Using Thermodynamic Diagrams

By Richard Kellerman

A guide to forecasting thermal activity using the standard SkewTLogP chart.

Thermodynamic diagrams — and the laws underlying them — are the basis for thermal soaring forecasts. They have been crafted to make it convenient to draw conclusions about the atmosphere and are rich in information useful to soaring pilots.

They are also a source of confusion: What is one to make of something looking like a cross between a graph and the work of a crazed weaver? Is it really worth figuring out what all those lines and numbers mean? To the soaring pilot the answer is simple: Yes, because once understood these diagrams can be used to forecast when lift will start, its height and strength. They make it possible to predict cumulus clouds, the likelihood of either lateral (spread out) or vertical (convective) overdevelopment, and the possibility that cumulus clouds will give way to blue conditions or *vice versa*. Readers who have first-hand experience of my forecasts will appreciate that there is uncertainty in thermal prediction, but the same is true of motorless flight, and it is no less enjoyable for that.

For this article, I chose the SkewTLogP chart, pretty much the standard here in the U.S. (Because we generally fly in the first 18,000' of the atmosphere, and with surface temperatures between 0 °C and 40 °C, I've used only a small part of the entire diagram.) The SkewTLogP chart is both a graphical display of data and an ingenious calculating device. If these are considered separately, it becomes less intimidating. The purely graphical

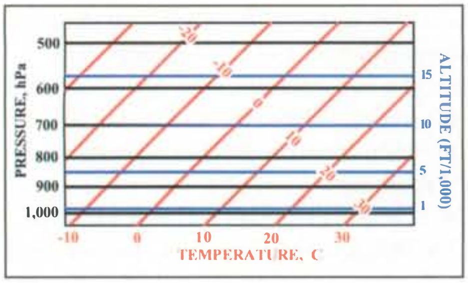

Figure 1.

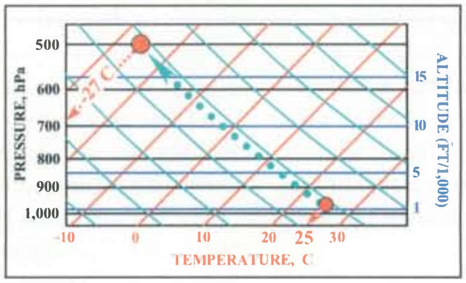

Figure 2.

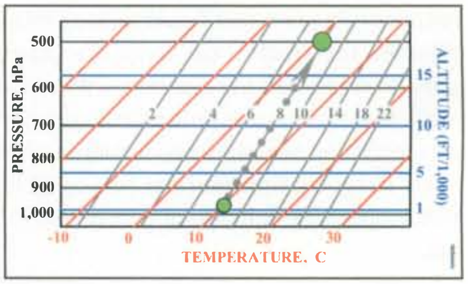

Figure 3.

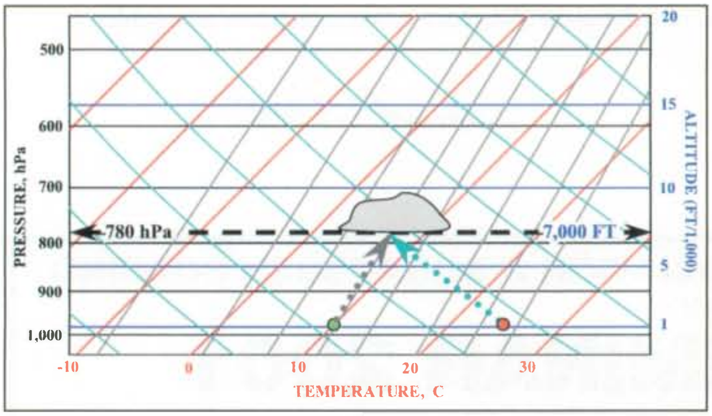

Figure 4.

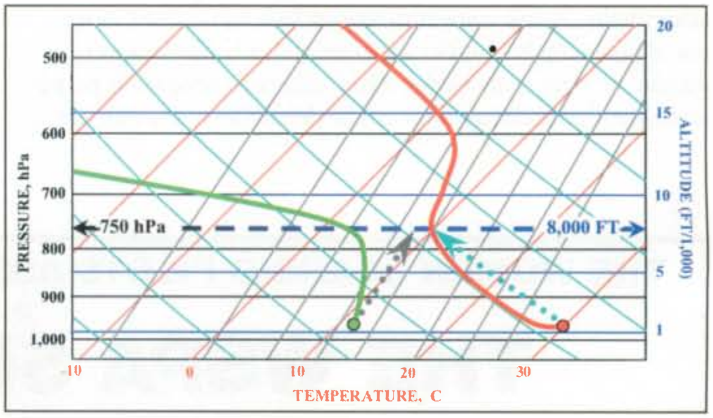

Figure 5.

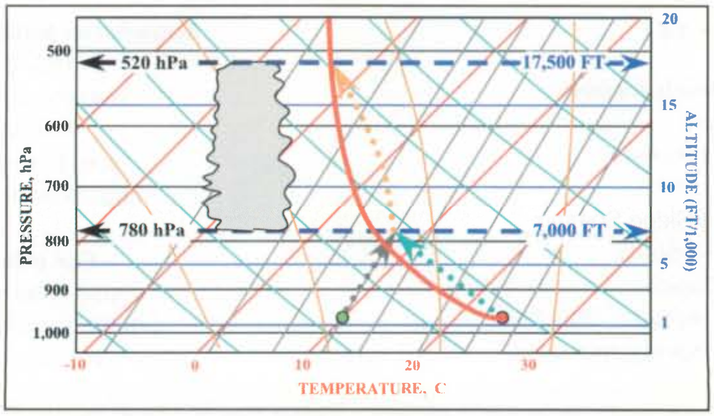

Figure 6.

aspects are depicted in Figure 1.

The vertical axis is pressure and the units are hPa (hectopascals). Although temperature values are printed along the horizontal axis, note that the red temperature lines are sloped (skewed) from bottom left to top right. Pressure increments are not equally spaced — they are logarithmic. Along with the skewed temperature axis, this accounts for the name "SkewTLogP." For convenience, pressure altitudes for a standard atmosphere are included to the right of the graph.

The sloping cyan (blue-green) lines in Figure 2 are dry adiabats – the first and most basic element of the calculator aspect of these diagrams.

Figure 2 also includes a single data point – the surface temperature, here set to 25 °C and represented by a red dot. Note that the surface in this example is at about 1,500' msl, and that the temperature is read either by constructing a line parallel to the sloping red temperature lines back down to the horizontal axis, or by reference to the sloping temperature lines themselves.

The dry adiabats show the adiabatic cooling of a rising parcel of air. They give *their* name to the Dry Adiabatic Lapse Rate (DALR). Suppose the red dot at 1,500' and 25 °C is warmer than its surroundings — it will be buoyant, and will ascend. Just how far and how fast will be considered later; for now we are asking a simpler question: How much does it cool as it rises? The cyan lines in general, and the dotted one in particular, supply the answer. Think of the temperature of the bubble as moving along this line as it ascends. By the time it is at 500 hPa (18,000') the bubble has cooled to -27 °C and expanded to about twice its initial volume. The surface air parcel does not happen to lie directly on a dry adiabat, so I have constructed one.

A closer look shows that the cyan lines slope at about 3 degrees for every 1,000' change in altitude. This matches the old rule-of-thumb that thermals cool at 3 degrees Celsius for every 1,000' they rise.

Figure 3 introduces another set of calculating lines: "Lines of Constant Mixing Ratio." These show the change in the dewpoint (T_D) of a rising parcel of air. The smaller of the two green dots represents the dewpoint of a parcel of air at the surface. For reasons which will soon be clear, we wish to know how T_D changes as the parcel rises. The gray lines supply the answer: The dewpoint decreases with height until, in this example, it has dropped from 10 °C at the surface to about 2 °C at 18,000'. Think of the dewpoint as tracking along the heavy gray line as the bubble ascends.

The numbers in the middle of the chart, starting at 2 and ending at 22, are the values, in units of grams of water per kilogram of air, of the concentration of water vapor in saturated air. These values illustrate that warm air can contain much more water vapor than can cold air. They are useful in determining the so-called "virtual temperature" of surface air.

Figure 4 brings together the two concepts of adiabatic cooling of a rising bubble of air, and the decrease in dewpoint for that bubble as it rises. The green dot represents T_D for the surface bubble, the red dot its temperature (they apply to the same surface bubble). Assuming that this bubble is hotter than its surroundings, it will be buoyant and will ascend. Since the rising air cools faster than the dewpoint decreases, it is only a matter of altitude before the two become equal, and condensation occurs. This happens at 7,000', and a cumulus cloud forms.

The discussion to this point has considered only two kinds of observation: The surface temperature (T), and the surface dewpoint (T_D). Balloon soundings, satellite soundings, and increasingly the output of numerical models, also make available the T and T_D profiles aloft. Figure 5 includes examples of these: red is temperature, green is dewpoint. These lines represent data — the measured (or predicted) values of temperature and dewpoint as a function of altitude.

The temperature profile must not be confused with the DALR, which is simply the rate at which ascending air cools due to expansion. Confusingly, the change in the air temperature with increasing height is often referred to as "the lapse rate" — a better term is "environmental lapse rate."

Note how the temperature decreases steadily from the surface to about 8,000', then much more slowly to about 13,000'. A "kink" like this in the environmental lapse rate is called an inversion, and is often important to the soaring forecast.

The dotted magenta arrow shows the DALR for the surface parcel of air, the solid red line shows the temperature of the air through which this parcel ascends. At 8,000' msl the environmental temperature is equal to the temperature of the ascending bubble. At this altitude the bubble is no longer buoyant, and its ascent quickly slows and stops. No cumulus cloud forms in this example — the ascent of the thermal is stopped by the inversion before the rising air can cool enough for condensation to occur.

The heavy green line also represents data – it depicts the measured (or predicted) dewpoint as a function of altitude. It must not be confused with the change in the dewpoint of an ascending bubble of air, shown by the gray constant mixing ratio lines.

The profile I have chosen for the green line is typical. Typical too is the tendency for the dewpoint to converge towards the temperature at the inversion. When this convergence is large enough, and T_D and T are separated by as little as 2 °C, clouds that form at this altitude will have difficulty in dispersing since the surrounding air is so moist. This, and the fact that the inversion often also stops the vertical motion of the atmosphere, is the origin of spreadout, or lateral overdevelopment.

There remains one more set of lines to add to our crowded chart – the Saturated Adiabatic Lapse Rates. In Figure 6 I have added these lines, which show how rising air cools when condensation occurs. The SALR lines make it clear that once clouds start to form, the rate of cooling with increasing altitude is much less.

The SALR allows us to say something about the depth of convection — the height of the cloud tops. The cloud depicted in Figure 6 grows to 17,500'. It does this because as soon as condensation starts (at 7,000') the orange dotted line (SALR) takes over from the cyan dotted line (DALR) and the rate of cooling with continuing ascent drops. This allows the cloud to grow through about 720 hPa (where the inversion would stop non-condensing air) all the way to 520 hPa where the inversion finally stops it.

It is often the case that the environmental lapse rate, coupled with a weak or nonexistent inversion at low altitudes, is such that once clouds have formed nothing stops them building until they reach 40,000' or more. This means vertical overdevelopment and thunderstorms.

As might be expected, one of the primary uses of thermodynamic diagrams is to predict thunderstorms, and we are fortunate that the same tools needed for that job can be used to make soaring forecasts. We are fortunate too that a very large amount of effort goes into producing frequent forecasts of the environmental lapse rate. It is the damage potential of convective storms that drives this effort – not any perceived need to have good soaring forecasts.

To produce a thermal soaring forecast we need to know the surface temperature and dewpoint, and the profile of the temperature and dewpoint aloft. We also need to know surface winds, and winds aloft, but not to explore stability issues. All of the data needed is readily available on the Web. Much of it is presented in the format of SkewTLogP charts. In this brief account I have attempted to show that these charts are a compact and efficient way to present a lot of data, and a simple and ingenious means to quickly answer the questions every soaring pilot asks: When will lift start, how high will it go, how strong will it be, will there be Cu, will it OD, and when will it end? In another article I will present examples which illustrate how to answer each of these eternal questions.

About the author:

Richard Kellerman lives in southeastern. Pennsylvania and flies his ASW-27 at most of the glider operations in that part of the world, including New Garden, Kutztown, Van Sant, Philadelphia Glider Council, and Ridge Soaring. His qualifications for writing about weather are informal, but he has been tested at several National contests at Mifflin County Airport. He also provides forecasts for Erik Mann's "Governors Cup" racing site. He is the CEO and part owner of Nielsen-Kellerman Co. which designs, manufactures and markets pocket-sized weather instruments and electronic monitors for rowers. Prior to his business career he was a practicing physical chemist. Some small part of that learning survives to this day, and helps with the trying task of trying to guess what the weather will do next.

TECHNICAL NOTES

What Happened to Millibars? Hectopascals ("hPa") have now replaced millibars ("mb") as the officially sanctioned unit of pressure. The "Pa" in hPa is in recognition of the contributions to hydrostatics made by Blaise Pascal. For the record, one Pascal is a pressure corresponding to a force of 1 Newton per square meter, and one hPa is numerically equal to one mb. The Pascal is inconveniently small (you need about 100,000 of them to get one atmosphere), and "hecto" (hundred) is not a standard metric prefix, but those who oversee international standards have spoken, and hPa it is.

Adiabatic Cooling: An adiabatic process is one that occurs without the exchange of energy or material with its environment. The ascent of a thermal is approximately adiabatic since it occurs without either giving up or receiving heat to the surrounding atmosphere, and without much mixing.

Why Thermals Cool as They Ascend: Gases cool as they expand against an external pressure because they must do work in the process of expanding. The air surrounding the expanding bubble opposes the expansion, and the energy needed to overcome this opposition can come only from the thermal energy of the bubble itself. The converse is also true: air that descends has work done on it as it decreases in volume and it gets hotter. This is why descending winds in the lee of mountain ranges are often hot.

Dewpoints, on the Ground and Aloft: The dewpoint is the temperature at which water vapor in the air condenses to liquid water. It is most accurately measured by slowly cooling a mirror until it fogs. It may also be measured with a wet bulb/dry bulb thermometer, and with various solid-state sensors.

The dewpoint of the air at the surface and aloft is of great importance to forecasters and is always measured, forecast, and reported. The dewpoint aloft has nothing to do with either the dewpoint of the air at the surface, or with the change in the dewpoint of surface air as it is lifted. The dewpoint aloft is a measured (or predicted) value.

The origin of the decrease in the dewpoint of the ascending bubble of air is simply the expansion of the bubble. With more space available, a given amount of water can remain in the vapor phase at a lower temperature. Condensation involves many water molecules coming together to form a droplet of liquid water. The chance of this happening is better when the molecules are closer together.

DALR's and SALR's: The Saturated Adiabatic Lapse Rate is much less than the Dry Adiabatic Lapse Rate because the transition of water from gas to liquid form releases a large amount of heat which opposes the cooling of the bubble. Just how much heat is released when water vapor condenses will be appreciated by anyone who has ever had even a minor brush with steam — it hurts. This is only in part because steam is hot – it is also because when it condenses onto (relatively) cold skin, it releases large amounts of heat energy.

Why Log, and Why Skewed? These seemingly perverse choices were made for good reasons: Most of the calculating lines are either straight, or at least approximately so over reasonably sized parts of the diagram, and some additional calculations (not considered in this article) are much more convenient.

Virtual Temperatures: Water vapor is considerably less dense than dry air, so as the dewpoint of air rises, density decreases. Since warm air can hold quite a lot of water vapor, its density can be significantly reduced. The primary source of buoyancy of thermals is the local heating of the surface air. A secondary source is the decrease in density occasioned by water vapor.

The simplest way to take account of this effect is to calculate a temperature – the virtual temperature – at which the density of dry air would be equal to the density of the actual moist air. The virtual temperature, T_V is easily determined from the formula

$T_V = T + W/6$, where T is the air temperature in °C and W is the mixing ratio in grams of water per kilogram of air. Reference to Figure 3 will show that W/6 can be significant when air is quite warm. For a surface dewpoint of 20 °C, W is about 15 g/kg so the virtual temperature of surface air is about 2.5C ° higher than the actual temperature.

Lines of "Constant Mixing Ratio": It is perhaps unfortunate that this term is used, since it obscures the primary use of these lines as a means to calculate the decrease in the dewpoint of a rising air bubble. The constant mixing ratio line passing through the surface dewpoint is by definition a line of saturation, as well as line of constant water vapor concentration, and this line tells us how the dewpoint of the surface air changes as this air is lifted.

Estimating Cloudbase: In the example of Figure 4 the surface temperature is 25 °C (77 °F) and the dewpoint is 10 °C (50 °F). Cloudbase is at 7,000'. There is a rule-of-thumb that says that cloudbase height in feet will be equal to one thousand times the difference between the surface temperature and dewpoint in degrees F, divided by 4.4:

Cloudbase = $1000 * (T - T_d)/4.4$ feet.

Applying the above formula yields a value for cloudbase of 6,100'. Add 1,000' for the assumed elevation of the surface and the value is 7,100' msl – close enough.

It should be noted that this rule-of-thumb assumes that the surface bubble is indeed unstable and that the instability will be sufficient to allow clouds to form. More precisely, the cloudbase prediction should be qualified: *If* clouds form, they will form at the height given by the formula. Whether or not the air is unstable, and whether or not clouds will form requires more information.