC).

The horizontal axis displays the date and time in regular intervals. The graph includes two separate sets of data:

- Wind speed, measured in miles per hour,
- Central pressure, measured in millibars (mb).

Wind speed values range from 0 to 160 mph, and pressure values range from 880 mb to 1020 mb.

Summary of the Data:

- In the early part of the timeline, wind speed remains low, around 30 mph, while central pressure is relatively high, above 1000 mb.
- Over the next couple of days, wind speed increases steadily, reaching a peak of over 140 mph around October 10. At the same time, central pressure drops to below 925 mb.
- This period of increasing wind and decreasing pressure represents the rapid intensification phase of Hurricane Michael.
- Following the peak, wind speed gradually decreases and pressure increases, marking the weakening phase of the storm as it moves inland or loses organization.
- By the end of the timeline, wind speed falls to around 60–70 mph, and pressure returns to values near 980–990 mb.

The data shows a clear inverse relationship between wind speed and central pressure: as pressure decreases, wind increases, which is typical behavior for strengthening tropical cyclones.

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