AMERICAN METEOROLOGICAL SOCIETY:



Project Atmosphere

The Atmosphere Aloft

—

TEACHER'S GUIDE

Project Atmosphere

This guide is one of a series produced by Project Atmosphere, a National Oceanic and Atmospheric Administration-sponsored initiative of the American Meteorological Society (AMS). Project Atmosphere is an annual K-12 teacher-focused professional development opportunity offered via hybrid delivery that includes several weeks of online coursework and a one-week residency at the National Weather Service Training Center in Kansas City, MO. The goal of Project Atmosphere is to create and train a diverse network of master teachers prepared to integrate atmospheric and climate science in their classrooms and provide peer training sessions. To support these teachers' educational experiences, Project Atmosphere develops and produces a series of course modules and other educational materials.

For further information, and the names of Project Atmosphere course alumni in your state or region, please contact:

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Module: The Atmosphere Aloft
Instructor: Project Atmosphere Instructor or Project Atmosphere Graduate
Audience/Grade Level: K-12 Educators

Standards:

Project Atmosphere Fundamental Understandings

1. Global Atmospheric Circulation:
    a. Describe how the distribution of solar energy affects broad atmospheric circulation patterns in both the Northern & Southern Hemispheres in the context of the 3-cell model (e.g., Hadley Cell, etc.).
    b. Evaluate the seasonal influences (i.e., changing solar radiative budget) on the distribution of the related pressure systems and the impacts of these circulation patterns.
3. Weather Charting and Maps:
    a. Decode surface and upper-air weather symbols, including pressure, temperature, and wind, to analyze current conditions.
    b. Analyze weather maps and charts that represent atmospheric conditions over various scales to forecast future atmospheric dynamics in the troposphere.
7. Atmospheric Stability and Instability:
    a. Understand the procedures necessary to launch a weather balloon to collect in-situ, near real-time observations of the upper atmosphere.
    b. Differentiate between stable and unstable atmospheres determined by the temperature and dewpoint profiles on a thermodynamic chart (e.g., Skew-T, Log p) and conjecture about the probability of vertically rising or sinking air parcels.
    c. Practice identifying layers of stability/instability on a thermodynamic chart.

Next Generation Science Standards (NGSS)

Performance Expectations

K-ESS2-1. Use and share observations of local weather conditions to describe patterns over time.

3-ESS2-1. Represent data in tables and graphical displays to describe typical weather conditions expected during a particular season.

MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses result in changes in weather conditions.

MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

Science and Engineering Practices

2. Developing and Using Models
4. Analyzing and Interpreting Data

Disciplinary Core Ideas

ESS2.D: Weather and Climate

Crosscutting Concepts

4. Systems and system models.
7. Stability and change.

Engage | The Atmosphere's Third Dimension

While air patterns near the surface influence weather, understanding weather systems more fully requires considering the third dimension of the atmosphere. Meteorologists routinely monitor the atmosphere aloft to assess both its vertical and horizontal structures. In the troposphere, the layer closest to Earth's surface, temperature and pressure generally decrease with elevation, driving the vertical movement of air.

This vertical gradient in temperature within the troposphere is due to how solar radiation passes through the atmosphere. As solar energy travels through the atmosphere, very little is absorbed by the air, so most of the energy is absorbed by Earth's surface. The surface then radiates infrared energy and heats the atmosphere from below. The average surface temperature of Earth is 15°C (59°F), while the average temperature at 11,000 m is –56.5°C (–70°F). The temperature decrease with elevation within the troposphere is evidenced by the need for additional clothing layers you experience hiking up a tall mountain. Even in summer, snow can be present near the mountain's summit, such as Mount Hood in Oregon (3400 m or 11,200 ft.) and Mount Rainier in Washington (4400 m or 14,400 ft.). For additional reference, the highest mountain in the US is Mount McKinley/Denali (6200 m or 20,300 ft.), and the highest in the world is Mount Everest (8850 m or 29,000 ft.).

You may have noticed changes in pressure as you ascend a mountain. As you climb, your ears may pop due to the decreasing pressure. If you ascend high enough, you may start to experience shortness of breath or altitude sickness due to the significant drop in oxygen molecules in the air around you. This decrease in oxygen can lead to lightheadedness, dizziness, nausea, headaches, and sometimes even more severe symptoms. For this reason, mountain climbers often carry supplemental oxygen when climbing above 6500 m (21,000 ft.). At 8000 m (26,000 ft.), there is only about one-third of the oxygen available at sea level. This altitude is often referred to as the "death zone" because there is not enough oxygen to sustain human life.

Group Review and Discussion:

1. *How do temperature and pressure change with altitude?*
2. *Have you ever experienced or spoken with someone else who has experienced the effects of altitude change when climbing a mountain?*

Explore | The Standard Atmosphere

The atmosphere is divided into four vertical layers (troposphere, stratosphere, mesosphere, and thermosphere) based on their temperature profile. **Figure 1** shows the average vertical temperature profile of the atmosphere above Earth's surface.

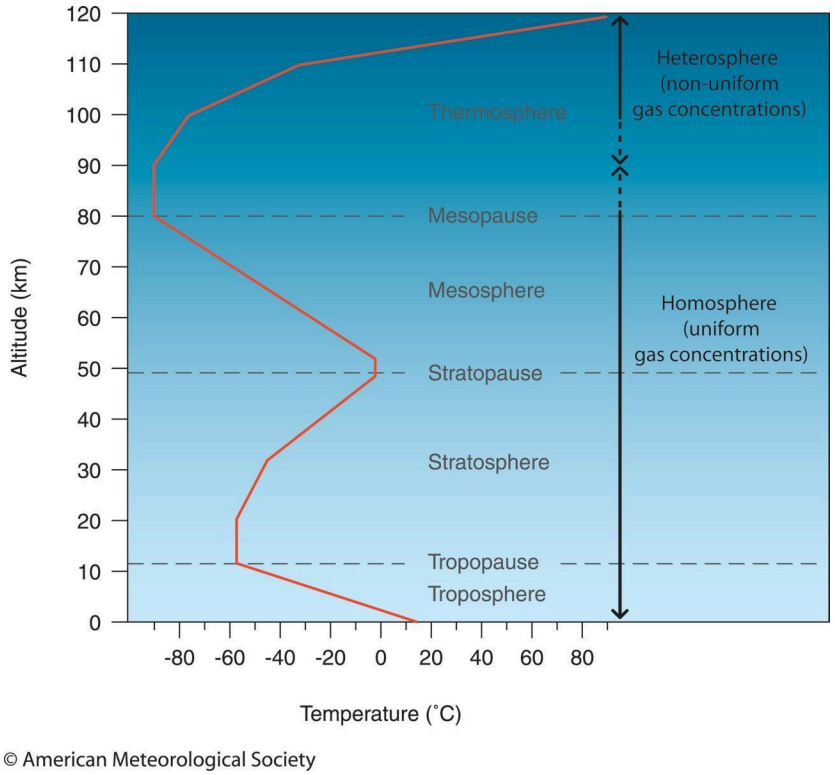


Figure 1. Variation of average temperature with altitude in the atmosphere. [Mills, 2020]

The temperature profile in the troposphere, the lowest level of the atmosphere, generally decreases with altitude. The boundary between the **troposphere** and the stratosphere, where the temperature stops decreasing and becomes nearly constant, is termed the **tropopause**. Further aloft, in the **stratosphere**, air temperatures remain steady with increasing altitude for several kilometers before rising in the upper portions. This increase is mainly due to the absorption of solar energy by the ozone layer. Because there is very little vertical movement in the stratosphere, it is often called the "stable layer."

Air pressure and air density decrease with increasing altitude. Air pressure is the weight per unit surface area of an air column extending to the top of the atmosphere. Therefore, as altitude increases, air pressure decreases since there is less atmosphere above that point. This means that air pressure is greatest at sea level. In meteorology, air pressure is typically measured in millibars (mb), with the average pressure at sea level being 1013.25 mb. For simplicity, meteorologists often round this to 1000 mb at sea level. Near the Earth's surface, air pressure decreases by approximately 100 mb for every 1000 meters of altitude.

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 radiosondes can also be tracked on their ascent to give wind information at various levels. In this way, routine measurements are made twice daily at about 70 stations around the continental U.S.

Standard Atmosphere Profile

Figure 2 is a Stüve diagram, one type of temperature-pressure graph of the troposphere and part of the stratosphere used to plot upper-air weather conditions. Figure 2 focuses on the lowest 16 km of Figure 1.

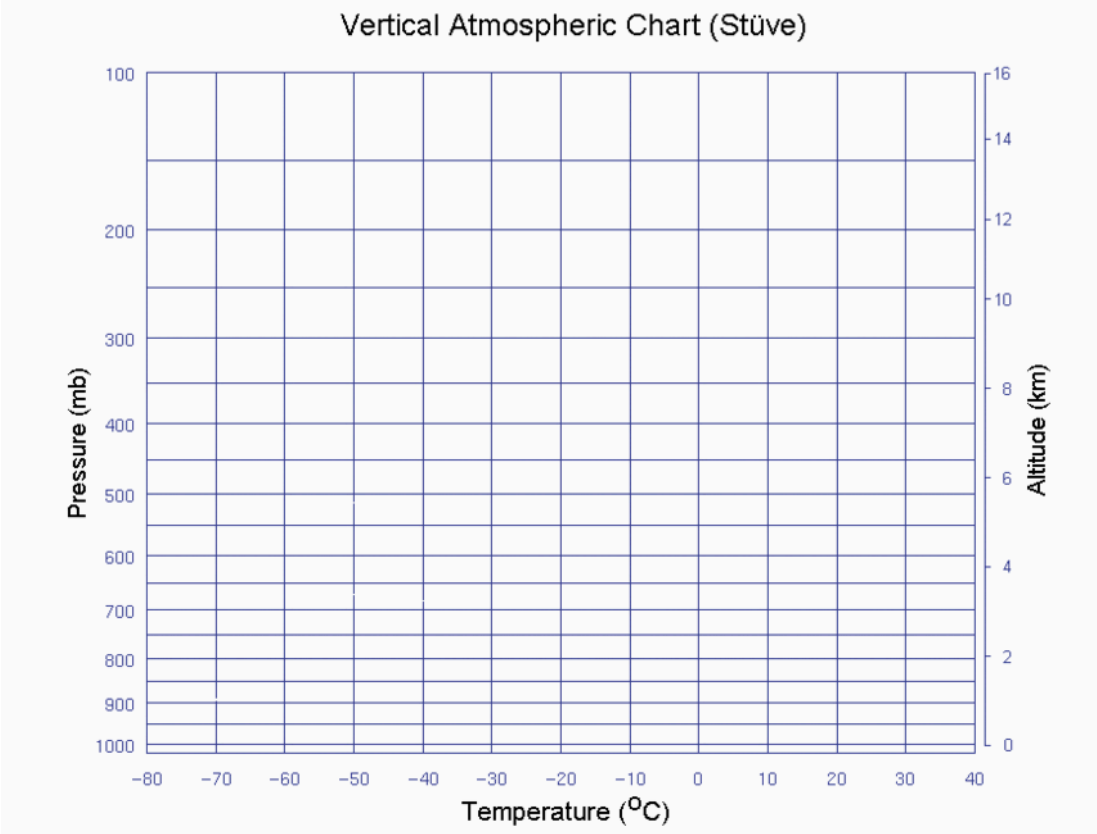


Figure 2. Vertical atmospheric chart (Stüve diagram). [AMS, Extras section]

The right vertical axis of this Stüve diagram is the altitude from the ground upward, starting from 0 km to 16 km. This contrasts with the left vertical axis, as the air pressure is greatest at sea level, which is at 1000 mb for the Standard Atmosphere. Because air pressure is the weight of the overlying air, as we go to higher altitudes, the pressure decreases. 500 mb is half the pressure of sea level (1000 mb), which means if you were at 5.5 km, 50% of the weight of the atmosphere would be above you and 50% would be below you. At 16 km, the pressure is only 100 mb.

Plot the data in **Table 1** onto your copy of Figure 2 and connect adjacent points with solid straight lines. The temperature is plotted along the horizontal axis, starting at –80°C on the left.

Table 1. Standard atmosphere temperature profile

Altitude (km)	Temperature (°C)
16	–56.5
11	–56.5
0	+15.0

On your copy of Figure 2, you created the Standard Atmosphere temperature profile, which describes the average conditions of the vertical atmosphere.

Group Review and Discussion:

1.) *According to your Stüve diagram, what is the altitude of the tropopause in the standard atmosphere? How do you know that?*

2.) *Air pressure 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 distance of about 1 km. However, the 100-mb pressure drop from 400 mb to 300 mb occurs over how much vertical distance? What about the same pressure drop from 200 mb to 100 mb?*

3.) *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 the standard atmosphere, the air pressure of 500 mb (half that at sea level) occurs at what height?*

4.) *According to the Standard Atmosphere data you plotted on Figure 2, the temperature within the troposphere (up to 11 km) decreases with altitude by how many degrees Celsius per km? This is also called the lapse rate.*

Explain | Vertical Weather Profiles

Atmospheric dynamics and processes aloft are important contributors to surface weather systems. Consequently, upper atmospheric observations are collected regularly using radiosondes.

These observations and data collection are part of a worldwide effort to describe the three-dimensional atmosphere for weather analysis and forecasting and are presented in a sounding of the vertical profile. 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. **Figure 3** displays the NWS sites launching radiosondes and tracking their movements to obtain wind information aloft. Upper Atmosphere (U/A) sites are shown as blue circles, and Global Climate Observing Stations (GCOS) are shown as red triangles.

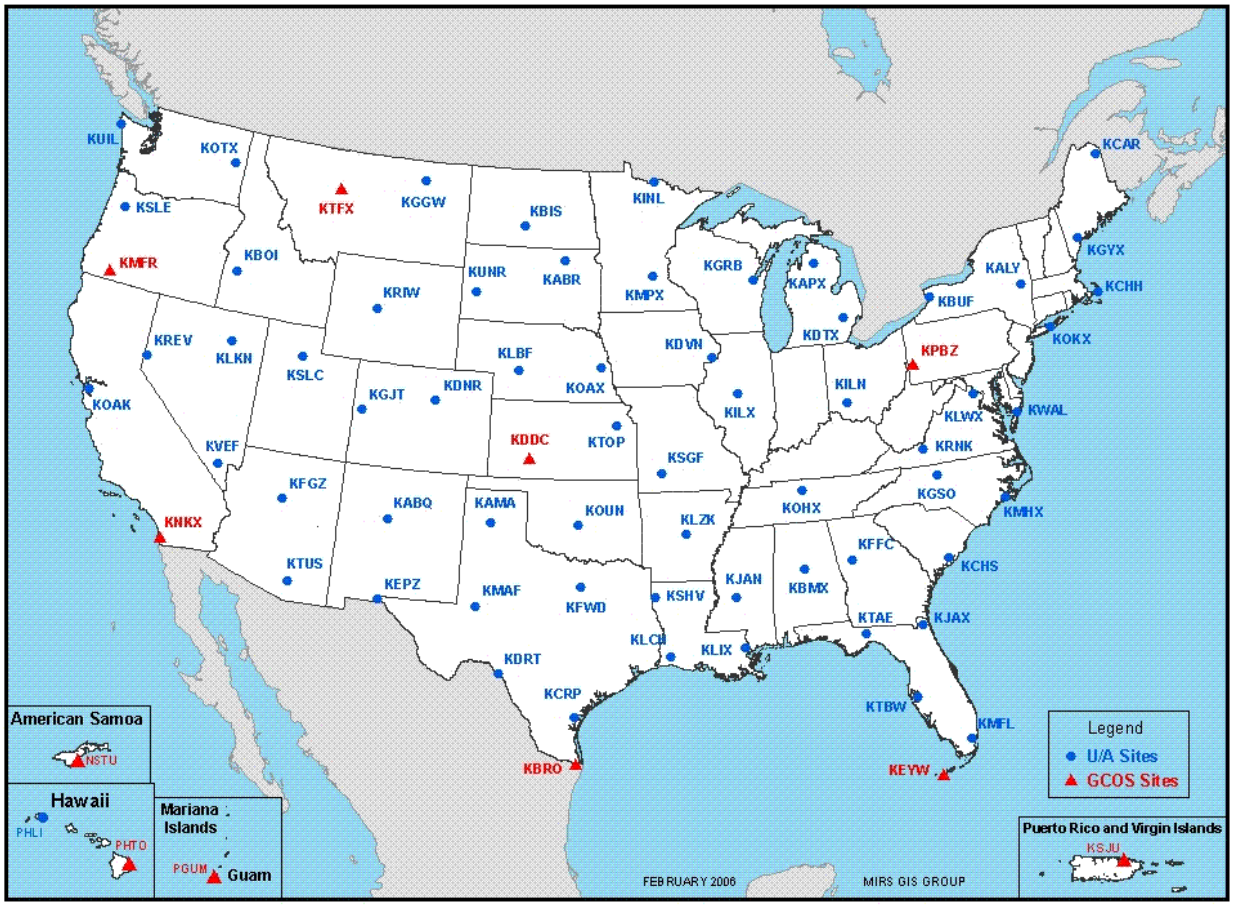


Figure 2. NWS upper-air network. [NOAA/NWS]

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.

An example of radiosonde observation data over Salem, OR (KSLE on Figure 2) in June is recorded in **Table 2**. Using the pressures from the table, plot the corresponding temperatures on your copy of Figure 2 to compare it to the Standard Atmosphere. Use different colors or dashed lines to represent the example data. Remember that the pressure scale decreases upward along the left side. Try plotting the data from the surface upward to represent how the radiosonde profile was created.

Table 2. Radiosonde observations over Salem, Oregon in June.

Pressure (mb)	Altitude (km)	Temperature (°C)
100	–55.7	17,220
150	–55.7	14,030
200	–56.1	12,200
250	–47.9	10,760
300	–37.7	9530
400	–20.3	7470
500	–7.9	5780
600	–0.7	4501
700	6.2	3092
800	8.0	2129
900	8.6	1095
1000 (surface)	13.8	141

The **tropopause** is a defined boundary that separates the troposphere (below) from the stratosphere (above). At the tropopause, the temperature trend changes from decreasing significantly as altitude increases to nearly constant (*isothermal*) or begins to increase with altitude (called a *temperature inversion*) in the lower stratosphere.

Since the weight of the overlying air determines air pressure, this means about half of the weight of air over Salem was above 500 mb and half below.

In the Standard Atmosphere, 500 mb occurs at 5574 m (18,289 ft.). The altitude of the 500-mb level in the example sounding was slightly higher than the Standard Atmosphere. This relatively warm mid-level atmospheric column reflected the conditions that existed in Oregon in June. Warm air is generally more vertically expansive.

Some soundings continue reporting atmospheric conditions up to ~10 mb (~30 km), where the expanding balloon lifting the radiosonde eventually bursts. Above that altitude, there is still about 1% air by weight.

Figure 4 is the plotted Stüve diagram from the same radiosonde data at the same time and location used in Table 2. However, Figure 4 uses all data collected from the radiosonde profile up to 100 mb and also includes the dewpoint, which measures atmospheric water vapor content. The heavy black curve to the right connects temperatures, while the heavy black curve to the left connects dewpoints.

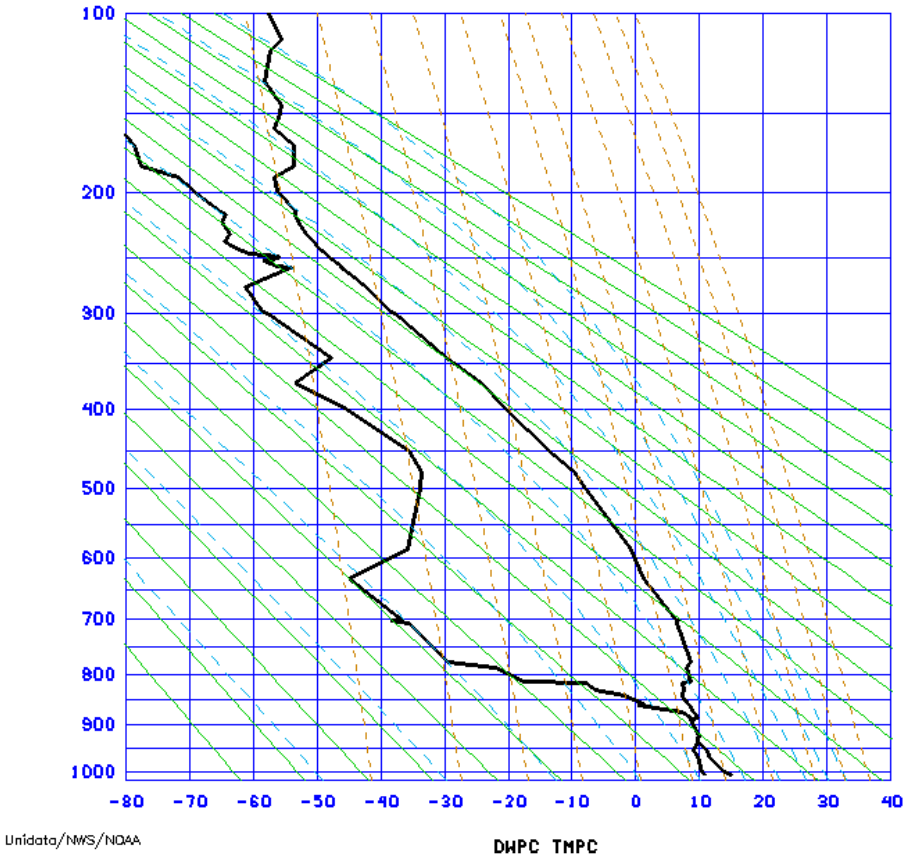


Figure 4. Example plotted radiosonde observations of temperature, dewpoint, and wind on a Stüve diagram, which references pressure, temperature, and altitude.

Knowledge of the temperature profile's finer structure is often important in interpreting atmospheric processes and motions above the surface.

Group Review and Discussion:

1.) *What changes in the Stüve temperature profile signal the altitude of the tropopause?*

2.) *For an atmospheric profile warmer than the Standard Atmosphere, how are the heights of pressure surfaces affected?*

3.) *Hypothesize how the height of the tropopause would vary between a tropical and polar location.*

Elaborate | Upper-Air Weather Maps and Data Visualization

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.

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 halfway 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. Upper-air constant-pressure maps typically display temperature, dewpoint, and wind speed and direction. Another important value reported is the altitude above sea level at which the designated map pressure occurred over each station. 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 elevation 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.

The 850-mb level generally occurs near 1500 m (5000 ft.). This level reflects temperature and humidity patterns in the free atmosphere (above the atmospheric boundary layer) associated with a weather system. Meteorologists use an 850-mb map to observe humidity and temperature advection, movements of higher or lower values of water vapor or heat energy into a region.

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.

The 500-mb level typically occurs around 5,500 m (18,000 ft). This level represents the mid-troposphere circulation pattern and is utilized by meteorologists to forecast the movement and intensification of large-scale weather systems, including surface highs and lows. Meteorologists view the 500 mb level as the steering mechanism for weather systems.

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.

Meteorologists use the 300-mb map (or 250 or 200 mb) for aviation forecasts and to identify wind flow patterns that intensify or weaken large-scale weather systems and move them along.

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 shown in **Figure 5.**

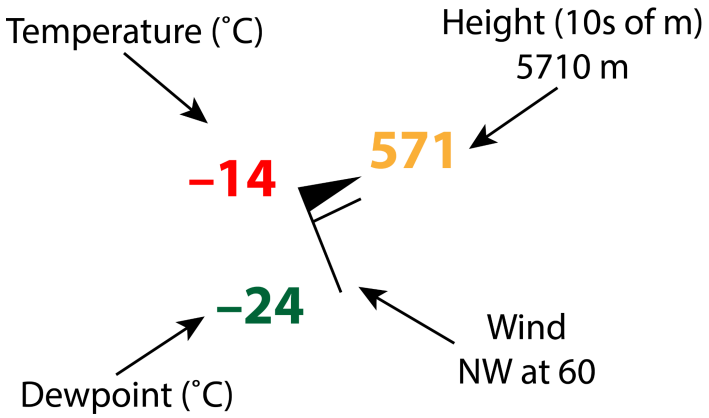


Figure 5. Sample 500-mb upper air weather station.

Figure 6 is the 500-mb map at the same time as the data presented in Table 2. 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. The solid blue lines display locations where 500-mb pressure is at the same altitude. These lines, called contours of height, are drawn at intervals of 60 m. The dashed, red lines are *isotherms*, lines of equal temperature.

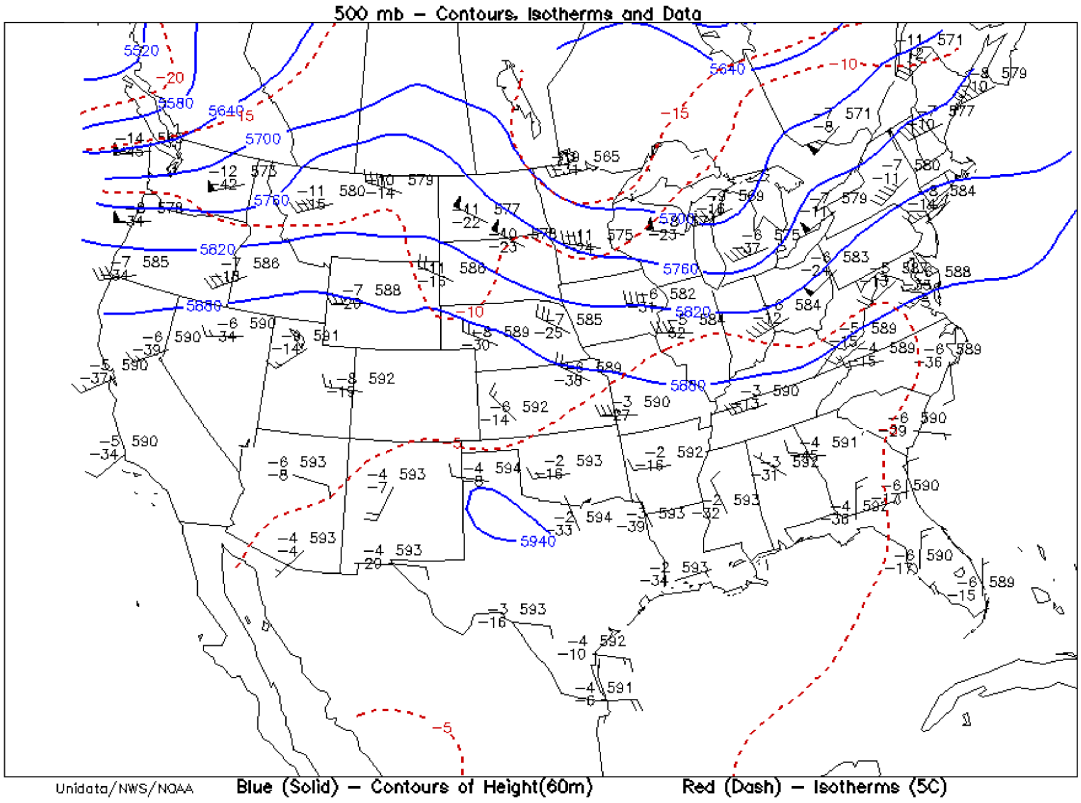


Figure 6. 500-mb upper-air, constant-pressure map with contours of height and isotherms.

1. In Figure 6, the lowest reported height for a pressure reading of 500-mb was _____ m in Washington, and the highest reported height was _____ m in Texas.
   a. 5520 ... 5840
   b. 5640 ... 5940
   c. 5790 ... 5930
   d. 5850 ... 5940

2. 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. As represented in Figure 6, which way is the 500-mb pressure surface generally tilted?
   a. from higher elevations in the south to lower in the north
   b. from higher elevations in the north to lower in the south
   c. it is similar across the country

3. Closed contour lines on constant-pressure upper-air maps identify topographic highs and lows. In Figure 6, the closed contour line in Texas encloses _____ elevations.
   a. higher

b. lower

4. 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, changing the height of the constant-pressure surface. As shown by the isotherms, the constant-pressure surface is lower where temperatures are _____.
   a. colder
   b. warmer

5. From this information, where is the height of a given constant-pressure surface generally highest?
   a. near the equator
   b. in the mid-latitudes
   c. near the poles

6. 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 5, how is wind direction generally aligned to nearby contour lines?
   a. parallel
   b. perpendicular
   c. at an angle to

Fluid Earth contains a variety of weather and climate datasets, including visualization of current, numerical model-derived temperatures, and winds at various atmospheric levels. Go to Fluid Earth. On the left side menu, click on the graph icon (Datasets) and make sure that Topic “weather,” Variable “temperature,” Height “surface,” and Animation “wind” are selected. Then, turn the globe to focus on North America as shown in **Figure 7**.

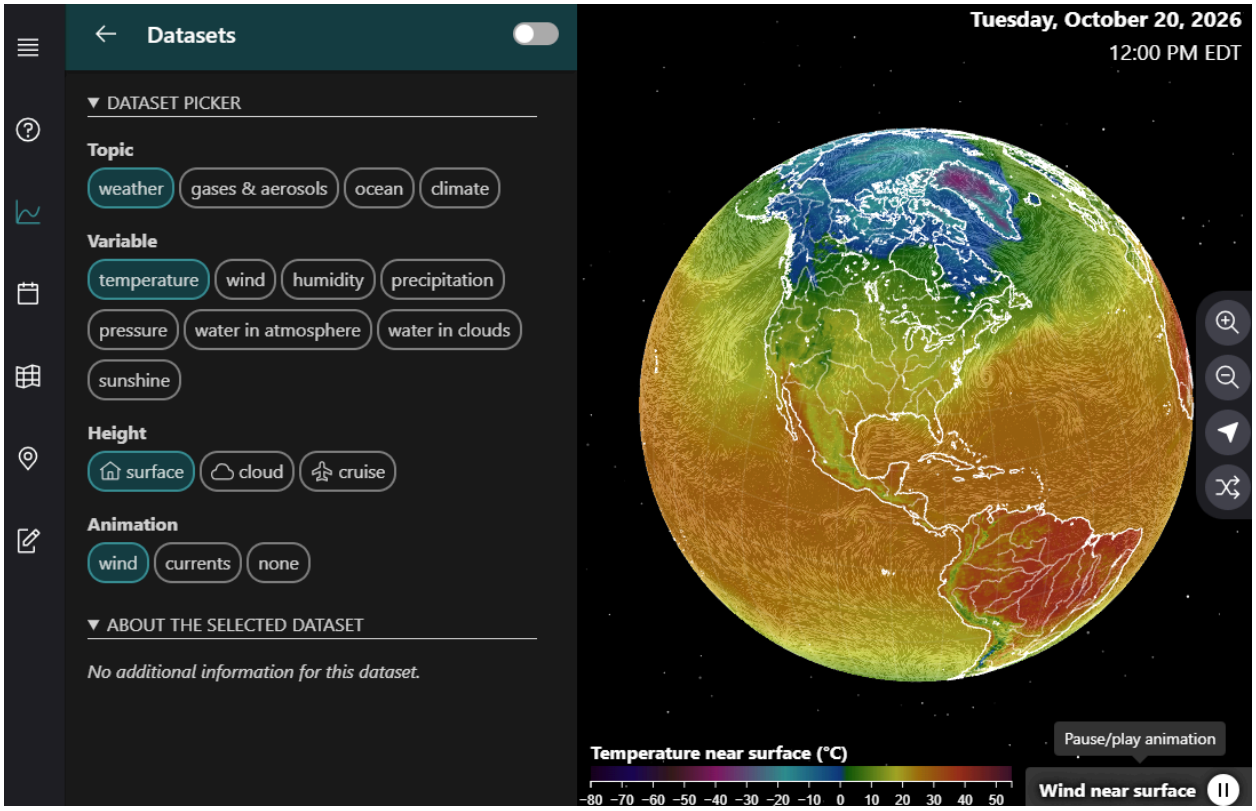


Figure 7. Screenshot of the Fluid Earth Dataset Picker with default selections [Fluid Earth].

You are looking at the most recent data, so keep in mind which season you are in. To compare temperatures at the surface to those higher in the atmosphere, toggle from "surface" to "cloud" level, defined as 500 mb or about 18,000 ft., and the "cruise" level, defined as 200 mb or about 39,000 ft. Note how temperature varies throughout North America and also with an increase in altitude. Move your cursor over any spot on the map to view the temperature in °C.

7. Compare surface temperature over southern Florida at the surface, cloud, and cruise levels. The temperature change from Earth's surface to 200 mb at cruise level (in the vicinity of the tropopause) varies _____ degrees Celsius.
   a. a few
   b. 10 to 20
   c. 20 to 60
   d. more than 100

8. Select the surface and then cloud level, moving your cursor from the equatorial region toward the North Pole. The temperature at both levels generally _____ as you travel north.

a. decreases
b. increases
c. remains constant

9. Select the cruise level, which is at about 200 mb. Moving your cursor from the equatorial region toward the North Pole. The temperature generally _____ as you travel north.
   a. decreases
   b. increases
   c. remains constant

You might find the answer to #9 somewhat counterintuitive. The pattern observed at the cruise (200 mb) level is influenced by the slope of the tropopause from higher near the equator, where the air is much warmer below it, downward toward the poles, where air below the tropopause is much cooler. At the cruise level, you generally observe the upper troposphere, below the tropopause, near the equator and the lower stratosphere, above the tropopause, near the North Pole.

Now, focus your attention on the white streamlines indicating wind flow. On the DATASET PICKER, change the Variable to “wind.” Use the + magnifying glass on the rightside of the screen to zoom in on the United States and Canada. Place your cursor at any point on the map to see the numerical model-derived wind speed in km/h. The longer the streamline on the map, the higher the wind speed.

10. Compare the wind speeds at the surface, cloud, and cruise levels by changing the height settings. Wind speed generally _____ with altitude.
    a. decreases
    b. increases
    c. remains constant

11. A “ribbon” of highest wind speeds is present at the _____ level. This is the jet stream.
    a. surface
    b. cloud, or 500-mb
    c. cruise, or 200-mb

12. The _____ level is considered the steering level for weather systems.
    a. surface
    b. cloud, or 500-mb
    c. cruise, or 200-mb

Evaluate | Review of the Atmosphere Aloft

To review what has been presented and investigated during this module:

13. Half of the air molecules within the atmosphere typically occur below an altitude of _____.
    a. 1 km
    b. 2.5 km
    c. 5.5 km
    d. 11 km

14. The boundary between the troposphere and stratosphere is called the _____.
    a. mesopause
    b. tropopause
    c. stratopause

15. Air pressure decreases most rapidly with altitude in the _____ troposphere.
    a. lower
    b. higher
    c. middle

16. Upper-air observations by NWS radiosondes *do not* include _____.
    a. air pressure
    b. temperature and dewpoint
    c. wind
    d. cloud cover

17. In winter, the height of the 500-mb pressure surface is generally highest in _____.
    a. Northern Canada
    b. Southern Canada
    c. the northern U.S.
    d. the southern U.S.

18. The highest wind speeds in the troposphere are found _____.
    a. just above the surface, near 850 mb
    b. near 500 mb
    c. between 300 and 200 mb
    d. at 10 mb

Workshop Extensions | Plotting RAOB Data

Plotting radiosonde data on a Stüve diagram (temperature, dewpoint, wind speed and direction)

References

Mills, E. W. (Ed.), 2020: *Weather Studies: Introduction to Atmospheric Science 7th Edition*. American Meteorological Society, 909 pp.

Acknowledgments

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