

**THE ATMOSPHERE
ALOFT**

TEACHER'S GUIDE

Project ATMOSPHERE

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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: The Atmosphere Aloft

Clouds, along with their motions, changes, and precipitation, provide visible evidence that the part of the atmosphere directly impacting our lives extends from the surface upwards for many kilometers. They also demonstrate connections between weather at Earth's surface and conditions and processes occurring aloft. For a more complete understanding of weather and weather systems, the third dimension of the atmosphere must be brought into consideration. Meteorologists regularly monitor the atmosphere aloft to determine its vertical and horizontal structure.

Many properties of air vary dramatically upward through the atmosphere. Because the Sun's rays readily pass through the clear atmosphere to warm the surface, the atmosphere is strongly heated from below. Thus, the highest temperatures are typically at Earth's surface, decreasing as altitude increases. This layer of decreasing temperatures, ranging from 6 to 16 km (4 -10 mi.) in depth is called the *troposphere* or "weather layer". Farther aloft, the air temperatures increase as much of the ultraviolet portion of incoming solar radiation is absorbed at the altitudes where heat-producing ozone formation and dissociation are taking place. The effect of this warming shows first as a layer of constant temperature, topped by increasing temperatures with altitude, forming what is called the *stratosphere* or "stable layer". The boundary between the troposphere and the stratosphere where the temperature stops decreasing and becomes constant is termed the *tropopause*.

Air pressure and air density decrease with an increase in altitude. Air pressure is the weight per unit surface area of an air column extending to the top of the atmosphere. Therefore, atmospheric pressure is greatest at sea level. Because air is highly compressible, as readily seen by inflating a tire, it is also most dense at the bottom of the atmosphere. The weight of the overlying atmosphere compresses the air near the surface more than does the lesser weight of overlying air at upper levels. The result is that air pressure and air density initially decrease very rapidly, then more slowly, with altitude. Half of all air molecules are within only 5.5 km (3.5 mi.) of sea level. The next one-quarter of the atmosphere is located between about 5.5 to nearly 11 km.

Clouds and weather systems provide visual evidence of the atmosphere's third dimension. Early attempts to scientifically probe the atmosphere above Earth's surface involved instruments attached to or carried aloft by kites, balloons, and airplanes. Current practice involves the use of *radiosondes*, instrument packages carried aloft by balloons. Information concerning temperature, humidity and pressure is transmitted by radio back to the launch site. The rising radiosondes can also be tracked to give wind information at the various levels. In this way, routine measurements are made twice daily at about 70 stations around the continental U.S.

Basic Understandings

1. The sunlit Earth's surface heats the atmosphere above, so the temperature in the lowest layer of the atmosphere decreases with altitude. The average surface temperature of Earth is 15 degrees Celsius (59 °F). At 11 km the average temperature is $-56.5\text{ }^{\circ}\text{C}$ ($-70\text{ }^{\circ}\text{F}$).
2. The average rate at which temperature decreases in the vertical ("lapse rate") is 6.5 degrees Celsius per 1000 meters (3.5 °F per 1000 ft.) throughout the lowest layer in the atmosphere that extends to 11 km (7 mi.). This temperature pattern is a property of the "Standard Atmosphere" and is known as the standard lapse rate.
3. The *troposphere* is the layer of the atmosphere nearest the Earth's surface and is the layer in which most weather occurs. In the troposphere air temperature generally decreases with altitude.
4. Above about 11 km, the temperature remains constant at $-56.5\text{ }^{\circ}\text{C}$ for several kilometers before rising with an increase in altitude up to about 50 km. This layer is called the *stratosphere*. The protective ozone (O_3) layer is within the stratosphere.
5. The boundary between the top of the troposphere and bottom of the stratosphere is the *tropopause*.
6. Atmospheric pressure is the weight of a column of overlying air extending to the top of the atmosphere acting on a unit of area.
7. In the air pressure units routinely used in meteorology, the average pressure at sea level is 1013.25 millibars (mb) or hectopascals (hPa). This pressure is equivalent to the pressure exerted at the base of a column of mercury 29.92 inches or 76 centimeters high.
8. Near sea level, atmospheric (barometric) pressure decreases with altitude by about 100 mb for every 1000 meters. The pressure decreases most rapidly near the surface and less rapidly as altitude increases.
9. Approximately one-half of the atmosphere by mass or weight (found between sea level and the height at which air pressure level is 500 mb) is within 5.5 km (3.5 mi.) of the Earth's surface. The tropopause is located at about 225 mb, so that roughly three-quarters of the atmosphere by mass or weight is found in the troposphere.
10. Weather systems are almost entirely tropospheric phenomena.

11. Air motions that accompany weather systems, along with air mass differences, cause temperature and pressure variations that differ from the average conditions of the Standard Atmosphere.
12. Radiosondes lifted by balloons are launched twice daily from many locations, measuring temperature, pressure and humidity as they rise through the atmosphere to altitudes typically reaching 30 km (19 mi.) above sea level. Tracking the horizontal motions of these devices also provides wind information.
13. Meteorologists employ a variety of charts to represent the vertical structure of the atmosphere based on radiosonde data. These charts can provide information including the probable existence of clouds, cloud thickness, and atmospheric stability or instability.
14. Upper-air data can be employed to draw essentially horizontal maps depicting atmospheric conditions at different levels above sea level. These levels are usually defined by a certain pressure value, so the resulting charts are called *constant-pressure maps*. Upper-air constant-pressure maps are routinely drawn at 850, 700, 500, 300, 250 and 200 mb.
15. Upper-air constant-pressure maps typically display temperature, dewpoint, and wind speed and direction conditions. Another important value reported is the altitude above sea level at which the designated map pressure occurred over each station.
16. Among the typical analyses made on upper-air maps is the drawing of height contours to determine the topographical relief of the particular map's constant pressure surface. The high and low height areas on a constant-pressure map correspond closely to high and low pressure areas that would be present if a constant-altitude map had been drawn at the average height of that chosen pressure level.
17. The 850-mb level generally occurs near 1500 m (5000 ft.). This level reflects temperature and humidity patterns in the free atmosphere associated with a weather system.
18. An 850-mb map is used by meteorologists for observing humidity and temperature *advections* - movements of higher or lower values of water vapor or heat energy into a region.
19. The 700-mb level generally occurs near 3000 m (10,000 ft.). This level reflects the wind patterns that steer individual thunderstorms, so it is used by meteorologists for predicting thunderstorm motion and intensification.

20. The 500-mb level generally occurs near 5500 m (18,000 ft.). This level represents the mid-troposphere circulation pattern and is used by meteorologists to predict the movement and intensification of large-scale weather systems (surface highs and lows).
21. The 300-, 250- and 200-mb levels occur between 9000 and 12,000 m (29,000 to 40,000 ft.). Depending on the time of year and the latitude, the highest horizontal wind speeds in the atmosphere are typically found at one of these levels.
22. The 300-mb map (or 250 or 200 mb) is used by meteorologists for aviation forecasts and to identify wind flow patterns that intensify or weaken large-scale weather systems and move them along.
23. Upper atmospheric information is essential to fully understand weather system structure, movement, and change.

Activity: The Atmosphere in the Vertical

Educational Outcomes:

The atmosphere has thickness as well as horizontal extent. For a more complete understanding of weather, knowledge of atmospheric conditions in the vertical is necessary. Air, a highly compressible fluid, is held to Earth by gravity and thins rapidly upward. The atmosphere is heated primarily from below, is almost always in motion, and contains a substance (water) that undergoes frequent phase changes.

After completing this activity, you should be able to:

- Describe the vertical structure of the atmosphere in the troposphere (the "weather" layer) and in the lower stratosphere.
- Compare the "Standard Atmosphere" with an actual observed sounding of the lower atmosphere.

Materials: Pencil, straight edge.

Investigations:

1. **Figure 1**, called a Stüve diagram, is designed to plot and interpret upper-air atmospheric data acquired by radiosondes. The atmospheric temperatures in Celsius degrees that can be plotted on the diagram range from -80 to _____ $^{\circ}\text{C}$. Air pressure is plotted in millibars (mb) with values decreasing upward and the approximate altitude scale is in kilometers (km) above sea level. The lowest pressure that is labeled on the diagram is _____ mb. This pressure is found in the atmosphere at an altitude of about _____ km above sea level.
2. Plot on the Figure 1 Stüve diagram the data points given below. Connect adjacent points with solid straight line segments or use colored line segments.

Altitude (kilometers)	Temperature (degrees C)
---------------------------------	-----------------------------------

0	+15.0
11	-56.5
16	-56.5

3. You have drawn the temperature profile of the lower portion of what is called the **Standard Atmosphere**. The Standard Atmosphere describes average conditions of the atmosphere in the vertical. The portion of the Standard Atmosphere from the surface to 11 km depicts the lowest layer of the atmosphere, called the _____, or “weather layer” where most clouds form. Above 11 km where temperatures remain steady with altitude is the lower portion of the _____, or “stable layer.” The boundary between the two layers is called the tropopause.
4. The actual troposphere is characterized generally by decreasing temperature with altitude, significant vertical motions, appreciable water vapor, and weather. According to the data provided in (2) above, the rate of tropospheric temperature decrease with altitude in the Standard Atmosphere is _____ C degrees per km. This is also called the free atmosphere lapse rate or that of air well away from Earth’s surface.
5. Air pressure, which is very close to 1000 mb at sea level in the Standard Atmosphere, decreases most rapidly with altitude in the lowest part of the atmosphere. The diagram shows that near sea level the air pressure drops 100 mb (from 1000 mb to 900 mb) over a vertical distances of about 1 km. However, the 100-mb pressure drop from 400 mb to 300 mb occurs over a vertical distance of about **[(1)(2)(3)]** km. The same pressure drop from 200 mb to 100 mb takes place over a vertical distance of nearly **[(1)(2)(4)]** km.
6. The diagram shows that air pressure of 500 mb (half that at sea level) occurs at an altitude of about _____ km.
7. Because air pressure is determined by the weight of the overlying air, half of the atmosphere by weight or mass is above the altitude where the air pressure is 500 mb and half of it is below that altitude. In other words, half of the atmosphere by weight or mass is within _____ km of sea level. According to the diagram, 90% of the atmosphere by weight or mass is within _____ km of sea level.

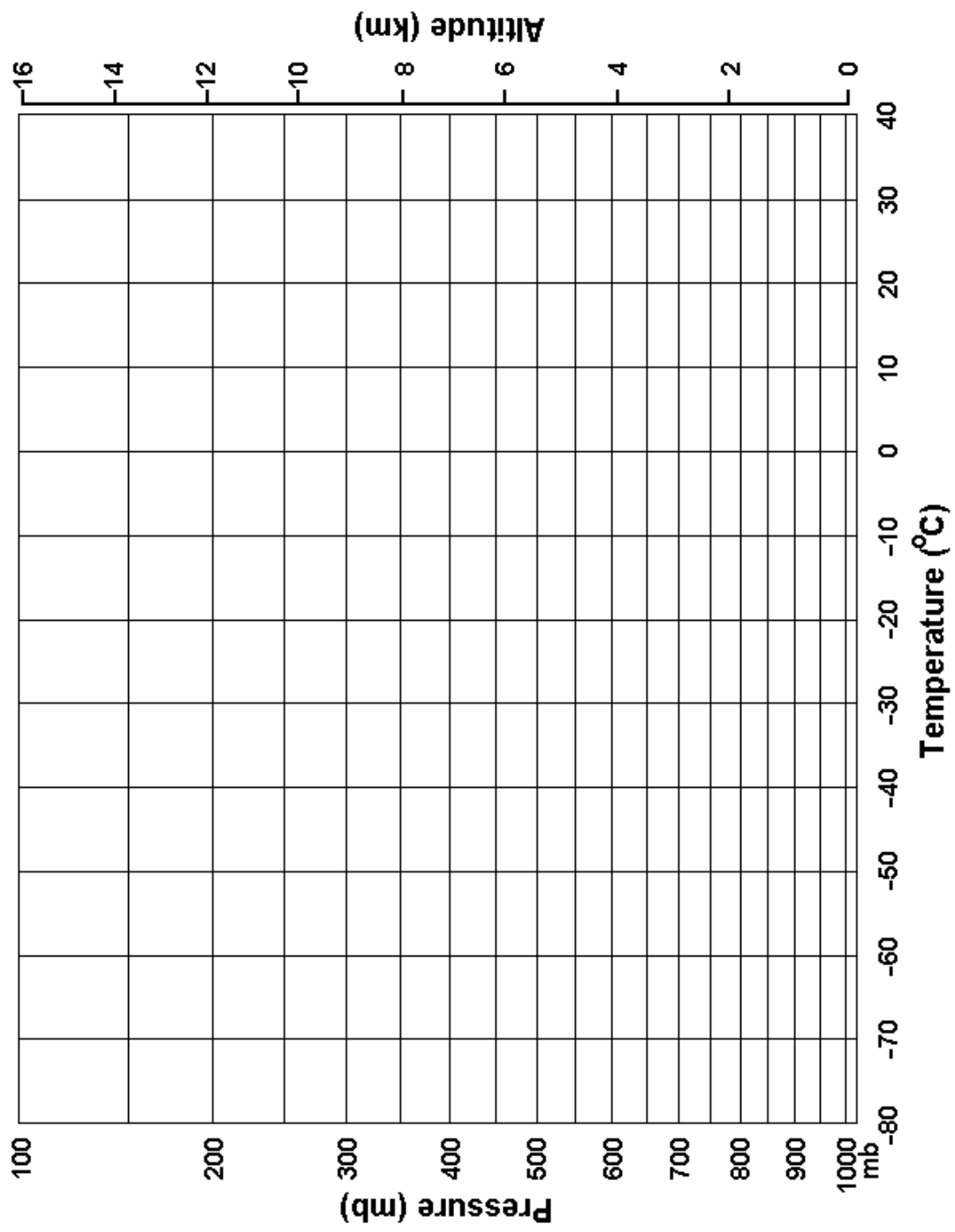
8. Upper-air observational data are collected twice every 24 hours at nearly 100 North American stations. The following data were measured by a radiosonde at Green Bay, WI at 12Z 23 January 2011 (6 am CST on 23 January):

<u>Pressure (mb)</u>	<u>Temperature (C)</u>
100	-51.1
200	-47.7
300	-57.3
400	-42.9
500	-31.3
700	-19.1
850	-21.5
1000 (surface)	-21.7

Plot these data points on the Figure 1, Stüve diagram. Connect adjacent points with dashed straight line segments or solid lines of contrasting color.

9. Compare the Standard Atmosphere and Green Bay temperature profiles you drew on the Stüve diagram. At the time of observation, the troposphere over Green Bay was generally **[(warmer)(colder)]** than specified by the Standard Atmosphere.
10. According to the plotted temperature profiles, the tropopause (found at the base of the stratosphere where temperatures are steady or increase with an increase in altitude) is located at about 225 mb pressure in the Standard Atmosphere. At Green Bay, it was located at _____ mb. This pressure occurred at an altitude of about _____ km.
11. The vertical thickness of the troposphere at Green Bay was **[(greater)(less)]** than the thickness of the Standard-Atmosphere troposphere.
12. These profiles illustrate the general relationship between average tropospheric temperature and the vertical extent of the troposphere; that is, the **[(warmer)(colder)]** the troposphere, the thinner it is.
13. This relationship means that on the average, on a global scale, the thickness of the troposphere **[(increases)(decreases)]** as the latitude increases.

Vertical Atmospheric Chart (Stüve)



Real World Applications

After a moderately cool beginning to the month of June, a heat wave struck the central and eastern U.S. in time for the beginning of (astronomical) summer. These temperatures were reflected in radiosonde profiles such as this one from Long Island, New York near the summer solstice. **Figure 2** is the Stüve diagram from the OKX radiosonde measurements of 00Z 21 June 2012 (8 pm EDT the previous night). The heavy black curve to the right on the Stüve is the temperature profile. The surface air temperature at launch time was 30 °C (86 °F). (On this Stüve diagram, no altitude values are shown.)

On the Figure 2 Stüve diagram, plot the points from the first part of the activity that define the Standard Atmosphere. Connect those points with dashed straight line segments or solid colored lines. Label that curve “Standard Atmosphere”.

1. Compare the Long Island and Standard Atmosphere temperature profiles you drew on the Figure 2 Stüve diagram. At the time of observation, the troposphere over Long Island was generally [**warmer**]~~(colder)~~ than specified by the Standard Atmosphere.
2. According to the plotted temperature profiles, the tropopause (found at the base of the stratosphere where temperatures are steady or increase with an increase in altitude) is located at about 225 mb pressure in the Standard Atmosphere. At Long Island on this profile, it was located at about _____ mb. The vertical thickness of the troposphere over Long Island was [**greater**]~~(less)~~ than the thickness of the Standard-Atmosphere troposphere.

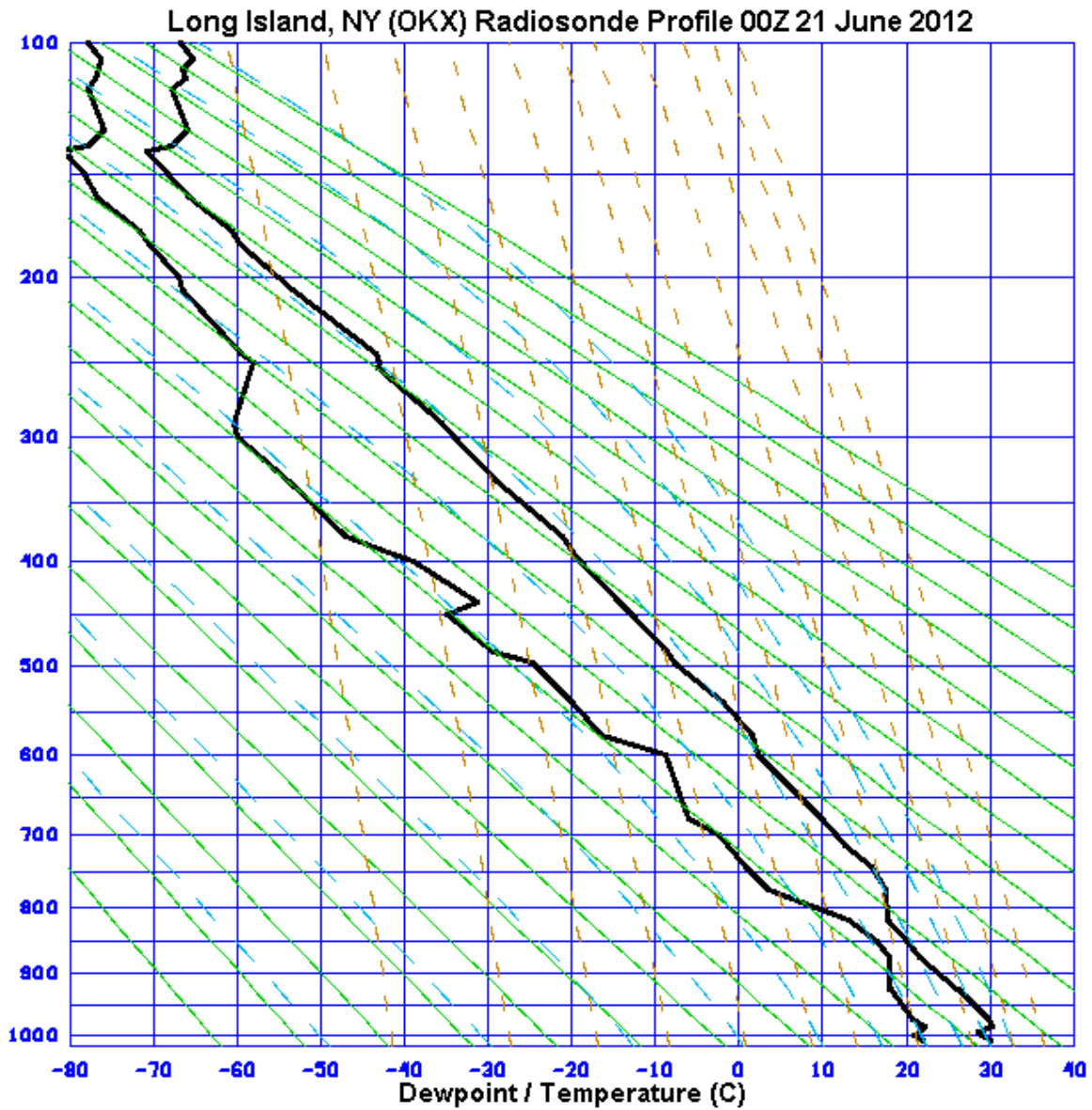


Figure 2. OKX Stüve diagram of 00Z 21 June 2012 [NCEP/NOAA].

Activity: Upper-Air Weather Maps

Educational Outcomes:

Weather as reported on surface weather maps provides us primarily with a two-dimensional view of the state of the atmosphere, that is, weather conditions observed at the Earth's surface. Atmospheric conditions reported on upper-air weather maps provide the third dimension, that is, conditions at various altitudes above the Earth's surface. Hence, for a more complete understanding of the weather, both surface and upper-air weather maps need to be consulted.

After completing this activity, you should be able to:

- Describe the topography of upper-air constant-pressure surfaces based on height contours, including the identification of Highs, Lows, ridges, and troughs.
- Describe the general relationship between height contours and the average temperature of the underlying atmosphere.
- Describe the relationship between the height contours and wind direction on upper-air maps.

Materials: Pencil

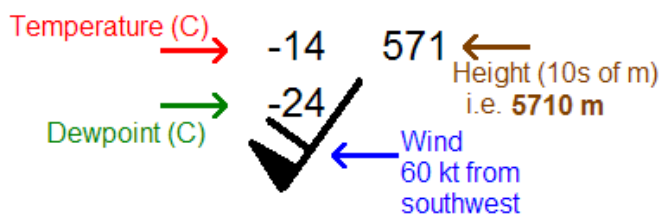
Investigations:

1. Upper-air weather maps differ from surface weather maps. Whereas surface weather conditions are plotted on a map of constant altitude (normally sea-level), upper-air weather conditions are plotted on maps of constant air pressure. The altitude at which the particular pressure is located is reported on these maps. Every twelve hours, upper-air maps are drawn for various pressure levels including, for example, 850 mb, 700 mb, 500 mb, and 200 mb. The 500-mb pressure level is about half way up in the atmosphere in terms of mass. Also, major weather systems tend to flow along the direction of the winds shown at 500 mb.

The data for these maps are obtained from rawinsonde reports. Rawinsondes are radiosondes which are tracked by Global Positioning System (GPS) positions to provide additional information on horizontal wind speeds and directions.

2. Plotted on upper-air maps are temperature (in °C), dewpoint (in °C), wind speed (in knots), wind direction, and coded height of the pressure surface above sea-level (in meters). Become familiar with the upper-air station model depicted below.

SAMPLE UPPER AIR STATION MODEL FOR 500 MB



3. **Figure 3** is the 500-mb map for 00Z 23 April 2012 (8 pm EDT of 22nd). The information is assembled from the 500-mb level of each station's reports at the same observation time. The 500-mb map is often employed by meteorologists because of its importance in revealing the direction of the steering winds, that is, the winds that steer weather systems across the Earth's surface.

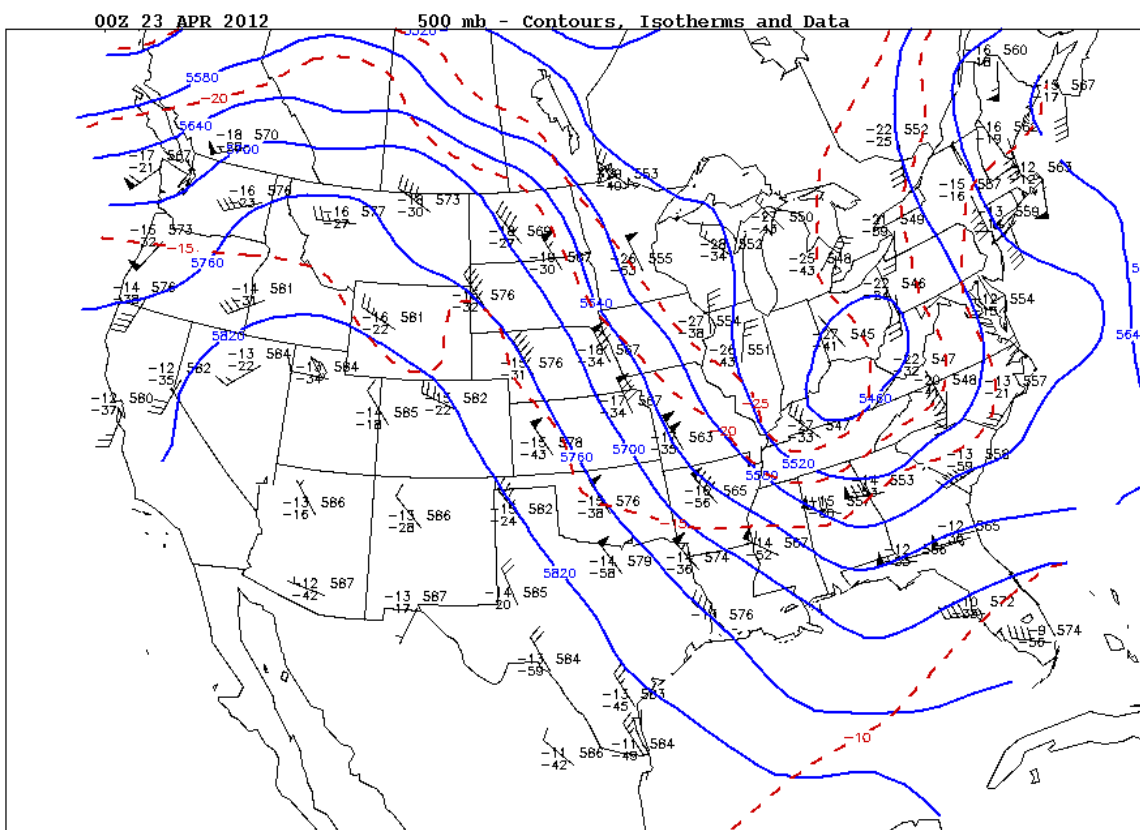


Figure 3. 500 mb upper air, constant-pressure map for 00Z 23 APR 2012 [NCEP/NOAA].

4. Solid lines on the 500-mb map display locations where 500-mb is at the same altitude. These lines, called *contours of height*, are drawn at intervals of 60 m. At 00Z, 23 APR 2012, the lowest reported height for a pressure reading of 500-mb was _____ meters, and the highest reported height was _____ meters.

5. The 500-mb map and other constant-pressure upper-air maps are similar to topographic maps. That is, the contour pattern reveals the “hills” and “valleys” of the constant-pressure surface. In general, the 500-mb surface (the surface where the air pressure is 500-mb) occurs at a **[(higher)(lower)]** altitude in southern Canada than in the southern United States.
6. Closed contour lines on constant-pressure upper-air maps identify topographic highs and lows. The closed 5460-m contour line on this map encloses **[(higher)(lower)]** 500-mb elevations. Therefore, the contour line encloses a topographic **[(Low)(High)]**. Place an appropriate large “H” or “L” on the map at the center of the area enclosed by the contour line.
7. The wave pattern of most contour lines consists of topographic ridges and troughs, that is, elongated crests and depressions, respectively. A broad **[(trough)(ridge)]** appears on the Figure 3 map in the eastern portion of the nation generally south of the closed contour. A **[(trough)(ridge)]** appears over western US.
8. A column of cold air is denser than a column of warm air. Hence, air pressure decreases more rapidly with altitude in cold air than in warm air. The height of the 500-mb surface is lower where the underlying air is relatively **[(cold)(warm)]** and higher where the underlying air is relatively **[(cold)(warm)]**. The air below the 500-mb Low in Figure 3 is **[(colder)(warmer)]** than the air below the surrounding higher 500-mb surfaces.
9. Dashed lines on the 500-mb map are isotherms. The interval between successive isotherms is 5 Celsius degrees. The general decline in temperature at 500 mb as latitude increases is accompanied by a(n) **[(increase)(decrease)]** in the altitude of the 500-mb surface.
10. Suppose that on 23 APR 2012 at 00Z you board an airplane and fly non-stop directly from Cincinnati Ohio, (on the Ohio-Kentucky border) to Tucson, Arizona (the southern station in the state). En route, the plane cruises along the 500-mb surface. Flying from Cincinnati to Tucson, the aircraft's cruising altitude **[(increases)(decreases)(does not change)]**. At the same time, the temperature of the atmosphere below the aircraft **[(rises)(falls)]**.
11. A relationship exists between the orientation of height contours and horizontal wind direction on 500-mb maps, especially at higher wind speeds. As seen in Figure 3, wind direction is generally **[(perpendicular)(parallel)]** to nearby contour lines.

Optional Upper-Air Map Activity

A physical, three-dimensional model depicting the relief of an upper-air map may be constructed by transferring the map to construction material of moderate thickness such as Styrofoam® or corrugated cardboard. The use of cardboard from boxes used to deliver pizzas is handy as it is thin and easily cut with scissors. The following procedure indicates how such a model can be assembled.

1. Enlarge the map in the Upper-Air Weather Maps activity by 175% using a photocopier. Make 6 copies of the enlarged map.
2. Glue the maps onto pieces of the construction material.
3. On one of the mounted maps, cut out the areas inside of the closed 5460-m and the looping 5520-m contour lines. Also note those same lines appear in the Pacific Northwest. Align and glue the map with the two holes onto an uncut copy of the map.
4. Cut out and discard the lower-altitude portions of successive mounted maps along 5580-, 5640-meter, etc. contour lines. Glue the remaining successive map pieces in sequence, one on top of the other, to produce a stepped relief map assembly.
5. Examine the assembled map from different angles, including looking straight down to see the full map. Turn to the Upper-Air Weather Maps activity and refer to the model as you answer or review your answers to the investigations. Be sure to compare the positions of the Lows, ridges, and troughs as they appear on the map and in the model.

Cautionary notes: The physical relief map you have constructed has a greatly exaggerated vertical to horizontal scale. Also, the stepped relief presented in the model is contrary to the actual continuous sloping of the existing pressure surface.

Real World Applications

Upper atmospheric flow patterns exhibit wave-like motions as the air moves generally from west towards east around the globe. These waves have swirls like eddies in streams of water. Surface weather systems are formed from the flows of air aloft that result from atmospheric temperature patterns. As noted, the heights of constant pressure levels depend on the temperatures within the air below that level. Cold air columns produce lower heights of surfaces such as the 500-mb level. Warm air columns produce higher heights of 500-mb surfaces.

In turn, surface weather systems move warm and cold air masses generally eastward and influence the columns of air above the surface. The surface weather and upper air patterns are inextricably linked. Over the course of several days, patterns of upper air flows can change from situations shown in Figure 3 where circular eddies form and contours display closed loops to generally smooth west-to-east flows. Patterns having large north and south excursions as seen in Figure 3 are called *meridional* from their flow generally north and south along meridians of longitude. The opposite extreme of flow generally west-to-east would be called *zonal* from the flow along zones of latitudes.

Figure 4 is the 500-mb constant-pressure map for 12Z (7 am EST) 20 January 2012. Compare the flow pattern shown in Figure 4 to that of Figure 3.

1. The flow seen in Figure 3 would be termed **[(*meridional*)(*zonal*)]** while that of Figure 4 would be **[(*meridional*)(*zonal*)]**.
2. Compare the temperature patterns shown by the red, dashed isotherms plotted on each figure. The general decrease of temperature as latitude increases occurs more smoothly when the flow is zonal as shown in **[(*Figure 3*)(*Figure 4*)]**.

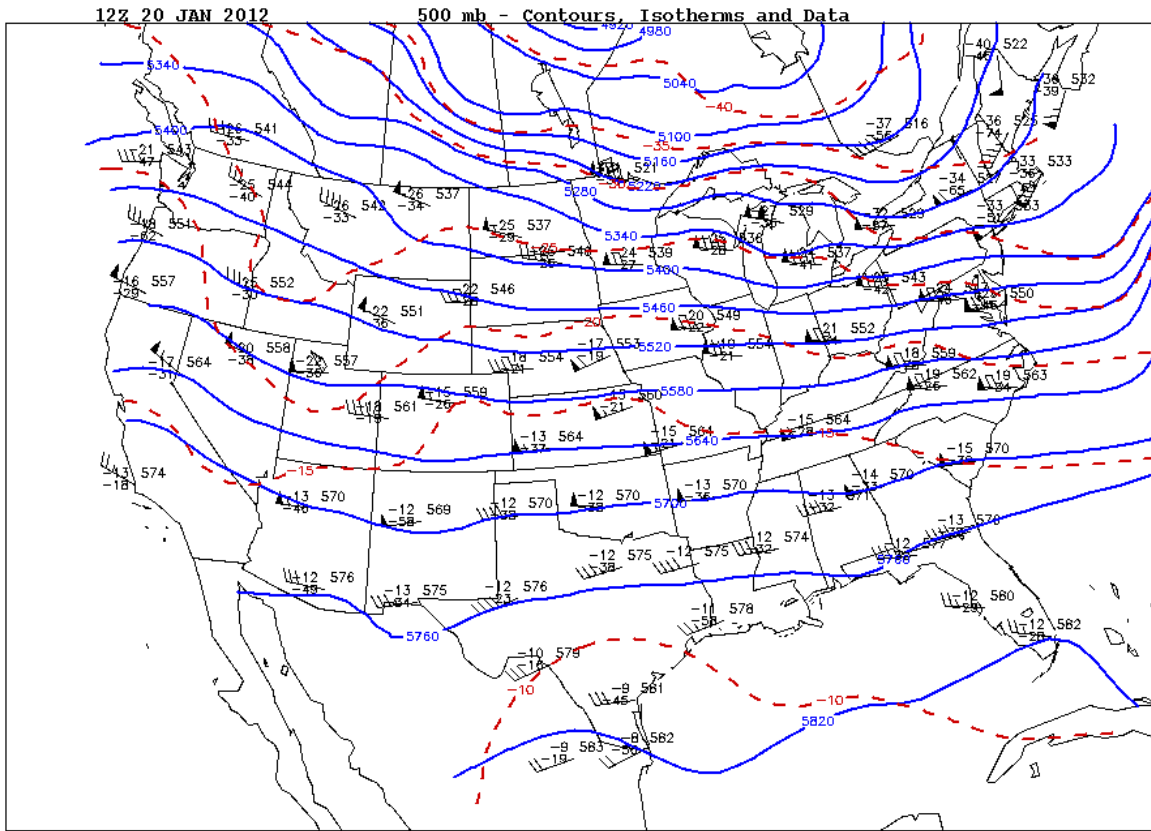


Figure 4. 500-mb map for 12Z 20 JAN 2012 [NCEP/NOAA].

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.

For Stüve diagrams and rawinsonde text data from upper air stations as well as upper air maps, see: <http://vortex.plymouth.edu/make.html>.