JET STREAMS

TEACHER'S GUIDE

Project ATMOSPHERE

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For further information, and additional background on the American Meteorological Society's Education Program, please contact:

American Meteorological Society
Education Program
1200 New York Ave., NW, Ste. 500
Washington, DC 20005-3928
www.ametsoc.org/amsedu

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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: Jet Streams

As World War II was approaching its conclusion, the United States introduced the first high-altitude bomber plane called the B-29. It could fly at altitudes well above 20,000 feet (6.1 kilometers). When the B-29s were being put into service from a Pacific island base, two air force meteorologists were assigned the task of producing a wind forecast for aircraft operations at such altitudes.

To make their prediction, the meteorologists used primarily surface observations and what is known in meteorology as the “thermal wind” relationship. In plain language, this relationship implies “that if you stand with your back to the wind, and the air is colder to the left and warmer to the right, the wind will get stronger on your back as you ascend in the atmosphere.” Using this relationship, the meteorologists then predicted a 168-knot wind from the west. Their commending officer could not believe the estimate. However, on the next day, the B-29 pilots reported wind speeds of 170 knots from the west! The ***jet stream*** was discovered.

Actually atmospheric scientists had theorized the existence of jet streams at least as early as 1937. The bomber pilots just confirmed it. Now many television weathercasts mention the positions of jet streams and their impact on daily weather events.

Jet streams are relatively strong winds concentrated as narrow currents in the upper atmosphere. The polar-front jet stream is of special interest to meteorologists because of its association with the regions where warm and cold air masses come in contact and middle latitude storm systems evolve. The polar-front jet stream encircles the globe at altitudes between 6 and 8 miles (9 and 13 kilometers) above sea level in segments thousands of kilometers long, hundreds of kilometers wide, and several kilometers thick. It flows generally from west to east in great curving arcs. It is strongest in winter when core wind speeds are sometimes as high as 250 miles (400 kilometers) per hour.

Meteorologists study the polar-front jet stream as they forecast weather. Changes in it indicate changes in weather. The jet stream is also of importance to aviation, as the B-29 pilots quickly found out. Westbound high-altitude flight routes are planned to avoid the jet-stream head winds. Eastbound flights welcome the time-saving tail winds. However, the jet stream produces strong wind shears in some locations because of large changes in wind speeds over short vertical and horizontal distances. The resulting air turbulence can be very hazardous to aircraft.

The polar-front jet stream’s location is one of the most influential factors on the daily weather pattern across the United States.

Basic Understandings

Characteristics of the Polar-Front Jet Stream

1. Jet streams are relatively high speed west-to-east winds concentrated as narrow currents at altitudes of 6 to 9 miles (9 to 14 kilometers) above sea level. These meandering “rivers” of air can be traced around the globe in segments thousands of kilometers long, hundreds of kilometers wide and several kilometers thick.

2. Two high-altitude jet streams affect the weather of middle latitudes; they are the subtropical jet stream and the polar-front jet stream.

3. The subtropical jet stream is located between tropical and middle latitude atmospheric circulations. Although not clearly related to surface weather features, it sometimes reaches as far north as the southern United States. It is an important transporter of atmospheric moisture into storm systems.

4. The polar-front jet stream is associated with the boundary between higher latitude cold and lower latitude warm air, called the polar front. Because of its link to surface weather systems and features, the polar-front jet stream is of special interest to weather forecasters.

5. The polar-front jet stream is embedded in the general upper-air circulation in the middle latitudes where winds generally flow from west to east with broad north and south swings. As seen from above, these winds display a gigantic wavy pattern around the globe.

6. The maximum wind speeds in the polar-front jet stream can reach speeds as high as 250 miles (400 kilometers) per hour.

7. The average position of the polar-front jet stream changes seasonally. Its winter position tends to be at a lower altitude and at a lower latitude than during summer.

8. Because north-south temperature contrasts are greater in winter than summer, the polar-front jet stream winds are faster in winter than in summer.

9. Small segments of the polar-front jet stream where winds attain their highest speeds are known as jet streaks. Across the United States, one or two jet streaks are commonly present in the polar-front jet stream.

What Causes the Polar-Front Jet Stream?

10. Fundamental to the formation of the polar-front jet stream is the physical property that warm air is less dense than cold air when both are at the same pressure.

11. The polar-front represents the boundary between higher latitude cold air and lower latitude warm air. This temperature contrast extends from Earth's surface up to the polar-front jet stream altitude.

12. Air pressure is determined by the weight of overlying air. In the vicinity of the polar front, air pressure drops more rapidly with an increase in altitude in the more dense cold air than in the less dense warm air.

13. The effect of temperature on air density results in air pressure at any given altitude being higher on the warm (equatorward) side of the polar front than on the cold (poleward) side.

14. When cold and warm air reside side by side, the higher the altitude the greater the pressure difference is between the cold and warm air at the same altitude.

15. Across the polar front, at upper levels (including the jet stream altitude), horizontal pressure differences cause air to flow from the warm-air side of the front towards the cold-air side of the front.

16. Once air is in motion, it is deflected by Earth's rotation (called the Coriolis effect). Upper-level air flowing poleward from higher pressure towards lower pressure is deflected to the right in the Northern Hemisphere (or to the left in the Southern Hemisphere). The result is a jet stream flowing generally towards the east, parallel to, and above the polar front.

Relationships Between the Polar-Front Jet Stream and Our Weather

17. The polar-front jet stream exists where cold air and warm air masses are in contact. Hence, your weather is relatively cold when the polar-front jet stream is south of your location and relatively warm when the jet stream is north of your location.

18. The polar-front jet stream can promote the development of storms. Storms are most likely to develop under a jet streak.

19. As a component of the planetary-scale prevailing westerly circulation, the polar-front jet stream steers storms across the country. Hence, storms generally move from west to east.

Activity 1: The Polar-Front Jet Stream

The polar-front jet stream is like a high-speed river of air in the upper atmosphere. It separates warm and cold regions at Earth's surface. It may be several hundred miles across from north to south, 5,000 to 10,000 feet (1,500 to 3,000 meters) thick and at an altitude of 30,000 to 43,000 feet (9,000 to 13,000 meters). The polar-front jet stream generally flows from west to east, and is strongest in the winter when core wind speeds are sometimes as high as 250 miles (400 kilometers) per hour. Changes in the jet stream indicate changes in the circulation of the atmosphere and associated local weather.

Upon completing this activity, you should be able to:

- Determine the location of the polar-front jet stream based upon upper-atmosphere wind data.

- Describe influences of the polar-front jet stream on weather and aviation.

Materials

- pencil

Investigation

The highest upper-level wind speeds are frequently observed at altitudes of approximately 6 to 8 miles (9 to 13 kilometers) above sea level. **Figure 1** is an upper air chart displaying wind speeds and directions observed at 12Z (7 am EST) on 10 March 2011 at altitudes where the air pressure was 300 millibars. At map time, the actual altitudes at which the air pressure was 300 millibars varied from 29,320 to 31,290 feet (8940 to 9540 meters) above sea level. Upper-level data are routinely displayed on constant-pressure charts because of the usefulness of such charts to meteorologists. The data were acquired by tracking balloon-borne weather instruments, called radiosondes, which measure and transmit weather data as they rise through the atmosphere.

Wind information is depicted by "arrows" shot into locations on the map where radiosondes were launched. On the arrow, the straight line represents wind direction while the feathers represent wind speed. Winds are named for the direction <u>from which</u> they are blowing. For example in Figure 1, a <u>northwest</u> wind was reported at Minneapolis, Minnesota. Wind speed is reported in knots (1 knot equals 1.0 nautical mile per hour or 1.15 statute miles per hour); a full length feather represents 10 knots, a half feather stands for 5 knots, and a flag means 50 knots. The wind speed at Minneapolis, at 300 millibars was 70 knots from the northwest (flag plus two full feathers).

Figure 1. Map of 300-mb winds at 12Z 10 MAR 2011.

1. Look at the accompanying Figure 1. With a pencil, shade a small oval around each station where wind speeds are 60 knots or greater, such as San Francisco. Then shade the area between adjacent shaded stations where the wind speeds are also presumed to be 60 knots of more. Next draw lines along the northern and the southern boundaries to highlight the shaded area limits of the 60 knot or greater region. Finally, draw a heavy, smooth, curved arrow through the core of the shaded highest wind speeds. Add an arrow head to show wind direction.

2. The large arrow you drew on your map approximates the location of the existing polar-front jet stream across the United States. Now imagine that you are in a gondola attached to a helium-filled balloon that is located over central Washington State. Assuming your balloon stays at the 300-millibar level and travels with the air flow, draw your path as you travel across the country. Through what state or states are you likely to leave the United States?

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3. What is your approximate speed measured with respect to the surface of Earth?

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4. Even though the wind speed is 60 knots or greater, as measured relative to the ground, an anemometer attached to the gondola shows the wind to be almost calm. Explain why.

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5. Look at winds on either side of the jet. The winds on either side of the jet are **[(*__slower__*)(*__faster__*)]** than the jet stream winds and have **[(*__the same__*)(*__a different__*)]** direction.

6. The polar-front jet stream varies considerably in location and strength from time to time. Examples of this variation can be seen in Figures 1 and 2. Both report upper-air wind information at the levels where speeds were generally very high.

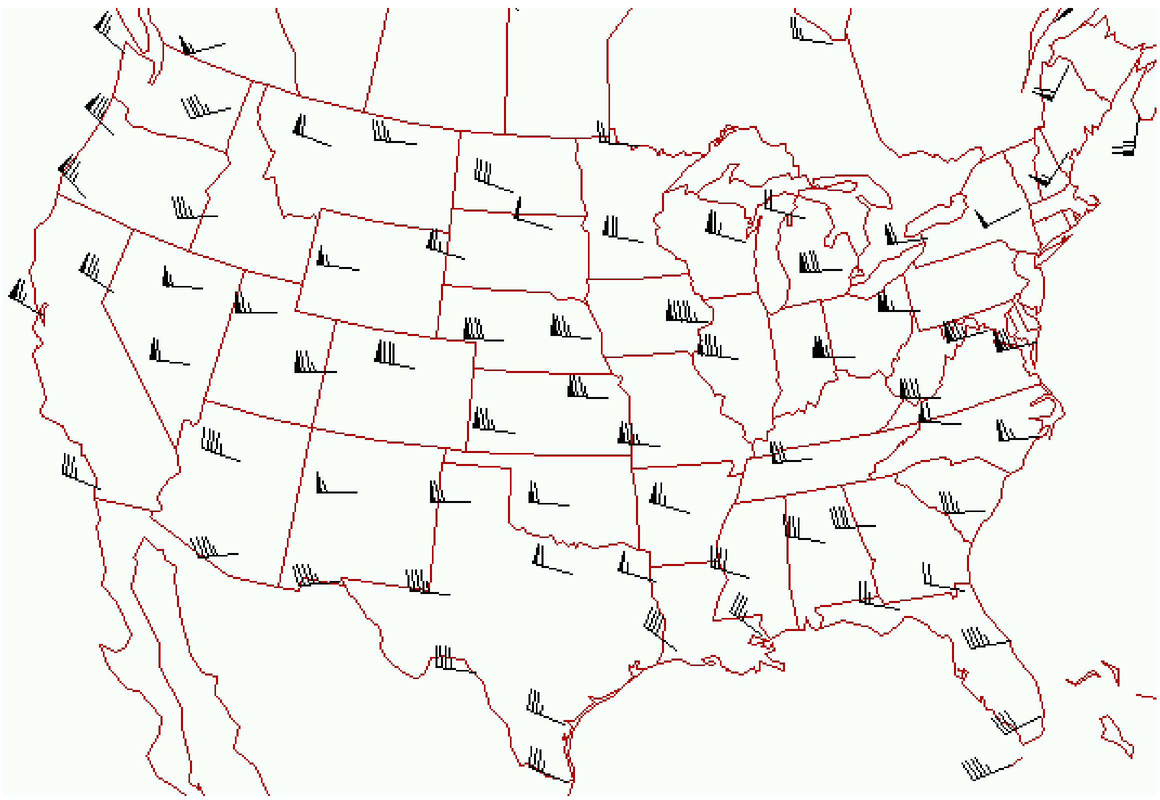
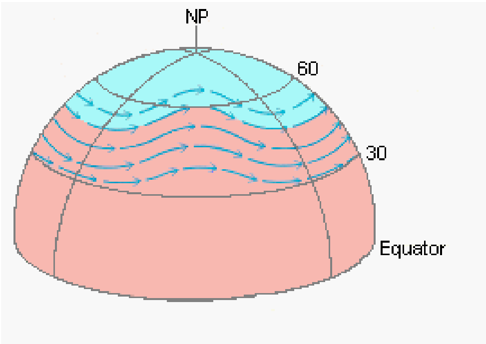


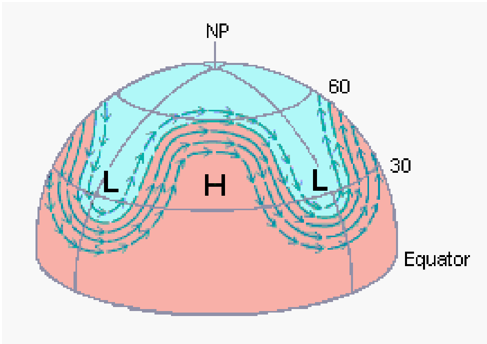
Figure 2. Map of 300-mb winds at 00Z 13 MAR 2011.

In **Figure 2** enclose the jet stream that existed at map time. As you did in Figure 1, lightly shade the enclosed area where winds are 60 knots or more and draw an arrow and arrow head to highlight the high-speed core of the jet stream winds.

7. The polar-front jet stream is like a “river” of high speed air embedded in the planetary-scale circulation of the atmosphere. The drawings below illustrate the wavy and generally eastward flow of air at upper levels in the middle latitudes of the Northern hemisphere (planetary-scale circulation). The wave pattern can vary considerably in amplitude (latitude range). Indicate which drawing better matches the upper-air flow of Figures 1 and 2.



Matches: **[(*__Figure 1__*)(*__Figure 2__*)]**



Matches: **[(*__Figure 1__*)(*__Figure 2__*)]**

8. The polar-front jet stream roughly aligns with the polar front separating high-latitude cold air from lower-latitude warm air. Wind information in Figure 1 suggests that surface temperatures across the coterminous United States are **[(*__low__*)(*__high__*)]** in the east-central U.S. compared to those in the west-central U.S.

9. Across the United States, storms tend to follow the path of the polar-front jet stream. In Figure 1, a storm in the Louisiana area at map time is likely to be moving towards **[(*__New England__*)(*__Florida__*)]**.

10. Knowledge of the location of the jet stream is very important to commercial aviation. Explain why at Figure 2 map time an airline flight from Washington, DC to San Francisco would take considerably more elapsed flying time than a flight from San Francisco to Washington, DC.

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Activity 2: Pressure, Air Pressure, and Jet Streams

Introduction

One of the most important properties of the atmosphere is air pressure. It is important because differences in air pressure from place to place put air into motion (just as in the case of air rushing out of the open valve of an inflated tire). Pressure differences at altitudes of nine or more kilometers lead to the development of high-speed winds, called <u>jet streams</u>.

This activity uses sets of blocks to investigation basic understandings about pressure and pressure differences produced by density variations. These understandings are then applied to the atmosphere to introduce the basic causes of jet streams.

Upon completing this activity, you should be able to:

- Explain what pressure is and how it can vary vertically and horizontally.

- Describe how density contrasts between warm and cold air produce pressure differences at different levels in the atmosphere.

- Explain how pressure differences in the atmosphere can lead to high-speed winds called jet streams.

Materials

- Set of plastic blocks consisting of 5 large red and 5 smaller blue blocks, three clear plastic strips

Investigation

To study pressure, we must first define it. <u>Pressure</u> is a force acting on a unit area of surface (*e.g.*, pounds per square inch is a pressure measurement). Air pressure is described as the weight (a force) of an overlying column of air acting on a unit area of horizontal surface. To investigate the concept of pressure we will simulate the use of tall and short “blocks”. Tall blocks are cube-shaped and short blocks have the same size base as the tall blocks but are half as high.

Whether tall or short, the blocks employed in this investigation have the following common characteristics:

a. All blocks have the same weight regardless of the volume they occupy.
b. All blocks have the same size square base.
c. All individual blocks exert the same downward pressure on the surface beneath them (because the equivalent weights are acting on the same size bases).

1. **Figure 1** shows one tall red block and one short blue block side-by-side on their square bases on the flat horizontal surface of a table (***T***). Because both blocks weigh the same (although they have different volumes) and their bases are the same size, the blocks exert **[(*equal*)(*unequal*)]** pressure on the surface of the table.

2. The shorter blocks occupy half of the volume of the taller blocks while containing equal masses. (We know this because they weigh the same.) Because density is a measurement of mass per unit volume, the smaller blocks are **[(*twice*)(*half*)]** as dense as the larger blocks.

3. In **Figure 2**, another identical block was placed on top of each block already on the table. Each stack is now exerting **[(*the same*)(*twice the*)]** amount of pressure on the table as the single blocks did initially.

4. The pressure exerted on the table by the tall stack is **[(*equal*)(*not equal*)]** to the pressure exerted on the table by the short stack.

5. As shown in **Figure 3**, the two stacks are side-by-side with another identical block added to each stack (for a total of 3 blocks in each stack). An imaginary surface (***1***) has been inserted horizontally through the two stacks so that two shorter blocks and one taller block are positioned beneath the surface. Compare the pressure exerted on the imaginary surface by the overlying blocks. The taller-block stack exerts **[(*greater*)(*equal*)(*less*)]** pressure on this imaginary surface than does the shorter-block stack.

6. **Figure 4** shows two more blocks added for a total of five in each stack. A second imaginary horizontal surface (***2***) is added beneath the top short block and the three top tall blocks. The pressure exerted on the table (T) by the tall stack is **[(*equal*)(*unequal*)]** to the pressure exerted on the table by the short stack.

7. On the lower imaginary surface (***1***) in Figure 4, the pressure exerted by all the overlying short blocks is **[(*one-half*)(*three-fourths*)(*the same as*)]** the pressure exerted by all the overlying tall blocks.

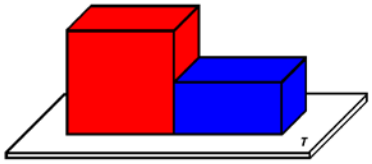

Figure 1.

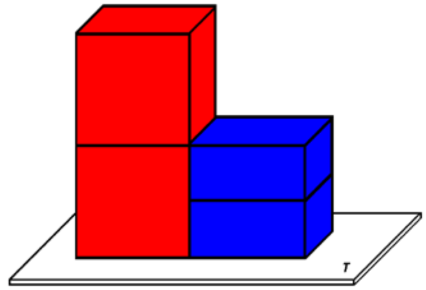

Figure 2.

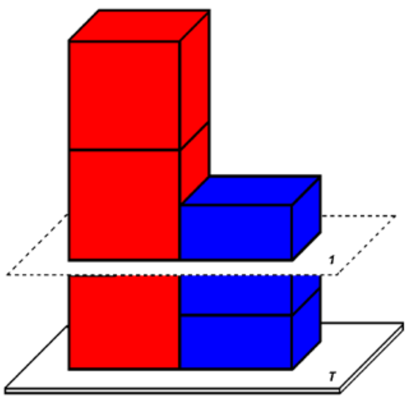

Figure 3.

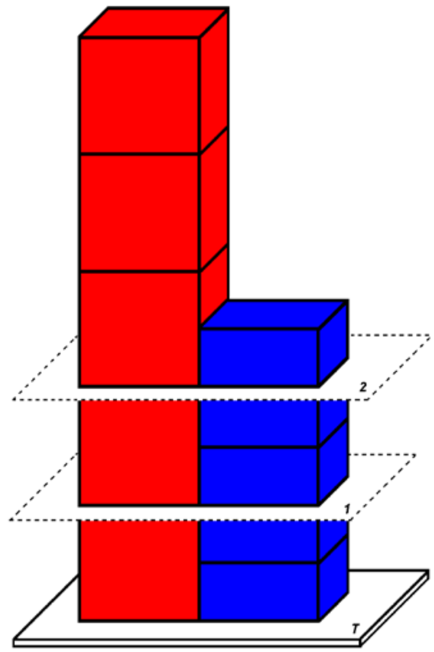

Figure 4.

8. On the top imaginary surface (***2***) in Figure 4, the downward pressure exerted by the overlying short block is **[(*equal to*)(*one-half*)(*one-third*)]** the pressure exerted by the overlying tall blocks.

9. On the table top in Figure 4, there are 5 blocks in each column and therefore, no pressure difference between the columns. From the table top upward in Figure 4, the difference in downward pressure on the other imaginary horizontal surfaces exerted by the overlying portions of the two stacks **[(*increases*)(*decreases*)]** from levels 1 to 2.

10. In the **[(*taller, less dense*)(*shorter, more dense*)]** stack, the pressure decreases more rapidly with height.

11. Look at **Figure 5** showing a side view of the two stacks of pressure blocks. It is a view of the same blocks seen in the previous figure. **Following the example shown with the bottom blocks, draw straight lines connecting the mid-points of bases of blocks exerting the same pressures.** These lines connecting equal pressure dots become **[(_more_)(_less_)]** inclined with an increase in height.

To this point we have been examining the change in pressure with height in stacks of blocks of different density (short blocks versus tall blocks). Now we apply what we have learned to the rate at which air pressure drops with altitude in the atmosphere.

12. **Figure 6**, *Vertical Cross-Section of Air Pressure*, shows a cross-section of the atmosphere based on upper-air soundings obtained by radiosondes simultaneously at Miami, Florida and at Chatham, Massachusetts, approximately 1250 mi. (2000 km) apart at 12Z 09 December 2010. Air pressure values in millibars (mb) are plotted as marks at the altitudes where they were observed, starting with identical values (1000 mb) at the Earth's surface. Over Florida, the atmosphere was exerting a pressure of 200 mb at an altitude of approximately **[(_11,600_)(_12,000_)(_12,200_)]** m above sea level.

13. The atmosphere above the Massachusetts weather station was colder and therefore denser than the air above the more southern and warmer Florida location. Following the examples shown at the surface and at 925 mb, draw straight lines connecting equal air-pressure dots on the graph. Above the Earth's surface these lines representing equal air pressures are **[(_horizontal_)(_inclined_)]**.

14. Compare the lines of equal pressure you drew on Figures 5 and 6. They appear quite different because one deals with rigid blocks whereas the other deals with compressible air, and their scales are much different. However, both reveal the effect of density on pressure. The lines of equal pressure slope **[(_upward_)(_downward_)]** from the lower-density tall blocks (warm air column) above Florida to the higher-density short blocks (cold air column) above Massachusetts, respectively.

15. Because of the slope of the equal-pressure lines in Figure 6, it is evident that at 12,200 m above sea level the air pressure in the warmer air over Florida is **[(_higher than_)(_the same as_)(_lower than_)]** the air pressure in the colder Massachusetts air at the same 12,200-m altitude.

16. The influence of air temperature on the rate of pressure drop with altitude has important implications for pilots of aircraft that are equipped with air pressure altimeters. An air pressure altimeter is actually a barometer in which altitude is calibrated against air pressure.

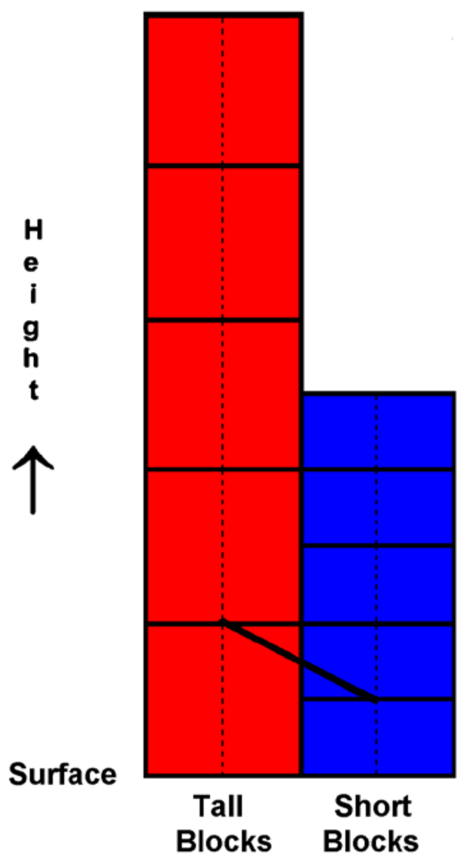

Figure 5. Stacked blocks.

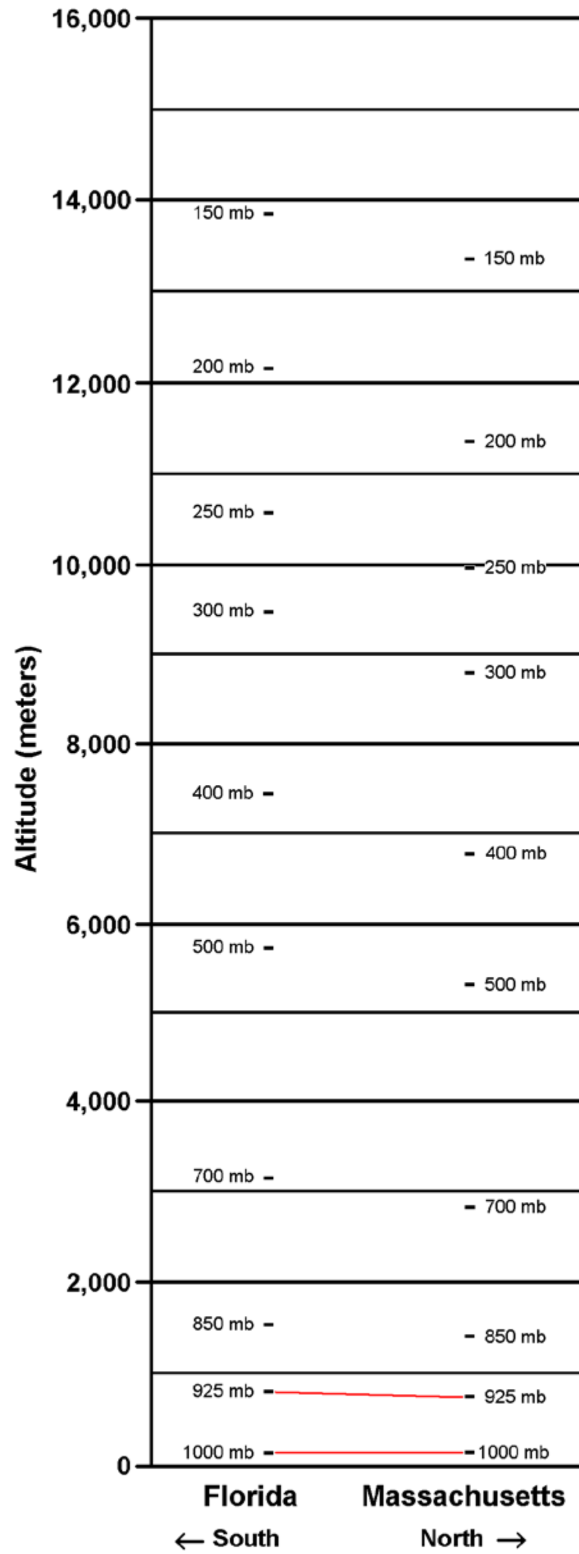

Figure 6. Vertical cross-section of air pressure at 12Z 9 December 2010.

Imagine that a little before 12Z on 09 December 2010 an aircraft starts its flight from Florida to Massachusetts. At 12Z over southern Florida, the onboard pressure altimeter indicates that the aircraft is at 5800 meters above sea level. From Figure 6, the air pressure is about **[(*<u>500</u>*)(*<u>400</u>*)]** mb at an altitude of 5800 meters over Florida.

17. Relying on the pressure altimeter, the pilot continues to fly toward Massachusetts along a constant pressure level with an <u>indicated</u> altitude of 5800 meters. En route, the air temperature outside the aircraft gradually falls but the pilot does not alter the calibration between air pressure and altitude. Over Massachusetts, the pressure altimeter still reads 5800 meters, the *indicated altitude* of the aircraft. From Figure 6, however, it is evident that the *true altitude* of the aircraft over Massachusetts is **[(*<u>lower than</u>*)(*<u>the same as</u>*) (*<u>higher than</u>*)]** the altitude indicated by the altimeter.

18. The *true altitude* of the aircraft over Massachusetts is about **[(*<u>5300</u>*)(*<u>5800</u>*)(*<u>6100</u>*)]** meters.

19. In this example, the aircraft flew along a constant pressure surface (the 500-mb surface) which is at a **[(*<u>higher</u>*)(*<u>lower</u>*)]** altitude in warm air than in cold air. In actual practice, a pilot must adjust the aircraft's pressure altimeter to correct for changes in the altitude of pressure surfaces due to changes in air temperature en route. This correction ensures a more accurate calibration between air pressure and altitude.

Real World Applications: Pressure, Air Pressure and Jet Streams

Figures A and **B** are plotted profiles of air temperatures and atmospheric humidity at a series of pressure levels determined by radiosondes launched from about 70 upper air stations around the country at 12Z (7 am EST) and 00Z (7 pm EST) daily. Figure A is the profile from Green Bay, Wisconsin at 12Z on 10 April 2012 while Figure B is from the Little Rock, Arkansas site at the same time. The heavy curve to the right on each graph is the temperature curve where the horizontal axis is temperature in degrees Celsius increasing from –80 to +40 °C. Pressures decrease upward along the vertical axis, as they do in the atmosphere, from about 1000 mb to 100 mb.

1. Compare the temperatures at the same pressure levels between Green Bay and Little Rock. The air from the surface to about 300 mb is **[(*warmer*)(*cooler*)]** over Little Rock than over Green Bay.

2. In the case of the rigid pressure blocks, the air column over Little Rock is therefore like the **[(*blue*)(*red*)]** blocks.

3. An aircraft flying from Little Rock to Green Bay along a constant pressure surface in the upper atmosphere would then be arriving at a **[(*lower*)(*higher*)]** altitude in Green Bay than that of the surface over Little Rock.

From the text data for these two soundings, the 250-mb level occurred at 10,570 meters over Little Rock while that same pressure was found at 10,100 meters over Green Bay. The downward slope of this pressure level from south (Little Rock) to north (Green Bay) is similar to Figure 6. Such a slope implies a strong change of height at a constant pressure (250 mb) or, conversely, a strong change of pressure at a fixed altitude. Strong pressure changes over distance, called pressure gradients, drive winds to high speeds.

4. Therefore, this change of pressure at the same altitude over these two stations **[(*would*)(*would not*)]** imply the existence of strong winds at upper levels, *i.e*. a jet stream, between the stations.

Figure C is the 250-mb map for 12Z 10 APR 2012 from NOAA's Storm Prediction Center. The areas of highest wind speeds are color-coded where the dark blue boundary is 75 knots and the enclosed medium blue is shading is 100 knots. The wind speed scale is along the left edge of the map area. Wind barbs are dark blue with speed indicated by the convention of Activity 1.

5. Note the locations of Little Rock, Arkansas and Green Bay, Wisconsin on the Figure C map. From the shading and wind barbs, there **[(*is*)(*is not*)]** a jet stream located between the cities at this time.

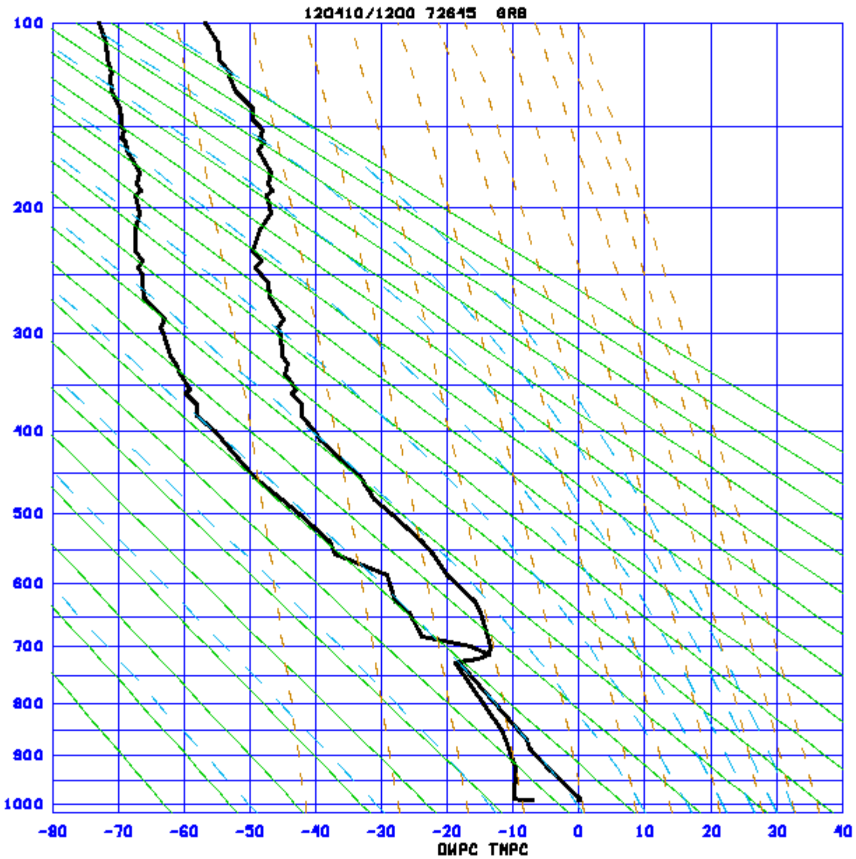

Figure A. Radiosonde observation from Green Bay, WI at 12Z 10 APR 2012.

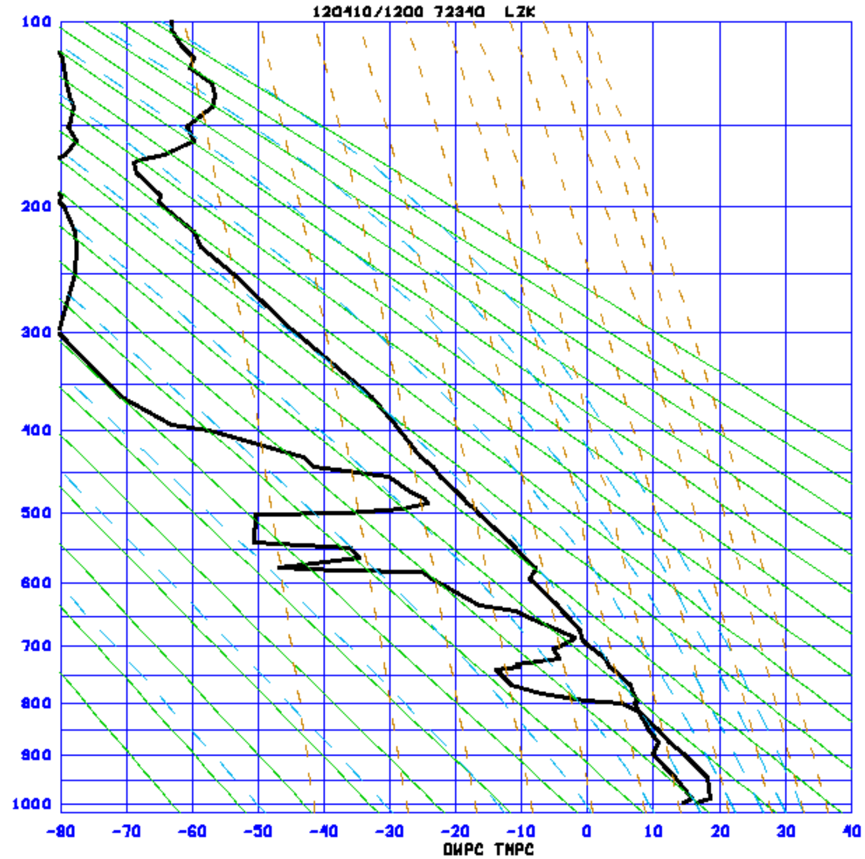

Figure B. Radiosonde observation from Little Rock, AR at 12Z 10 APR 2012.

6. The 250-mb flow pattern displayed on the map is most like that of **[(*Figure 1*) (*Figure 2*)]** of Activity 1 in this module.

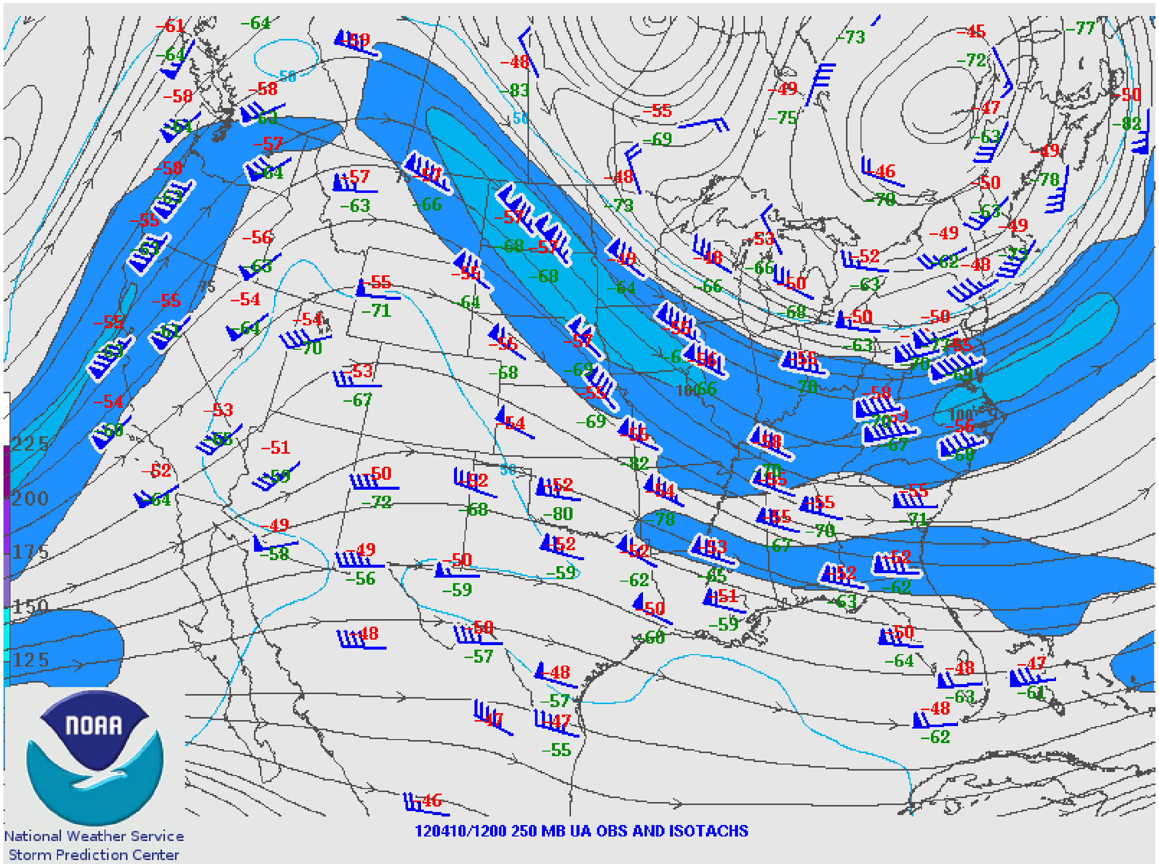

Figure C. 250 mb map for 12Z 10 APR 2012 (NOAA SPC).

Information Sources

Books

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

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.