Forecasting THUNDERSTORMS

An understanding of convection provides clues to these atmospheric monsters.

BY ED BROTAK


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Convection remains a serious problem for the aviation community. Severe turbulence above the ground and strong winds with wind shear near the surface are among the hazards caused by convective activity, which plays a role in many aircraft accidents each year. Moreover, the massive hailstorm at Dallas–Fort Worth (Texas, U.S.) International Airport in April demonstrated how convection can seriously disrupt flight operations. Hundreds of flight delays and cancellations occurred, and damage to aircraft on the ground was extensive.

Meteorologists must know how convection operates in order to forecast it. They must make a model of the atmosphere, and even of the potential thunderstorm itself, to predict the weather that may be generated. The aviation industry would benefit from a better understanding of the workings of convection.

A simple key to understanding convection is to know that warm air rises and cold air sinks. More precisely, warm air is less dense and therefore buoyant (think of a hot air balloon). Cold air is denser and sinks (e.g., cold air drainage into a valley at night). The terms *warm* and *cold* are relative. A balloon with an inside air temperature of 32 degrees F (0 degrees C) still will rise if the outside air temperature is minus 40 degrees F (minus 40 degrees C). Similarly, convection can occur with temperatures below freezing.

Lapse Rate

So, to determine if air is going to rise, sink or remain where it is, we need to know the temperature of the "inside air" (inside the balloon or inside a cloud) and the temperature of the air outside. We also need to know the *lapse rate* — that is, the change in temperature with height. Outside air temperatures are measured at least twice a day — typically at 0000 and 1200 Greenwich Mean Time (GMT) — from dozens of sites across the United States and hundreds of other stations around the world. Balloon-borne instrument packs, called *radiosondes*, are launched to obtain data on temperature, moisture, pressure and winds up to 100,000 ft. Forecasters then have to determine the inside air temperature so that comparisons can be made.

Starting with the simple case of *dry convection* (no condensation or cloud), we know that air expands as it rises, and the expansion results in cooling. Using the basic laws of physics, we can derive the rate at which dry air should cool when lifted. This is called the *dry adiabatic lapse rate* ("adiabatic" refers to the expansion effect in this case), and the value is 5.5 degrees F per 1,000 ft (10 degrees C per 1,000 m). If the actual measured lapse rate is greater than this, then the parcel of air would be warmer than the environment and would continue to rise on its own. This is an unstable situation. We find lapse rates like this fairly close to the ground, usually on days with abundant sunshine. Columns of rising air, the *thermals* that glider pilots use, are common in this situation. But lapse rates of this magnitude are unusual at higher altitudes, and this type of convection is not "deep" (i.e., not extensive).

Dynamic and Dangerous

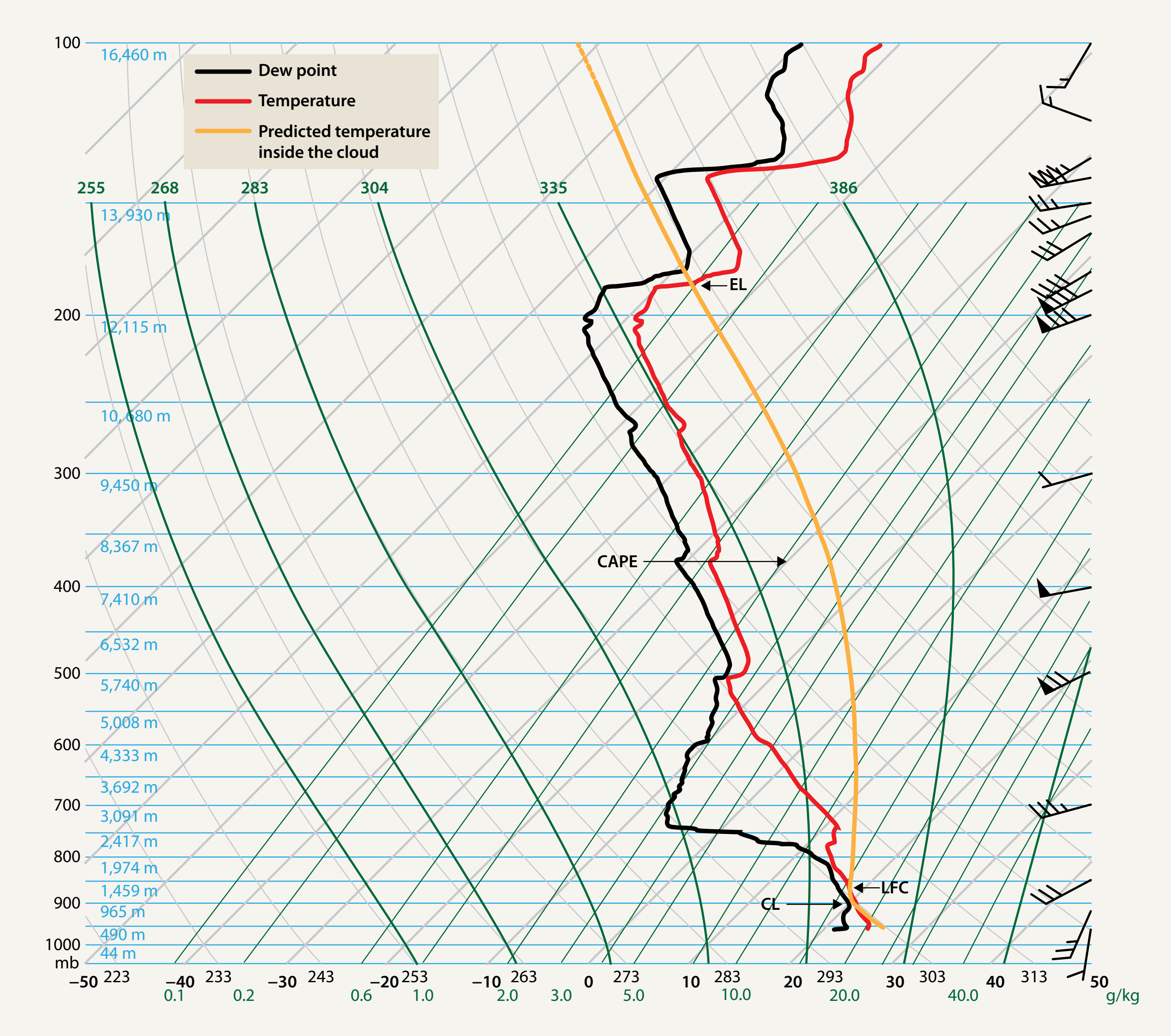
When water is added to the mix, the situation becomes more dynamic and potentially dangerous. Convective clouds, the cumulus cloud family, always provide some turbulence, which can range from a few bumps in "fair weather cumulus" to the potent updrafts and downdrafts in cumulonimbus thunderheads that can rip an airplane apart. On the plus side, the condensed water makes the air currents visible as clouds. Imagine if a pilot could not see currents of air rising and sinking at speeds that can exceed 100 mph (161 kph).

Besides making convective clouds and the various forms of precipitation associated with them, water plays a critical role in convective development. When water vapor condenses, heat is released. Technically, when water molecules go from the energetic gas form (vapor) to the more confined liquid form (water) or solid form (ice), energy is released. This *latent heat release* raises the temperature of the air within the cloud. If the parcel of air continues to rise, it will cool at a slower rate — the *moist adiabatic lapse rate*: 3 degrees F per 1,000 ft

(5 degrees C per 1,000 m). With the parcel cooling at a slower rate, it is still likely to be warmer than the surrounding air. Therefore, moist air is potentially more unstable. This process does not require a lot of moisture. Convective lifting is so strong, a moist layer near the surface, perhaps only a few thousand feet thick, is all that is needed to support convection. Interestingly, dry air aloft helps promote strong convection, whereas a deep moist layer aloft often produces heavy rain but less wind and turbulence.

So, the two primary factors that meteorologists look at to forecast convection are the lapse rate and low-level moisture. To quantify the forecasts, meteorologists have developed a number of indices that incorporate these two factors. The *Lifted Index*, the *Showalter Index*, the *Total-Totals Index* and the *K Index* can be calculated for each situation, and the numerical

Sounding at Springfield, Missouri, U.S., May 23, 2011



CL = condensation level LFC = level of free convection EL = equilibrium level CAPE = convective available potential energy

Source: Ed Brotak, from the Plymouth State Weather Center

Figure 1

values determined from the calculations can be compared to standard values for the occurrence of convection or severe convection. All of these indices were developed prior to the advent of computer technology. Although they are still used today, computer-generated products are much better.

Sounding the Atmosphere

The main tool meteorologists use to forecast convection is the *sounding*, a vertical profile of the atmosphere. A standard plotted sounding consists of two lines showing temperature and dew point, with wind data usually given on the side of the plot. Forecasters can use actual morning soundings and allow for expected changes by afternoon or, with today's sophisticated numerical models, use computer-generated forecast soundings for later in the day.

For an example, Figure 1 is the 0000 GMT 23 May 2011 sounding for Springfield (Missouri, U.S.) Municipal Airport. This sounding represents the atmospheric conditions that produced the thunderstorm that spawned the tornado that devastated nearby Joplin, Missouri. The red line is the actual temperature trace, and the black line is the dew point from the surface to 16,460 m (54,000 ft). From the surface temperature and dew point, we can calculate the *condensation level* (CL). For this calculation, we simulate the lifting of this surface air by using the dry adiabatic lapse rate to determine the height at which the air would be cooled sufficiently that its temperature equals the dew point. In this case, the condensation level is 840 m (2,750 ft). The condensation level typically marks the base of the cloud. Below this level, where the parcel of air is cooler, energy or lift must be provided for condensation to occur. The energy required is called *convective inhibition* (CINH). If this value is large (e.g., 200 or more) or there is nothing to help the parcel rise, there will be no convection. In this example, the CINH is a minimal value of 3.

The yellow line is the predicted temperature of the air inside the cloud. The red and yellow lines intersect initially at 1,300 m (4,200 ft). This is called the *level of free convection* (LFC). Above this level, the air inside the cloud is warmer than the air outside and will rise on its own. This becomes the updraft, the core of the storm. The lines cross again up at 13,000 m (42,000 ft), at what is known as the *equilibrium level* (EL). Above this level, the air in the cloud is colder than the environment. This often corresponds with the cirrus anvil of the thunderstorm cloud.

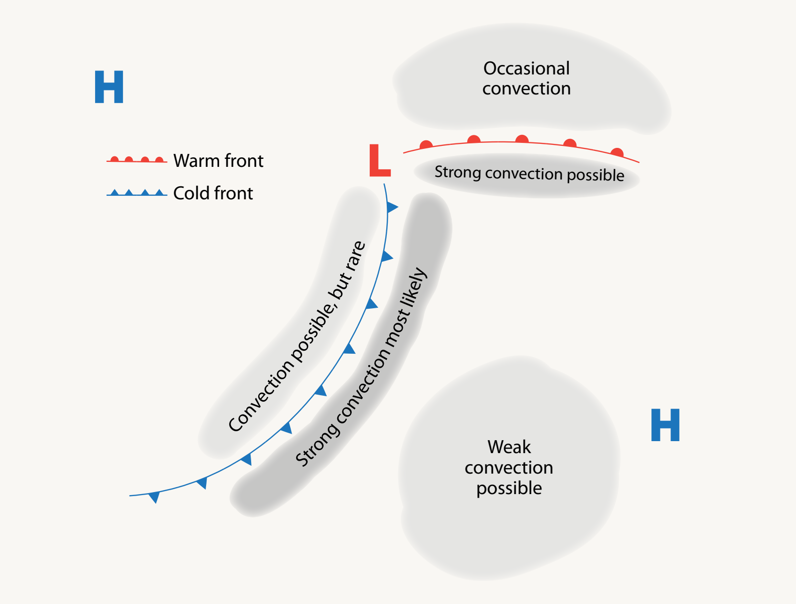
The updraft does not stop at the equilibrium level because the air in the updraft has accumulated upward momentum, or energy. This energy is proportional to the area on the sounding between the actual temperature trace and the parcel temperature trace — that is, where the parcel is warmer than the environment between the level of free convection and the equilibrium level. Meteorologists call this the *convective available potential energy* (CAPE). The CAPE indicates the potential strength of the updraft. A CAPE of 500 usually would support only weak convection, but the CAPE value here, 3,692, is indicative of severe thunderstorms. This excess energy propels the actual top of the cloud well above the anvil in what is referred to as an *overshooting top*. Viewed from above, the top of a thunderstorm looks like a boiling cauldron. The air in the updraft surges upward and then sinks back down in bursts. The actual height is a function of the CAPE. In this case, the predicted cloud top was an impressive 17,000 m (57,000 ft). With the tropopause height of 13,930 m (46,000 ft), this storm extended well into the stratosphere.

So far, we have discussed only the updraft of a thunderstorm. In terms of development, it is the updraft that produces the storm. But turbulence also consists of downdrafts, which can produce strong winds and wind shear at the ground. Initially, downdrafts are started as rain begins to fall from the cloud, pulling some air down with it. Evaporative cooling lowers the temperature of this descending air, accelerating the downdraft even more. Dry air aloft, which would intensify the cooling effect, is one thing meteorologists look for in predicting strong downdrafts. Large thunderstorms and thunderstorm complexes often develop complex circulations. Outside air can be pulled into this circulation and produce a mid-level (10,000 ft or 3,000 m) inflow. This colder, drier air can become a powerful downdraft. Also, this air brings with it momentum gained from the winds aloft. These strong winds can be brought down to the surface by the downdraft.

Convective Triggers

Even if the environment is potentially unstable, something is needed to start or trigger the convection. Typically, parcels of air need a boost to reach the condensation level — something to lift the unsaturated air upward, causing it eventually to cool to the dew point. From there, the latent heat that is released can help the parcels utilize the inherent instability. As mentioned above, strong heating of the surface by the sun in the late spring or summer is a typical convective trigger. If the temperature of the air near the surface warms sufficiently, the *convective*

Convection Catalysts



H = high pressure area L= low pressure area

Source: Ed Brotak

Figure 2

temperature can be reached, and parcels of air will start to rise on their own.

Orographic lifting is another common cause of convection. Winds blowing upslope can lift parcels of air to their condensation level. This is why convection is more prevalent over mountainous terrain. *Convergence* at low levels also can cause convection. When air converges near the ground, it is forced upward. This can happen ahead of a true front, along a gust front or the outflow boundary from previous convection, or beneath various upper-level systems.

The surface weather features shown in Figure 2 can cause typical “air mass” showers and thunderstorms to develop in the warm, humid, southerly flow on the west side of a high pressure area, away from any fronts or lows. Air mass thunderstorms are the result of daytime heating. This convection is not organized and usually is fairly weak. When convection occurs closer to the low and fronts, but still in the warm air, it tends to be more organized and stronger. The convection is aided by divergence aloft with upper-level troughs and the jet stream. This is what meteorologists call *synoptic forcing*.

When synoptic forcing is very strong, convection often organizes along lines parallel to the mean wind. These are the familiar squall lines. Often, the convection itself is strong to severe. Beside extreme turbulence aloft, strong winds at the surface are common, and hail is possible. Interestingly, moderate amounts of synoptic forcing and significant instability can combine to produce the strongest thunderstorms: the supercells. This was the case with the Joplin storm.

Rotating Updrafts

Another factor that forecasters examine at low levels is wind shear. When winds veer (turn clockwise) from the surface to several thousand feet, the updraft in a thunderstorm can convert this vertical wind shear into horizontal rotation. Rotating updrafts are associated with the strongest storms and produce the most severe weather, including strong straight-line winds, large hail and even tornadoes. To quantify this, meteorologists calculate the *helicity*, the difference between the winds at different levels. High helicity values (over 300) indicate greater potential for severe storms.

On many days, the convection is shallow, resulting in only fair weather cumulus clouds with little vertical development. The air may be too dry, and the clouds literally evaporate; or the atmosphere may be too stable to allow much development. In this situation, meteorologists often say the atmosphere is “capped.” Stable lapse rates occur at levels above the effects of surface heating. When the atmosphere is uncapped and unstable, updrafts can soar tens of thousands of feet, producing *cumulus congestus*, or towering cumulus. When the updraft air finally reaches its thermal equilibrium level, it spreads out to form the anvil characteristic of a cumulonimbus cloud, the “thunderstorm cloud.” Regardless of whether an anvil top has developed, cumulus clouds of this magnitude pose the greatest risks to pilots.

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