CLOUDS

TEACHER'S GUIDE

Project ATMOSPHERE

This guide is one of a series produced by Project ATMOSPHERE, an initiative of the American Meteorological Society. Project ATMOSPHERE has created and trained a network of resource agents who provide nationwide leadership in precollege atmospheric environment education. To support these agents in their teacher training, Project ATMOSPHERE develops and produces teacher's guides and other educational materials.

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Foreword

This guide has been prepared to introduce fundamental understandings about the guide topic. This guide is organized as follows:

Introduction

This is a narrative summary of background information to introduce the topic.

Basic Understandings

Basic understandings are statements of principles, concepts, and information. The basic understandings represent material to be mastered by the learner, and can be especially helpful in devising learning activities in writing learning objectives and test items. They are numbered so they can be keyed with activities, objectives and test items.

Activities

These are related investigations. Each activity typically provides learning objectives, directions useful for presenting and completing the activity and questions designed to reinforce the learning objectives.

Information Sources

A brief list of references related to the guide topic is given for further study.

Introduction

Clouds are an ever-present feature of Earth's atmosphere. Everyday, around the world, many types of clouds are seen above our heads. We often look at these clouds and try to imagine the shapes and figures they resemble. But clouds tell us much more. They are visible signatures of the motion and conditions of the air in which they exist.

Clouds consist of tiny droplets or liquid water or ice crystals. Because these particles are so small, even weak swirls of air movement can keep them suspended indefinitely. It is the multitude of tiny water particles, whether liquid or ice, that interacts with rays of light to make clouds visible.

Water Vapor and Clouds

If you have ever been in a fog (literally) or have seen your breath on a cold day, or perhaps, flown in an airplane through the clouds, you have seen clouds first hand. To make a cloud, air needs only to be cooled to saturation and beyond. What does this mean?

All air contains water vapor although the amount can range widely. But there are limits to the maximum amount of water vapor that can be in air. Temperature is the factor that is best related to the maximum amount of water vapor that can be present. Usually the water vapor amounts in air are less that this amount. When this is the case, we describe the air as being *unsaturated*. If we add more vapor to such air, we could reach the maximum for the temperature. This air would then be *saturated*. More commonly in the atmosphere, saturated conditions are achieved by the cooling of air. This occurs because the capacity to hold water vapor decreases as temperature decreases. Consequently, cooling will eventually reduce the water-vapor capacity until it is equal to the amount of water vapor present in the volume. The temperature at which saturation is achieved by cooling is called the *dewpoint*.

Most clouds are produced by the cooling of air that, for one reason or another, moves upward in the atmosphere. The cooling accompanies the expansion that occurs when rising air is subjected to the lower air pressures at higher altitudes. As air moves upward, perhaps lifted by a weather frontal surface, by flow up a mountainside or simply solar heating of the ground below, the parcel of air will encounter the lower pressures and expand. This expansion cools the unsaturated air by 10 Celsius degrees for each kilometer of rise (5.5 F° per 1000 ft.). With cooling comes the lower capacity for vapor. Continued cooling will eventually cause saturation and begin the condensation of cloud particles. With condensation is the release of latent heat to the air. This heating offsets some of the cooling by expansion, decreasing the cooling rate of rising air.

Air sinking through the atmosphere is compressed and warmed. Unsaturated air warms 10 Celsius degrees for each kilometer the air descends. Sinking air in clouds warms at a lower rate as cloud particles evaporate away. Clouds can, and often do, disappear entirely this way.

Cloud Formation

The actual details of cloud formation are quite complex. There must exist particles, called condensation nuclei, on which the water can condense. There are almost always enough particles including sea salt, smoke, and automobile exhaust to act as condensation nuclei. Then, rising motions must be sufficiently persistent to continually supply excess vapor to growing droplets.

Upward motions in air may be the consequence of air flow over rising terrain, by passage of a weather front, or from local heating of air by warm surfaces. If unstable atmospheric conditions exist, upward motion will be accelerated. Once condensation begins, the release of heat by the forming droplets will also help the air to continue rising. Persistent lifting may even reach temperatures cold enough to cause ice crystals to form.

Convection and Clouds

Sunlight passes through the atmosphere to arrive at Earth's surface. Much of this energy is absorbed to warm the surface. The air immediately above the heated surface is warmed by direct contact in a transfer of energy called *conduction*. This heated air expands to become less dense than the cooled air above. Variations in surface heating and other factors result in surrounding cooler, denser air pushing in and forcing the lighter air up. In this way the warm air is carried upward. This motion of the air, resulting in the transport and mixing of its properties, is called *convection*. Convection is a major transport process for heat energy once it is in the atmosphere. This warm air also serves as the carrier of water vapor from one place to another in the atmosphere.

Rising currents of warm air, called *thermals*, are produced by solar heating through out the year but are especially strong during the spring through autumn months. Soaring birds and sailplane pilots seek these currents to gain altitude for long glides across the countryside. If the rising air remains intact and warmer than its surroundings, thermals may cool sufficiently to produce saturated air and make their presence known by producing cumulus clouds.

Clouds and Air Motions

The resulting shapes, numbers, sizes and motion of clouds give clues to what the invisible air is doing. While rising unsaturated air is cooling at the 10 C° per kilometer rate (or at a lower rate within a saturated cloud), the surrounding air has temperatures, too. A rising air parcel or cloud may be warmer or cooler than its surroundings. When cooler, it is “heavier” than surrounding air and tends to sink back to lower elevations – it is *stable* air.

Clouds formed in stable air tend to be long, flat layers, termed *stratus*-type clouds. The air flow is generally smooth and associated precipitation, if any, is light and steady. Stable air is likely to be present in fair weather. Those temperature patterns that make air stable can also lead to air pollution episodes. The flattened smoke plumes from chimneys and smoke stacks during stable conditions demonstrated why this is so.

On the other hand, rising air, though cooling, may remain warmer that the surrounding air and be “lighter”. Like an overheated hot-air balloon, the ascent of such air could speed up while causing turbulent swirls and eddies. These vertical motions, known as updrafts, are characteristic of *unstable* air. The resulting vertical, “lumpy” and “heaped” clouds are of *cumulus*-type. Clear weather can bring locally rising motions caused by solar heating to create fair-weather cumulus clouds while surrounding blue skies show adjacent sinking air motions. Wide-spread unstable conditions lead to dramatic thunderstorms and severe weather. Showers and rapidly changing conditions usually accompany these clouds.

Each general type of cloud has individual characteristics that portray its environment as well. On very windy days, the fair-weather cumulus clouds are torn and scattered, while calmer days produce the classic cotton puffs that seem to hang in the sky. Higher winds at upper atmospheric levels can cause cloud tops to tip from their bases. The most dramatic examples of these winds are the distant tops of thunderstorms that take on “anvil” shapes. Waves may even form on cloud tops or in bands of clouds as the air moves up and down in its travels or at different speeds in various layers.

The accompanying figure shows the basic classification of clouds determined by their appearance and, where possible, their process of formation. Cirrus-type clouds are always composed of ice crystals while most other cloud types are entirely liquid or a mix of ice crystals and droplets. The term “alto” refers to middle level clouds while “nimbus” means precipitation. Along with cumulus and stratus, the terms can be combined to describe ten general cloud forms. For additional photos and descriptions, see http://www.nws.noaa.gov/os/brochures/cloudchart.pdf.

Clouds and Precipitation

Clouds are necessary if precipitation is to occur, but not all clouds produce rain or snow. In fact, precipitation is a relatively rare event considering clouds are so common. For precipitation to occur, conditions within a cloud must include sufficient rising motion to create adequate condensation. Additionally, there must be enough water vapor fed into the cloud to sustain growth. Processes must operate which, on a massive scale, bring together the numbers of cloud particles to make precipitation happen. On average, one million cloud droplets have to be brought together to form one typical raindrop! Once grown, the raindrops or ice crystals must be heavy enough to overcome the cloud updraft to fall earthward. Then, they must survive evaporation as they drop to the surface.

In the United States, clouds year-round generally form first as water droplets in rising air motions. The more water vapor in the air, the sooner the air is cooled to saturation and the more moisture available for droplet growth. Continued rising and cooling will condense more water, but ice crystals are usually needed to initiate precipitation. At freezing temperatures where ice and liquid droplets co-exist, the crystals grow faster than the droplets from surrounding vapor. Ice crystals soon collide, with each other or with droplets that freeze on them, causing further enlargement. The large ice particles that form may more easily overcome the cloud's updrafts than smaller liquid drops. The large water vapor amount in summer thunderstorms, combined with the strong updrafts, may produce large ice particles that finally plummet to earth as hailstones.

The form of precipitation that arrives at ground level is closely related to atmospheric temperatures. With completely freezing temperatures from the surface upward, precipitation reaches earth as *snow*. The same beginning ice particles melt in warmer air and become *rain*. Seasons with surface temperatures hovering around the freezing point bring combination of precipitation types, some of which can be especially hazardous. Snow may fall to melt into rain and be refrozen to *ice pellets* or *sleet*. However, the same snow to rain may cool to freezing temperatures, remaining liquid while falling until solidifying on surface features as *freezing rain*.

Severe Weather

It is from late spring to early summer when most severe weather outbreaks occur. As the march towards mid-summer progresses, the occurrence of severe weather moves northward. The National Oceanic and Atmospheric Administration's (NOAA) Storm Prediction Center (SPC) in Norman, Oklahoma, keeps an eye on the stability conditions across the country and issues *watches* when conditions for severe weather are predicted. Local NOAA National Weather Service offices issue *warnings* to the public when the severe weather actually does occur or is imminent. Severe weather can include severe thunderstorms with their frequent lightning, heavy rain, strong winds (greater than 50 knots or 56 mph) hail (over 1 in. diameter), and tornadoes. Tornado deaths are not uncommon and their property damage is many millions of dollars yearly. Lightning kills over one hundred people each year. Annually, hail produces several tens of millions of dollars of mainly crop and property damage. But the major severe weather threat is flash floods, a growing problem that kills more people and causes more damage than the other conditions during a typical year.

When hurricanes and winter storms are included, the United States is affected by more numbers and types of weather-related threats than ay other country in the world.

The ideal conditions for severe thunderstorms and tornadoes are produced when the lowest few kilometers of the atmosphere are warm and humid. The warm, humid air may arise from increasingly strong solar heating and ground evaporation or by northward flow from the Gulf of Mexico caused by large-scale weather patterns. A few kilometers above the surface cool, dry air is flowing across the Rocky Mountains. Often air near the ground is further divided by the humid warm flow from the Gulf of Mexico encountering an equally warm but drier air flow from western Texas and Mexico. As the day progresses, the air at the ground is warmed and rises, the cooling within the cumulus cloud formations becomes not as cold as the surrounding Rocky Mountain air stream and the warmer clouds become unstable, rising a dozen or more kilometers into the sky almost explosively. The massive thunderheads produce heavy rains, lightning and strong gusty winds. With enough instability and proper wind patterns within the storms, tornadoes are spawned. Another severe weather outbreak has come to the central U.S.

Cloud Types

High Clouds

Cirrus (Ci)

Cirrocumulus (Cc)

Cirrostratus (Cs)

Middle Clouds

Altocumulus (Ac)

Altostratus (As)

Low Clouds

Stratocumulus (Sc)

Stratus (St)

Nimbostratus (Ns)

Clouds of Vertical Development

Cumulus (Cu)

Cumulonimbus (Cb)

Auxiliary Cloud Features

Mammatus

Lenticular, wave clouds

Wall cloud, tornado

Pileus (cap cloud)

Basic Understandings

Clouds

1. Clouds are collections of tiny water droplets or ice crystals in the atmosphere in concentrations great enough to be seen.

2. Clouds present visible signs of air motions.

3. Clouds are essential atmospheric components of the water cycle, producing the rain and snow that return water to Earth's surface.

Cloud Formation

4. Clouds form when air is cooled to temperatures at which some of the contained water vapor condenses to liquid or ice. This happens because temperature drops are accompanied by reduction in the capacity of a volume to hold water vapor.

5. Most cloud formation and growth results from the cooling that occurs due to the expansion of rising air.

6. Cloud particles form as water vapor condenses on salt, dust and other minute particles in the atmosphere.

7. Clouds can be composed of liquid or frozen particles, or both. Clouds can contain liquid droplets through a broad range of freezing temperatures.

8. Fog is a cloud in contact with Earth's surface.

Air Motions and Temperatures

9. Rising air encounters lower atmospheric pressures. This allows expansion that results in the lowering of temperatures within the upward moving air.

10. Rising air, as long as it is not filled to capacity with water vapor, cools by expansion at the rate of 10 degrees Celsius for each kilometer gain in altitude.

11. Rising air, when filled to capacity with water vapor, cools at a lower rate than air that is not saturated with water vapor. The release of heat accompanying condensation in saturated rising air decreases the cooling rate.

12. Sinking air encounters greater air pressure and warms by compression. Warming leads to the evaporating away of any existing clouds.

Cloud Shapes and Air Motions

13. Cloud shapes are keys to determining atmospheric conditions and motions.

14. Generally, widespread, smooth, layered cloud forms are indicators of more horizontal than vertical air motions. They signal a *stable* atmosphere.

15. Air is *stable* when, if forced to rise, its cooling produces temperatures lower than those in surrounding air at the same levels. The uplifted air, being cooler, is denser than the air around it.

16. "Heaped" or "lumpy" clouds result during times when strong vertical motions exist in the atmosphere. They point to *unstable* atmospheric conditions that can mean stormy or severe weather.

17. Air is unstable when, if forced to rise, its cooling results in temperatures higher than those in surrounding air at the same elevations. The rising air, being relatively warmer and less dense, accelerates upward producing turbulent eddies and strong vertical movements.

18. Local surface heating on sunny days can produce "fair-weather" clouds with vertical development. The clouds, which form where air is rising, are separated by clear regions where air is sinking.

19. The tops of towering clouds lean downstream when winds aloft are faster than those below. Thunderstorm anvils are samples of these high-level wind signatures.

Clouds and Precipitation

20. Cloud particles must be greatly enlarged if they are to attain sizes large enough to fall as rain or snow. Typically, it takes close to a million cloud droplets to provide enough water for each raindrop.

21. Precipitation at middle and high latitudes ordinarily begins in clouds where ice crystals and supercooled water droplets co-exist. At temperatures below 0 degree Celsius, ice crystals grow at the expense of surrounding water droplets. As the crystals enlarge, they fall faster through the cloud.

22. Ice crystals falling through a cloud can grow by adhering to other crystals or by accumulating supercooled droplets that freeze to them. These cloud particles may grow large enough to overcome the rising air currents and fall

earthward as precipitation. When freezing temperatures exist down to earth's surface, falling ice crystals arrive at ground level as snow. Warmer temperatures beneath the cloud melt the ice to raindrops. Conditions occasionally occur when raindrops fall into near-surface layers of freezing air, producing hazardous freezing rain.

23. Rain can start in clouds whose temperatures are entirely above freezing. Here droplets, initially of different sizes, fall at different rates, causing larger droplets to capture smaller ones.

24. Variations in raindrop sizes can result from the motions within clouds. Larger drop are formed in strong updrafts that can hold them aloft longer while smaller drop are associated with weaker rising motions.

25. The heights of cloud bases infer humidity conditions and the likelihood of precipitation. Clouds with low bases form easily in humid air with precipitation being possible. High-based clouds mean drier air with precipitation reaching the ground being less likely.

26. Severe thunderstorms in unstable conditions can produce heavy rains with localized flooding, frequent lightning, hail, damaging winds and tornadoes.

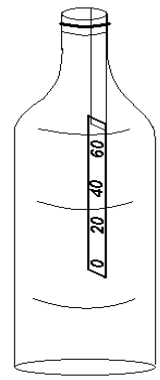
Activity: Clouds, Air Pressure and Temperature

Materials

A clean, clear, dry plastic 2-liter or larger beverage bottle with cap, thin liquid crystal temperature strip (available in aquarium supply stores), tape. *****

Approach

Cut or tear a strip of transparent tape about 15 cm long. Attach one end to the temperature strip so the numbers can be seen. Hang the temperature strip in the middle of the bottle away from the sides and affix the other end to the opening of the bottle with just a small overhang outside of the opening. Screw the cap on tightly.



Objectives:
After completing this investigation, you should be able to:

- Describe how air temperature changes as air pressure changes.
- Make clouds appear and disappear.
- Explain how most clouds form in the atmosphere.

Method:
Examine the sealed bottle given to you. Stand the bottle up so the temperature strip inside can be read. Do not handle the bottle any more than necessary, so that its inside temperature will not be affected by the warmth of your hands.

Questions:

A. Air Pressure and Temperature Relationships

Read and record the temperature of the air inside the bottle as indicated by the temperature strip. Beginning temperature: __________ °F.

Place the bottle so about half extends beyond the edge of your desk or table. Standing and with one hand on each end, push down on both ends of the bottle so it bends in the middle and compresses the trapped air. Hold it this way to keep the air compressed while carefully watching the temperature strip. After half a minute or so, release the pressure by letting up on the bottle. Continue to carefully observe the temperature for at least a minute.
Final temperature: __________ °F.

1. What happened to the temperature as a result of the air being compressed?

2. When you released the bottle so the air inside was no longer being squeezed, what happened to the air temperature in the bottle?

3. State, in your own words, the relationship between changes in air pressure and temperature.

4. Air pressure decreases with an increase in altitude. This is because air pressure is determined by the weight of the overlying air. Consequently, air rising upward experiences lower pressure and expands. Based on your findings in (2) above, what must happen to the temperature of air rising through the atmosphere?

5. What happens to the temperature of air when it moves downward in the atmosphere? Explain your answer.

B. Making Clouds Appear and Disappear

Open the bottle and pour a few drops of water in it. Twist and turn the bottle to wet the inner surface. Cap tightly and let stand for a couple of minutes so enough water evaporates to saturate the air.

Lay the bottle on its side, open the bottle and push down to flatten the bottle about half its normal diameter. Have someone light a match, blow it out, and insert the smoking end into the bottle opening. Quickly release your pressure on the bottle so it returns to its rounded shape and the smoke from the extinguished match is drawn inside. Quickly cap the bottle tightly. The smoke was added to the air because atmospheric water vapor needs particles present on which to condense.

Now apply and release pressure on the bottle as before, keeping track of the temperature changes. Look very carefully in the bottle for any evidence of a cloud. It would be detected by a change in air visibility. If you cannot detect cloud, repeat the process of applying and releasing pressure until you do.

6. Did the cloud form when you applied pressure or when you released pressure? Did it form when temperatures rose or when they fell? Why?

7. Most clouds in the atmosphere form in the same basic way as the cloud in the bottle. In your own words, describe this process in the open atmosphere.

8. Once you have a cloud in the bottle, make the cloud disappear. What makes it disappear?

9. Most clouds in the atmosphere appear and disappear the way your bottle cloud did. State in your own words the temperature and pressure relationships that lead to cloud formation and, assuming no precipitation, cloud dissipation.

10. Based on this activity, what can you infer about vertical motions in the atmosphere where (a) it is cloudy and (b) it is clear?

11. Generally, High pressure areas in the atmosphere tend to be clear and Low pressure areas have clouds. What must be the vertical motions in these weather systems?

12. Examine a weather satellite picture, preferably today's, and point out broad areas where air is probably rising and those where air is likely to be sinking.

***** Pressure changes in the bottle may also be accomplished by using a device to keep the carbonation in opened soda bottles, termed "pump caps" or "fizz keepers" available from supermarkets.

Additional Activities

1. Keep a journal of cloud types and weather conditions over a period of a week. Make observations at least three times each day at intervals such as morning, afternoon and evening. You may wish to add photographs to your record. Can you relate the predominant cloud types seen to the weather conditions. Watch television weathercasts or call up weather charts on the Internet and note the passage of any fronts during this time. When were there convective-type clouds present, how do you know?

2. On a clear sunny day watch the development of cumulus clouds as the day goes on. If possible try to determine what types of ground the clouds form over. Additionally one might try to videotape short segments at regular intervals or make a movie and playback later as a study of cloud formation.

3. If you have episodes of fog, what were the conditions that preceded the fog? What changes occurred to cause the fog to dissipate? How do these conditions relate to cloud formation as described above?

4. Observe the turbulent motions that keep cloud droplets aloft by watching the specks of dust moving in a beam of sunlight through a window by viewing from the side, at right angles to the beam.

5. Watch convection currents set up in a pan of water put on a stove and heated. The water motions may be made more visible by adding pepper, tea leaves or other non-soluble specks.

6. Obtain a dry cleaning or other large, thin plastic bag. Tape any holes shut except the bottom opening with transparent tape. Tape a loop of thin wire around the opening inside the bag to keep the opening expanded. Use a hair dryer to fill the bag with hot air. How long does it take the bag to become buoyant? How high does the bag rise before falling again?

7. Make a Cartesian diver. A Cartesian diver operates because of buoyancy just as atmospheric vertical motions do. Fill a 2-liter, clear plastic soda bottle with water to within about 10 cm of the top. Take a small cylinder open at one end (such as a ballpoint pen cap) and fill partially with water. This diver must be just barely buoyant – that is, it must just barely float. Place it in the soda bottle and cap securely. When properly balanced, the diver will float to the top of the water. When the bottle is squeezed, the diver's air bubble will be compressed and be just small enough to cause the diver to sink to the bottom of the bottle. Releasing the pressure will allow the bubble to expand and the diver to rise to the top again.

Real World Applications

As mentioned in question 11 of the Activity, High pressure systems are generally tend to be clear and Low pressure systems have extensive clouds. The large scale circulations set up in these pressure systems involve broad areas of sinking air in High pressure and rising air in Low pressure (see the **Project ATMOSPHERE** guide on *Highs and Lows* for additional information). The types of vertical motions generated are similar to those you produced in the bottle activity of cloud formation. Can this pattern be seen in the atmosphere?

Figure 1 is the surface weather map for the coterminous U.S. for 18Z (2 pm EDT, 1 pm CDT, etc.) 8 October 2011. The map shows the locations of centers of expansive Highs and Lows by their lettered labels, H and L respectively. One High is located over the Virginia-Maryland-Delaware area. A strong Low is centered on the eastern Colorado border.

1. Based on these locations for the weather systems in Figure 1, one should expect:

   a. Clear skies over the eastern U.S.
   b. Clear skies over the central U.S.
   c. Cloudy skies over the eastern U.S.
   d. Cloudy skies over the central U.S.
   e. Both (a) and (b).
   f. Both (c) and (d).
   g. Both (a) and (d).
   h. Both (b) and (c).

Figure 2 is the visible satellite image for the coterminous U.S. for 1815Z 8 October 2011, essentially the same time as the Figure 1 map of weather system locations. On the Figure 2 satellite image note the location of the Hs and Ls from Figure 1. Bright white shadings denote clouds; small “bumpy” blobs are cumulus-type clouds and wispy feathered areas are cirrus-type clouds. The darker gray shadings are Earth’s surface with water bodies where sunlight is absorbed generally being darker than land where more sunlight can be reflected.

2. Is the large clear area in the eastern U.S. in the Figure 2 satellite view located where the High was analyzed on the Figure 1 weather map?

3. Is the broad cloudy area in the central U.S. in the Figure 2 satellite view generally located where the Low was analyzed on the Figure 1 weather map?

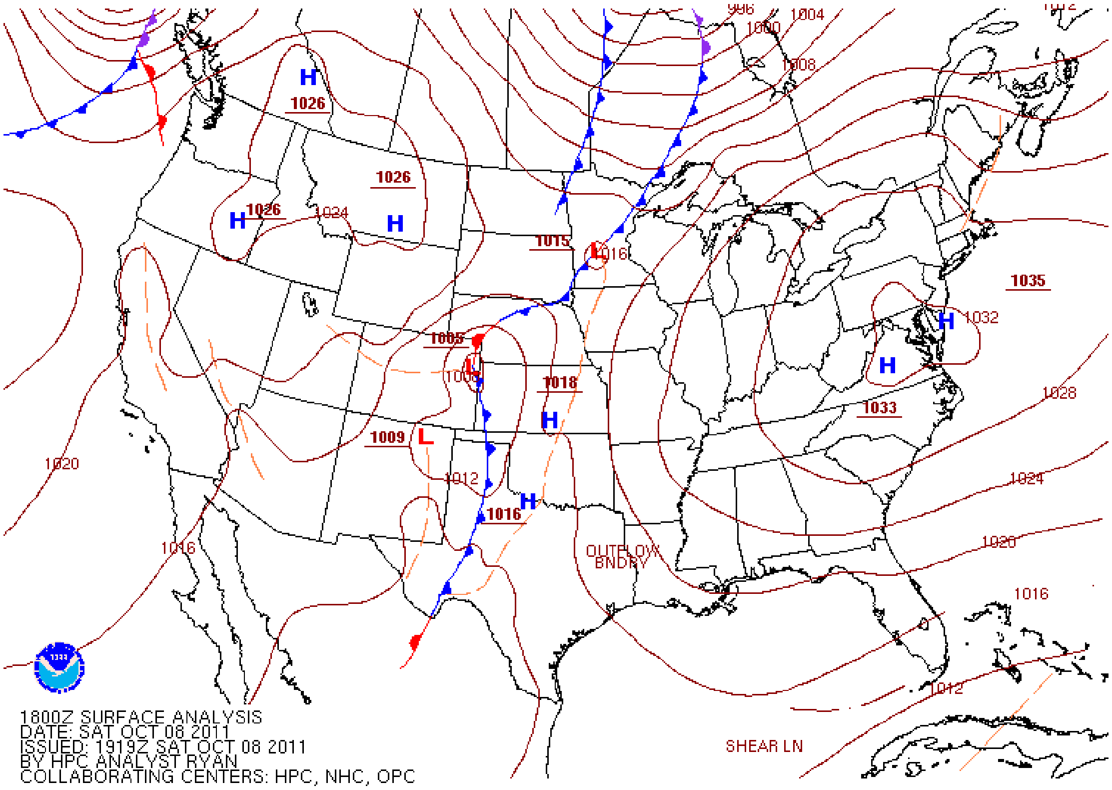


Figure 1. Map of surface weather pressure centers and fronts at 1800Z (2 PM EDT) 8 October 2011. [NOAA/HPC]

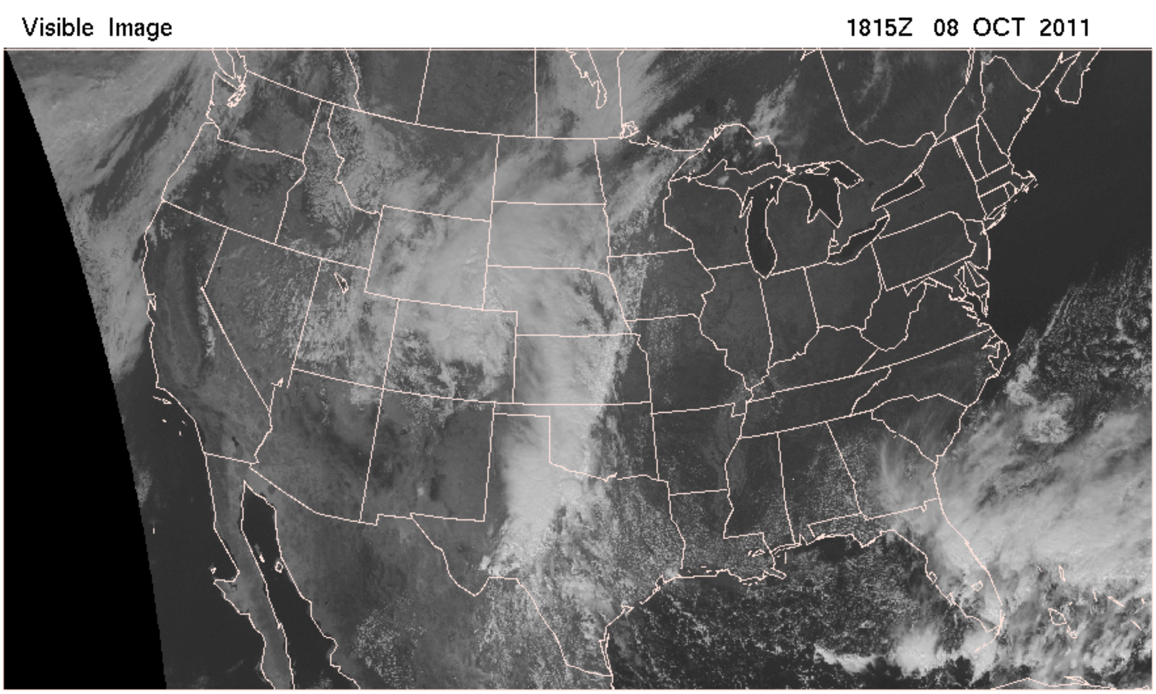


Figure 2. A visible satellite image of the coterminous U.S. at 1815Z (2:15 PM EDT) 8 October 2011 showing cloudy and clear areas. [NOAA/NCEP]

Information Sources

Books

Moran, Joseph M. Weather Studies: Introduction to Atmospheric Science, 5th Ed. Boston, MA: American Meteorological Society, 2012.

LeMone, Margaret. The Stories Clouds Tell. Boston, MA: American Meteorological Society Education Program, 2008. (*www.ametsoc.org/amsedu/AERA/ed_mats.html*)

Periodicals

Weatherwise. Bimonthly magazine written in association with the American Meteorological Society for the layperson. Weatherwise, 1319 Eighteenth St., NW, Washington, DC 20036.

USA Today. National newspaper with extensive weather page. Available at local newsstands and by subscription.

Radio and Television

NOAA Weather Radio. The voice of the National Weather Service and All Hazards Emergency Alert System. Local continuous broadcasts from over 1000 transmitting stations nationwide.

The Weather Channel. A continuous cable television program devoted to reporting weather. Includes frequent broadcast of local official National Weather Service forecasts.

Internet

DataStreme Atmosphere (*www.ametsoc.org/amsedu/dstreme/*). Atmospheric education distance-learning website of the AMS Education Program.

JetStream – Online School for Weather (*www.srh.noaa.gov/jetstream/*). Background weather information site from the National Weather Service.