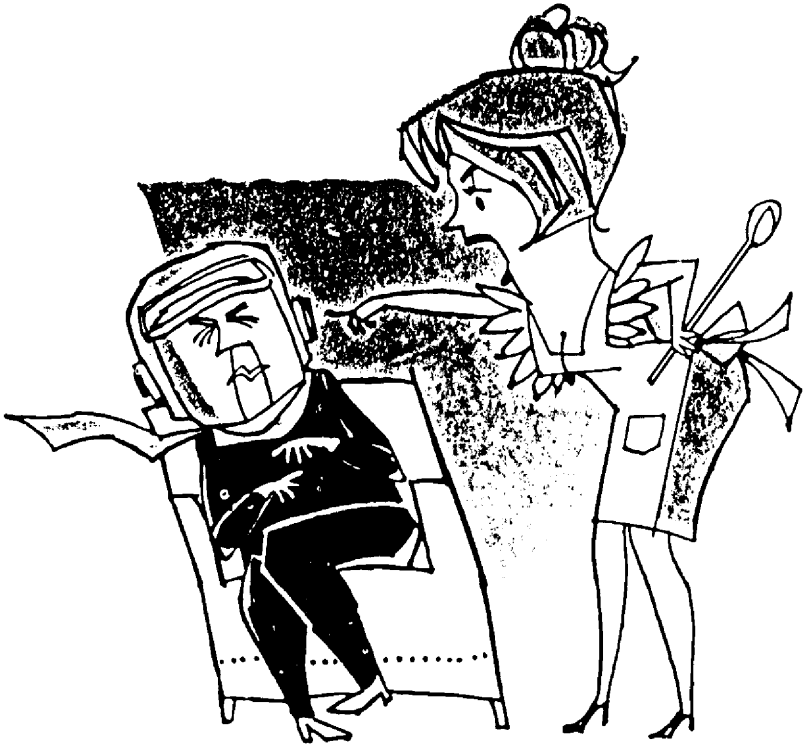


Chapter 3
ATMOSPHERIC PRESSURE AND ALTIMETRY

When you understand pressure, its measurement, and effects of temperature and altitude on pressure, you can more readily grasp the significance of pressure and its application to altimetry.

ATMOSPHERIC PRESSURE

Atmospheric pressure is the force per unit area exerted by the weight of the atmosphere. Since air is not solid, we cannot weigh it with conventional scales. Yet, Toricelli proved three centuries ago that he could weigh the atmosphere by balancing it against a column of mercury. He actually measured pressure converting it directly to weight.

MEASURING PRESSURE

The instrument Toricelli designed for measuring pressure is the barometer. Weather services and the aviation community use two types of barometers in measuring pressure—the mercurial and aneroid.

The Mercurial Barometer

The mercurial barometer, diagrammed in figure 8, consists of an open dish of mercury into which we place the open end of an evacuated glass tube. Atmospheric pressure forces mercury to rise in the tube. At stations near sea level, the column of mercury rises on the average to a height of 29.92 inches or 760 millimeters. In other words, a column of mercury of that height weighs the same as a column of air having the same cross section as the column of mercury and extending from sea level to the top of the atmosphere.

Why do we use mercury in the barometer? Mercury is the heaviest substance available which remains liquid at ordinary temperatures. It permits the instrument to be of manageable size. We could use water, but at sea level the water column would be about 34 feet high.

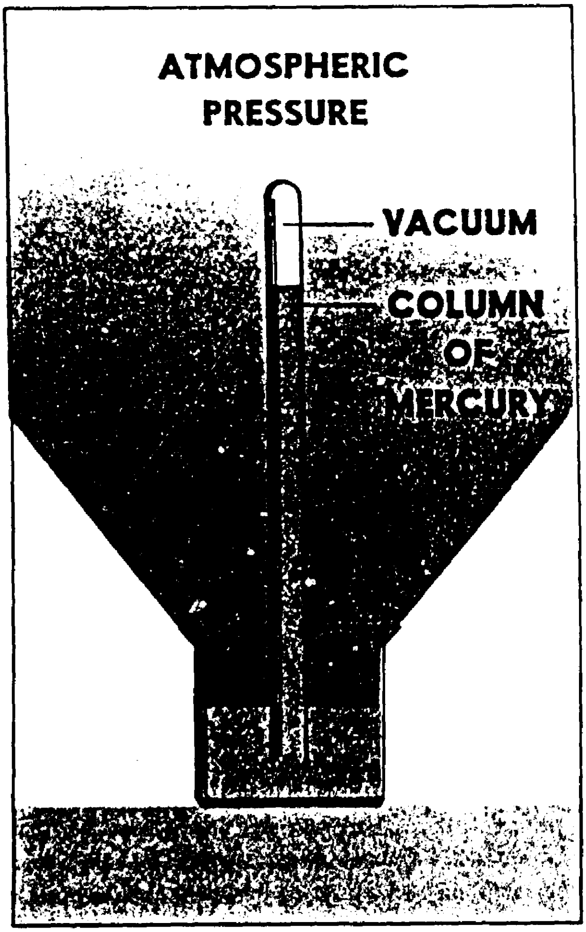


FIGURE 8. The mercurial barometer. Atmospheric pressure forces mercury from the open dish upward into the evacuated glass tube. The height of the mercury column is a measure of atmospheric pressure.

The Aneroid Barometer

Essential features of an aneroid barometer illustrated in figure 9 are a flexible metal cell and the registering mechanism. The cell is partially evacuated and contracts or expands as pressure changes. One end of the cell is fixed, while the other end moves the registering mechanism. The coupling mechanism magnifies movement of the cell driving an indicator hand along a scale graduated in pressure units.

Pressure Units

Pressure is expressed in many ways throughout the world. The term used depends somewhat on its application and the system of measurement. Two popular units are "inches of mercury" or "millimeters of mercury." Since pressure is force per unit area, a more explicit expression of pressure is "pounds per square inch" or "grams per square centimeter." The term "millibar" precisely expresses pressure as a force per unit area, one millibar being a force of 1,000 dynes per square centimeter. The millibar is rapidly becoming a universal pressure unit.

Station Pressure

Obviously, we can measure pressure only at the point of measurement. The pressure measured at a station or airport is "station pressure" or the actual pressure at field elevation. We know that pressure at high altitude is less than at sea level or low altitude. For instance, station pressure at Denver is less than at New Orleans. Let's look more closely at some factors influencing pressure.

PRESSURE VARIATION

Pressure varies with altitude and temperature of the air as well as with other minor influences which we neglect here.

Altitude

As we move upward through the atmosphere, weight of the air above becomes less and less. If we carry a barometer with us, we can measure a decrease in pressure as weight of the air above decreases. Within the lower few thousand feet of the troposphere, pressure decreases roughly one inch for each 1,000 feet increase in altitude. The higher we go, the slower is the rate of decrease with height.

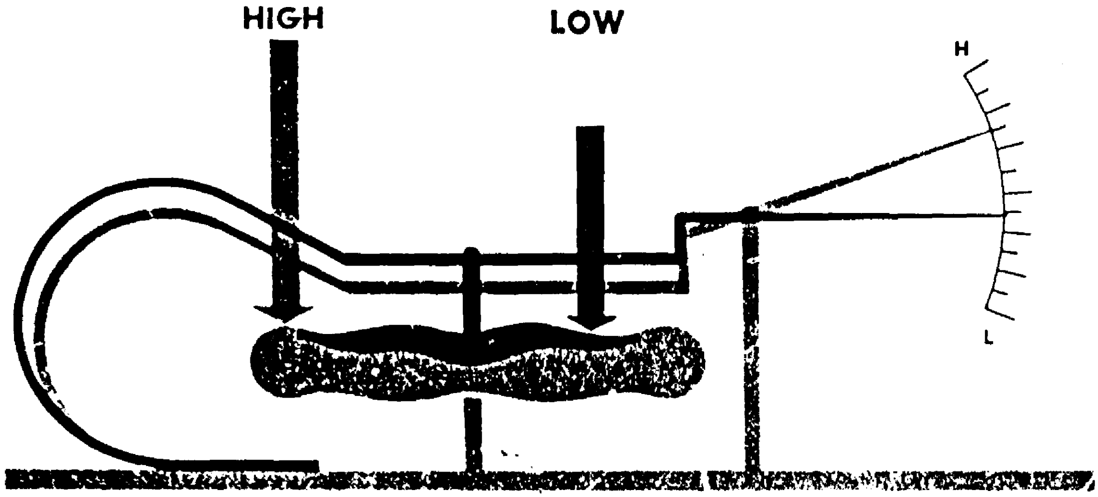


FIGURE 9. The aneroid barometer. The aneroid consists of a partially evacuated metal cell, a coupling mechanism, and an indicator scale. The cell contracts and expands with changing pressure. The coupling mechanism drives the indicator along a scale graduated in pressure units.

Figure 10 shows the pressure decrease with height in the standard atmosphere. These standard altitudes are based on standard temperatures. In the real atmosphere, temperatures are seldom standard, so let's explore temperature effects.

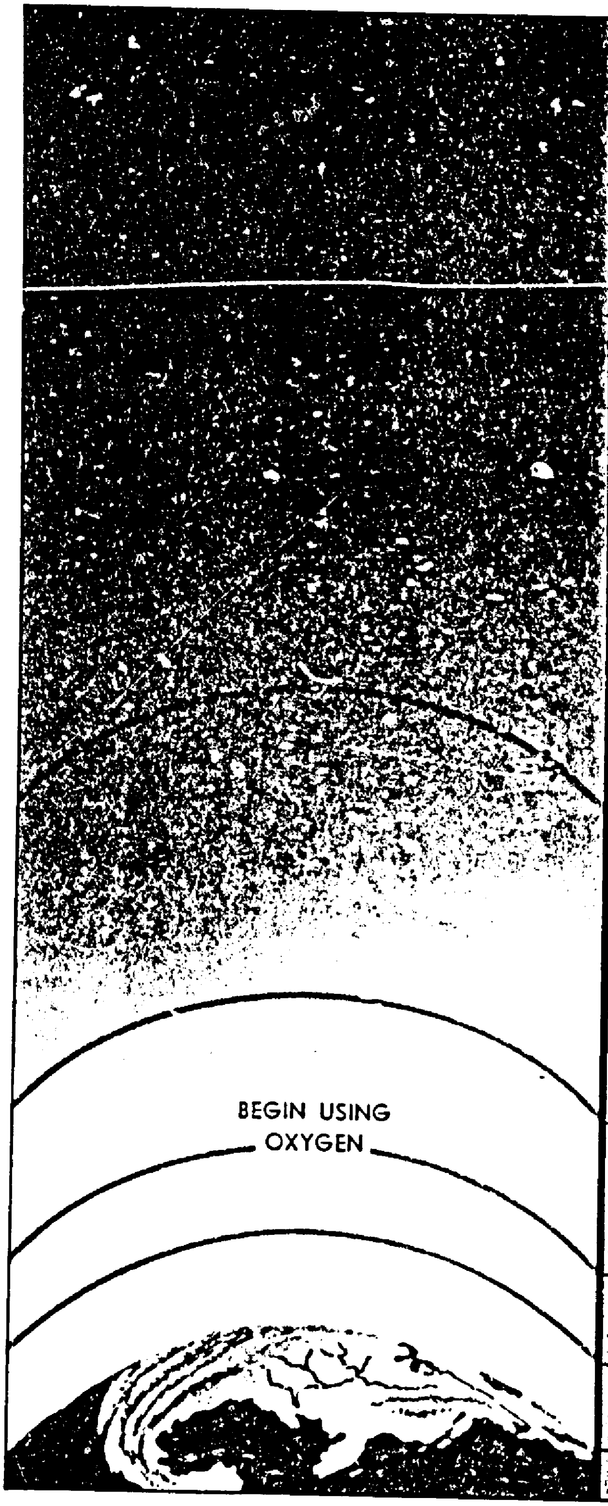
Temperature

Like most substances, air expands as it becomes warmer and shrinks as it cools. Figure 11 shows three columns of air—one colder than standard, one at standard temperature, and one warmer than standard. Pressure is equal at the bottom of each column and equal at the top of each column. Therefore, pressure decrease upward through each column is the same. Vertical expansion of the warm column has made it higher than the column at standard temperature. Shrinkage of the cold column has made it shorter. Since pressure decrease is the same in each column, the *rate of decrease* of pressure with height in warm air is less than standard; the rate of decrease of pressure with height in cold air is greater than standard. You will soon see the importance of temperature in altimetry and weather analysis and on aircraft performance.

Sea Level Pressure

Since pressure varies with altitude, we cannot readily compare station pressures between stations at different altitudes. To make them comparable, we must adjust them to some common level. Mean sea level seems the most feasible common reference. In figure 12, pressure measured at a 5,000-foot station is 25 inches; pressure increases about 1 inch for each 1,000 feet or a total of 5 inches. Sea level pressure is approximately 25 + 5 or 30 inches. The weather observer takes temperature and other effects into account, but this simplified example explains the basic principle of sea level pressure reduction.

We usually express sea level pressure in millibars. Standard sea level pressure is 1013.2 millibars, 29.92 inches of mercury, 760 millimeters of mercury, or about 14.7 pounds per square inch. Figures 23 and 24 in chapter 4 show world-wide averages of sea level pressure for the months of July and January. Pressure changes continually, however, and departs widely from these averages. We use a sequence of weather maps to follow these changing pressures.



ALTITUDE (feet)	ALTITUDE (kilometers)	PRESSURE (inches of mercury)	PRESSURE (millibars)	TEMPERATURE (degrees Celsius)
70,000	21.3	1.3	44.0	-55.2
50,000	15.2	3.4	116.1	-56.5
35,000	10.7	7.0	237.1	-54.0
18,000	5.5	14.9	504.6	-20.6
10,000	3.0	20.6	707.8	-4.8
5,000	1.5	24.9	843.2	5.1
MEAN SEA LEVEL		29.92	1013.2	15.0 (59°F)

FIGURE 10. The standard atmosphere. Note how pressure decreases with increasing height; the rate of decrease with height is greatest in lower levels.

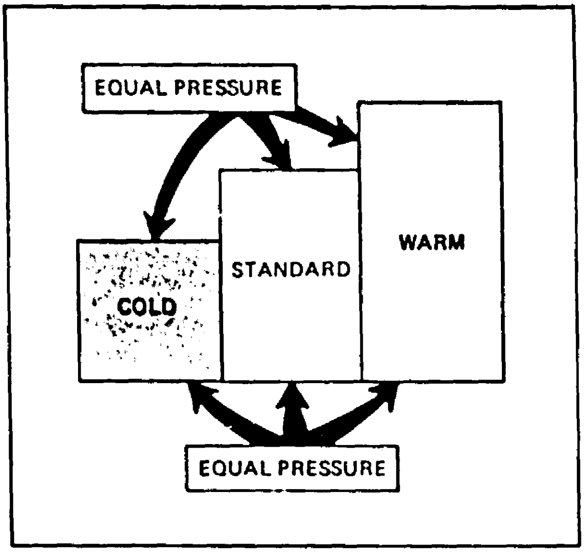


Figure 11. Three columns of air showing how decrease of pressure with height varies with temperature. Left column is colder than average and right column, warmer than average. Pressure is equal at the bottom of each column and equal at the top of each column. Pressure decreases most rapidly with height in the cold air and least rapidly in the warm air.

Pressure Analyses

We plot sea level pressures on a map and draw lines connecting points of equal pressure. These lines of equal pressure are *isobars*. Hence, the surface map is an *isobaric analysis* showing identifiable, organized pressure patterns. Five pressure systems are shown in figure 13 and are defined as follow:

1. LOW—a center of pressure surrounded on all sides by higher pressure; also called a cyclone. Cyclonic curvature is the curvature of isobars to the left when you stand with lower pressure to your left.
2. HIGH—a center of pressure surrounded on all sides by lower pressure, also called an anticyclone. Anticyclonic curvature is the curvature of isobars to the right when you stand with lower pressure to your left.
3. TROUGH—an elongated area of low pressure with the lowest pressure along a line marking maximum cyclonic curvature.
4. RIDGE—an elongated area of high pressure with the highest pressure along a line marking maximum anticyclonic curvature.
5. COL—the neutral area between two highs and two lows. It also is the intersection of a trough and a ridge. The col on a pressure surface is analogous to a mountain pass on a topographic surface.

Upper air weather maps reveal these same types of pressure patterns aloft for several levels. They also show temperature, moisture, and wind at each level. In fact, a chart is available for a level within a few thousand feet of your planned cruising altitude. Aviation Weather Services lists the approximate heights of upper air maps and shows details of the surface map and each upper air chart.

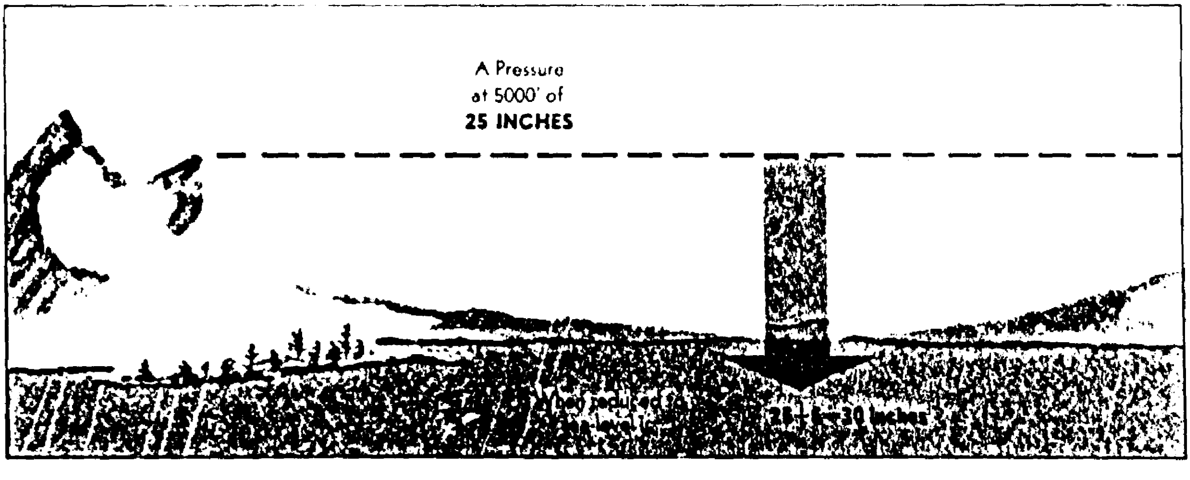


Figure 12. Reduction of station pressure to sea level. Pressure increases about 1 inch per 1,000 feet from the station elevation to sea level.

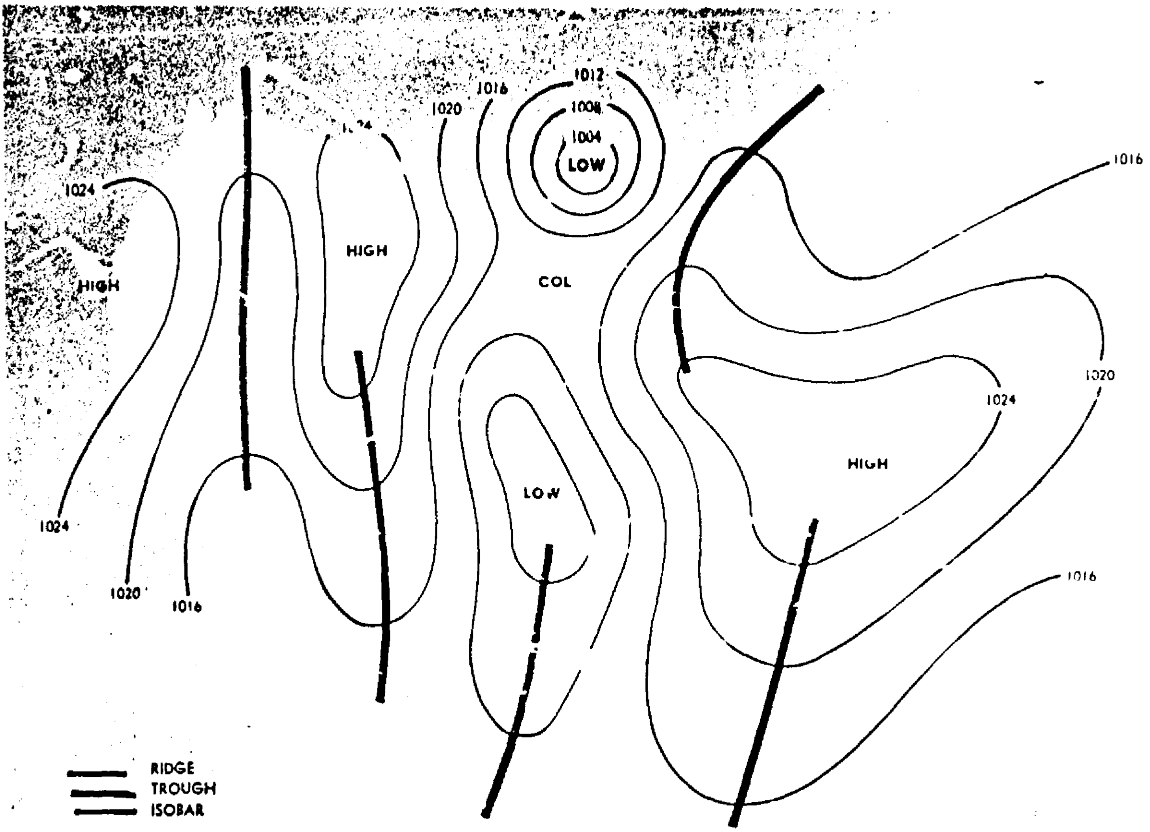


FIGURE 13. Pressure systems.

Chapter 4 of this book ties together the surface chart and upper air charts into a three-dimensional picture.

An upper air map is a *constant pressure analysis*. But, what do we mean by "constant pressure"? Constant pressure simply refers to a specific pressure. Let's arbitrarily choose 700 millibars. Everywhere above the earth's surface, pressure decreases with height; and at some height, it decreases to this constant pressure of 700 millibars. Therefore, there is a "surface" throughout the atmosphere at which pressure is 700 millibars. We call this the 700-millibar constant pressure surface. However, the *height* of this surface is *not* constant. Rising pressure pushes the surface upward into highs and ridges. Falling pressure lowers the height of the surface into lows and troughs. These systems migrate continuously as "waves" on the pressure surface. Remember that we chose this constant pressure surface arbitrarily as a reference. It in no way defines any discrete boundary.

The National Weather Service and military weather services take routine scheduled upper air observations—sometimes called soundings. A balloon carries aloft a radiosonde instrument which consists of miniature radio gear and sensing elements. While in flight, the radiosonde transmits data from which a specialist determines wind, temperature, moisture, and height at selected pressure surfaces.

We routinely collect these observations, plot the heights of a constant pressure surface on a map, and draw lines connecting points of equal height. These lines are *height contours*. But, what is a height contour?

First, consider a topographic map with contours showing variations in elevation. These are height contours of the terrain surface. The Earth surface is a fixed reference and we contour variations in its height.

The same concept applies to height contours on a constant pressure chart, except our reference is a *constant pressure surface.* We simply contour the heights of the pressure surface. For example, a 700-millibar constant pressure analysis is a contour map of the heights of the 700-millibar pressure surface. While the contour map is based on variations in height, these variations are small when compared to flight levels, and for all practical purposes, you may regard the 700-millibar chart as a weather map at approximately 10,000 feet or 3,048 meters.

A contour analysis shows highs, ridges, lows, and troughs aloft just as the isobaric analysis shows such systems at the surface. What we say concerning pressure patterns and systems applies equally to an isobaric or a contour analysis.

Low pressure systems quite often are regions of poor flying weather, and high pressure areas predominantly are regions of favorable flying weather. A word of caution, however—use care in applying the low pressure-bad weather, high pressure-good weather rule of thumb; it all too frequently fails. When planning a flight, gather *all* information possible on expected weather. Pressure patterns also bear a direct relationship to wind which is the subject of the next chapter. But first, let's look at pressure and altimeters.

ALTIMETRY

The altimeter is essentially an aneroid barometer. The difference is the scale. The altimeter is graduated to read increments of height rather than units of pressure. The standard for graduating the altimeter is the standard atmosphere.

ALTITUDE

Altitude seems like a simple term; it means height. But in aviation, it can have many meanings.

True Altitude

Since existing conditions in a real atmosphere are seldom standard, altitude indications on the altimeter are seldom actual or true altitudes. *True altitude is the actual or exact altitude above mean sea level.* If your altimeter does not indicate true altitude, what does it indicate?

Indicated Altitude

Look again at figure 11 showing the effect of mean temperature on the thickness of the three columns of air. Pressures are equal at the bottoms and equal at the tops of the three layers. Since the altimeter is essentially a barometer, altitude indicated by the altimeter at the top of each column would be the same. To see this effect more clearly, study figure 14. Note that in the warm air, you fly at an altitude higher than indicated. In the cold air, you are at an altitude lower than indicated.

Height indicated on the altimeter also changes with changes in surface pressure. A movable scale on the altimeter permits you to adjust for surface pressure, but you have no means of adjusting the instrument for mean temperature of the column of air below you. *Indicated altitude is the altitude above mean sea level indicated on the altimeter when set at the local altimeter setting.* But what is altimeter setting?

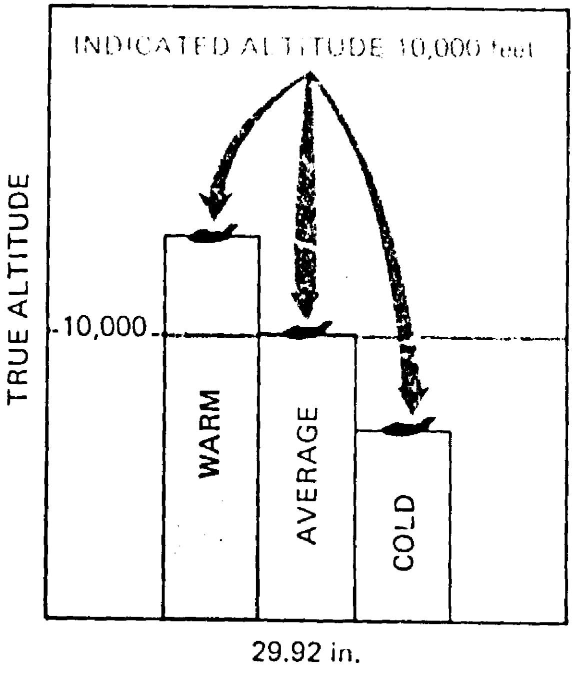


FIGURE 14. Indicated altitude depends on air temperature below the aircraft. Since pressure is equal at the bases and equal at the tops of each column, indicated altitude is the same at the top of each column. When air is colder than average (right), the altimeter reads higher than true altitude. When air is warmer than standard (left), the altimeter reads lower than true altitude.

Altimeter Setting

Since the altitude scale is adjustable, you can set the altimeter to read true altitude at some specified height. Takeoff and landing are the most critical phases of flight; therefore, airport elevation is the most desirable altitude for a true reading of the altimeter. *Altimeter setting is the value to which the scale of the pressure altimeter is set so the altimeter indicates true altitude at field elevation.*

In order to ensure that your altimeter reading is compatible with altimeter readings of other aircraft in your vicinity, keep your altimeter setting current. Adjust it frequently in flight to the altimeter setting reported by the nearest tower or weather reporting station. Figure 15 shows the trouble you can encounter if you are lax in adjusting your altimeter in flight. Note that as you fly from high pressure to low pressure, you are lower than your altimeter indicates.

Figure 16 shows that as you fly from warm to cold air, your altimeter reads too high—you are lower than your altimeter indicates. Over flat terrain this lower than true reading is no great problem; other aircraft in the vicinity also are flying indicated rather than true altitude, and your altimeter readings are compatible. If flying in cold weather over mountainous areas, however, you must take this difference between indicated and true altitude into account. You must know that your true altitude assures clearance of terrain, so you compute a correction to indicated altitude.

Corrected (Approximately True) Altitude

If it were possible for a pilot always to determine mean temperature of the column of air between the aircraft and the surface, flight computers would be designed to use this mean temperature in computing true altitude. However, the only guide a pilot has to temperature below him is free air temperature at his altitude. Therefore, the flight computer uses outside air temperature to correct indicated altitude to approximate true altitude. *Corrected altitude is indicated altitude corrected for the temperature of the air column below the aircraft, the correction being based on the estimated departure of the existing temperature from standard atmospheric temperature.* It is a close approximation to true altitude and is labeled *true altitude* on flight computers. It is close enough to

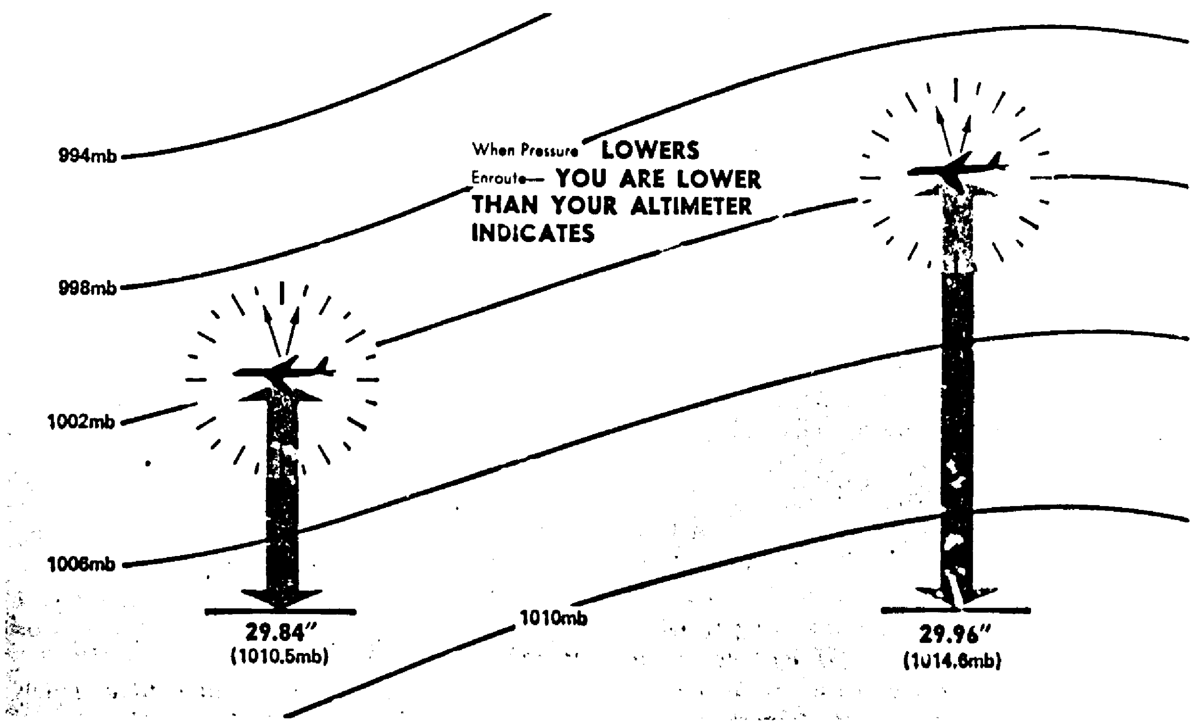


FIGURE 15. When flying from high pressure to lower pressure without adjusting your altimeter, you are losing true altitude.

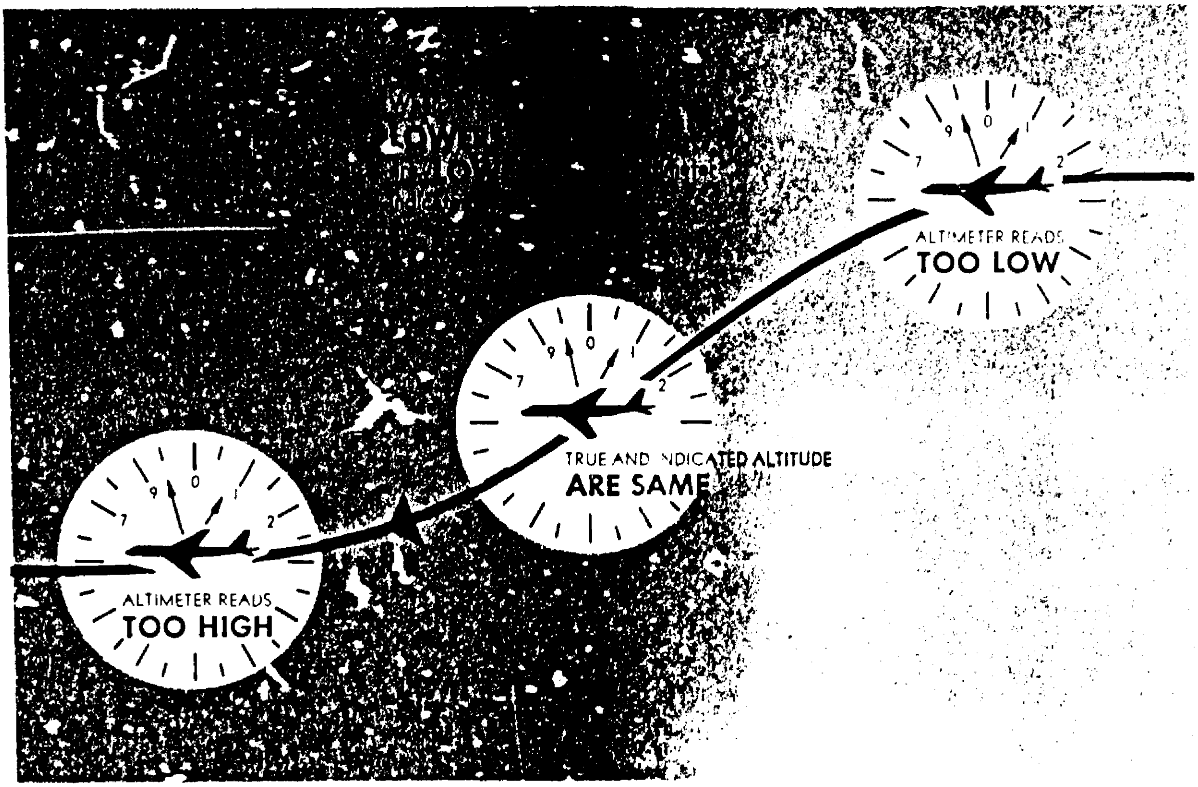


FIGURE 16. Effect of temperature on altitude. When air is warmer than average, you are higher than your altimeter indicates. When temperature is colder than average, you are lower than indicated. When flying from warm to cold air at a constant indicated altitude, you are losing true altitude.

true altitude to be used for terrain clearance provided you have your altimeter set to the value reported from a nearby reporting station.

Pilots have met with disaster because they failed to allow for the difference between indicated and true altitude. In cold weather when you must clear high terrain, take time to compute true altitude.

FAA regulations require you to fly indicated altitude at low levels and pressure altitude at high levels (at or above 18,000 feet at the time this book was printed). What is pressure altitude?

Pressure Altitude

In the standard atmosphere, sea level pressure is 29.92 inches of mercury or 1013.2 millibars. Pressure falls at a fixed rate upward through this hypothetical atmosphere. Therefore, in the standard atmosphere, a given pressure exists at any specified altitude. *Pressure altitude is the altitude in the standard atmosphere where pressure is the same as where you are.* Since at a specific pressure altitude, pressure is everywhere the same, a constant pressure surface defines a constant pressure altitude. When you fly a constant pressure altitude, you are flying a constant pressure surface.

You can always determine pressure altitude from your altimeter whether in flight or on the ground. Simply set your altimeter at the standard altimeter setting of 29.92 inches, and your altimeter indicates pressure altitude.

A conflict sometimes occurs near the altitude separating flights using indicated altitude from those using pressure altitude. Pressure altitude on one aircraft and indicated altitude on another may indicate altitude separation when, actually, the two are at the same true altitude. All flights using pressure altitude at high altitudes are IFR controlled flights. When this conflict occurs, air traffic controllers prohibit IFR flight at the conflicting altitudes.

DENSITY ALTITUDE

What is density altitude? *Density altitude simply is the altitude in the standard atmosphere where air density is the same as where you are.* Pressure, temperature, and humidity determine air density. On a hot day, the air becomes "thinner" or lighter, and its density where you are is equivalent to a higher altitude in the standard atmosphere—thus the term "high density altitude." On a cold day, the air becomes heavy; its density is the same as that at an altitude in the standard atmosphere lower than your altitude—"low density altitude."

Density altitude is not a height reference; rather, it is an index to aircraft performance. Low density altitude increases performance. ***High density altitude*** is a real hazard since it ***reduces aircraft performance.*** It affects performance in three ways. (1) It reduces power because the engine takes in less air to support combustion. (2) It reduces thrust because the propeller gets less grip on the light air or a jet has less mass of gases to spit out the exhaust. (3) It reduces lift because the light air exerts less force on the airfoils.

You cannot detect the effect of high density altitude on your airspeed indicator. Your aircraft lifts off, climbs, cruises, glides, and lands at the prescribed indicated airspeeds. But at a specified indicated airspeed, your true airspeed and your groundspeed increase proportionally as density altitude becomes higher.

The net results are that high density altitude lengthens your takeoff and landing rolls and reduces your rate of climb. Before lift-off, you must attain a faster groundspeed, and therefore, you need more runway; your reduced power and thrust add a need for still more runway. You land at a

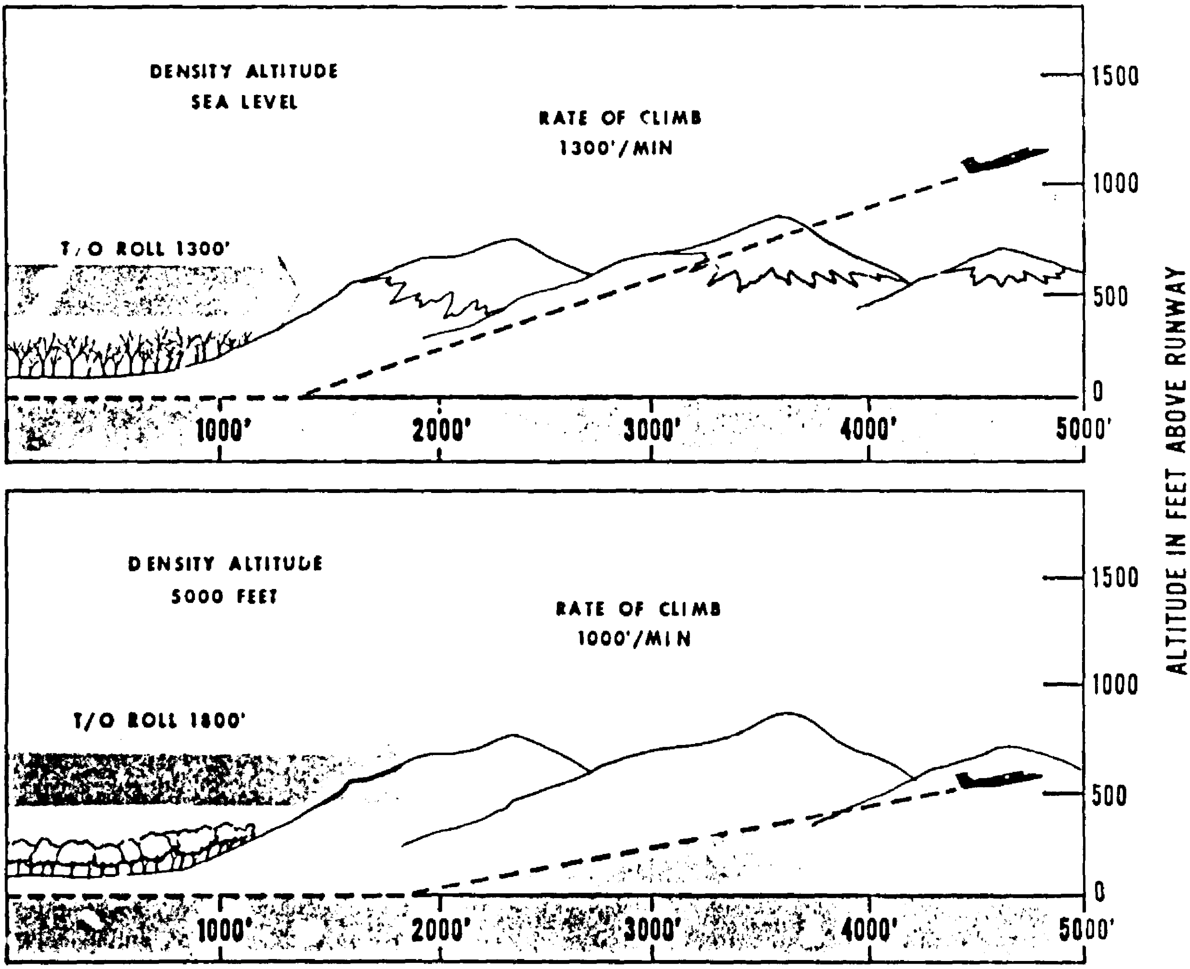


FIGURE 17. Effect of density altitude on takeoff and climb. High density altitude lengthens takeoff roll and reduces rate of climb.

faster groundspeed and, therefore, need more room to stop. At a prescribed indicated airspeed, you are flying at a faster true airspeed, and therefore, you cover more distance in a given time which means climbing at a more shallow angle. Add to this the problems of reduced power and rate of climb, and you are in double jeopardy in your climb. Figure 17 shows the effect of density altitude on takeoff distance and rate of climb.

High density altitude also can be a problem at cruising altitudes. When air is abnormally warm, the high density altitude lowers your service ceiling. For example, if temperature at 10,000 feet pressure altitude is 20° C, density altitude is 12,700 feet. (Check this on your flight computer.) Your aircraft will perform as though it were at 12,700 indicated with a normal temperature of -8° C.

To compute density altitude, set your altimeter at 29.92 inches or 1013.2 millibars and read pressure altitude from your altimeter. Read outside air temperature and then use your flight computer to get density altitude. On an airport served by a weather observing station, you usually can get density altitude for the airport from the observer. Section 16 of AVIATION WEATHER SERVICES has a graph for computing density altitude if you have no flight computer handy.

IN CLOSING

Pressure patterns can be a clue to weather causes and movement of weather systems, but they give only a part of the total weather picture. Pressure decreases with increasing altitude. The altimeter is an aneroid barometer graduated in increments of altitude in the standard atmosphere instead of units of pressure. Temperature greatly affects the rate of pressure decrease with height; therefore, it influences altimeter readings. Temperature also determines the density of air at a given pressure (density altitude). Density altitude is an index to aircraft performance. Always be alert for departures of pressure and temperature from normals and compensate for these abnormalities.

Following are a few operational reminders:

1. Beware of the low pressure-bad weather, high pressure-good weather rule of thumb. It frequently fails. Always get the ***complete*** weather picture.
2. When flying from high pressure to low pressure at constant indicated altitude and without adjusting the altimeter, you are losing true altitude.
3. When temperature is colder than standard, you are at an altitude *lower* than your altimeter indicates. When temperature is warmer than standard, you are *higher* than your altimeter indicates.
4. When flying cross country, keep your altimeter setting current. This procedure assures more positive altitude separation from other aircraft.
5. When flying over high terrain in cold weather, compute your true altitude to ensure terrain clearance.
6. When your aircraft is heavily loaded, the temperature is abnormally warm, and/or the pressure is abnormally low, compute density altitude. Then check your aircraft manual to ensure that you can become airborne from the available runway. Check further to determine that your rate of climb permits clearance of obstacles beyond the end of the runway. This procedure is advisable for any airport regardless of altitude.
7. When planning takeoff or landing at a high altitude airport regardless of load, determine density altitude. The procedure is especially critical when temperature is abnormally warm or pressure abnormally low. Make certain you have sufficient runway for takeoff or landing roll. Make sure you can clear obstacles beyond the end of the runway after takeoff or in event of a go-around.
8. Sometimes the altimeter setting is taken from an instrument of questionable reliability. However, if the instrument can cause an error in altitude reading of more than 20 feet, it is removed from service. When altimeter setting is estimated, be prepared for a possible 10- to 20-foot difference between field elevation and your altimeter reading at touchdown.