Thermal Structure and Behavior

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Thermals are the fuel of sailplane flight. This article describes what thermals look like (if we could see them!) and how they behave. I hope that your flying experience will be improved by knowing a little more about thermals. To start with I need to say that the atmosphere is endlessly complex and capable of doing almost anything. I'm going to try to talk about the simplest and most common cases. That means clear to partly cloudy skies, light to moderate winds, and daytime. I'll say a little about more complex cases toward the end.

For impatient readers, here are the basics: Thermals are like fat trees, with small, chaotic roots near the surface and large trunks above. The trees tilt and sway with the wind and change with time, and sometimes they let go of their roots and drift. Between the trees is sinking air. Where thermals form, their exact shape, and how fast they change is hard to predict, since it depends on details of the interaction between the ground and the air. Key principles to remember are:

< Thermals are driven by temperature contrast between the ground and the air.

< Air exists in parcels (blobs) that have mass and momentum as well as temperature and humidity.

< Plumes near the surface look and act different from thermals well above the surface.

The boundary layer

The part of the atmosphere in which we fly is the atmospheric boundary layer (BL for short). It's the air that's affected by the ground surface on time scales of an hour or so. In the kind of conditions we're talking about, it's the lowest 500 - 2000 meters (1500-6000 feet) of the atmosphere. The BL is shallow (100-200 m) at night, builds up in the daytime as the sun heats the ground, and becomes shallower again in the evening. BL height is governed by the amount of sunlight, the amount of moisture available at the surface, and the stability of the atmosphere. Areas with lots of surface moisture, especially with crops that use a lot of water, tend to have relatively shallow boundary layers and weak thermals; deserts have deep BLs and huge, booming thermals. Figure 1 shows the buildup of the boundary layer. The main panel is the reflectivity measured by a special radar called a boundary layer wind profiler. It's sensitive to turbulence at gradients of temperature and humidity, so it sees the BL top as a very strong signal. The small panels show the virtual potential temperature and the specific humidity measured by weather balloons. Virtual potential temperature is a direct measure of buoyancy; it's temperature corrected for the effects of humidity and for the heating and cooling effect of changes in pressure with height. If the virtual potential temperature line slopes to the left with height in a layer of atmosphere, that layer is unstable. If it slopes to the right, the layer is stable, and a vertical line shows a neutral layer.

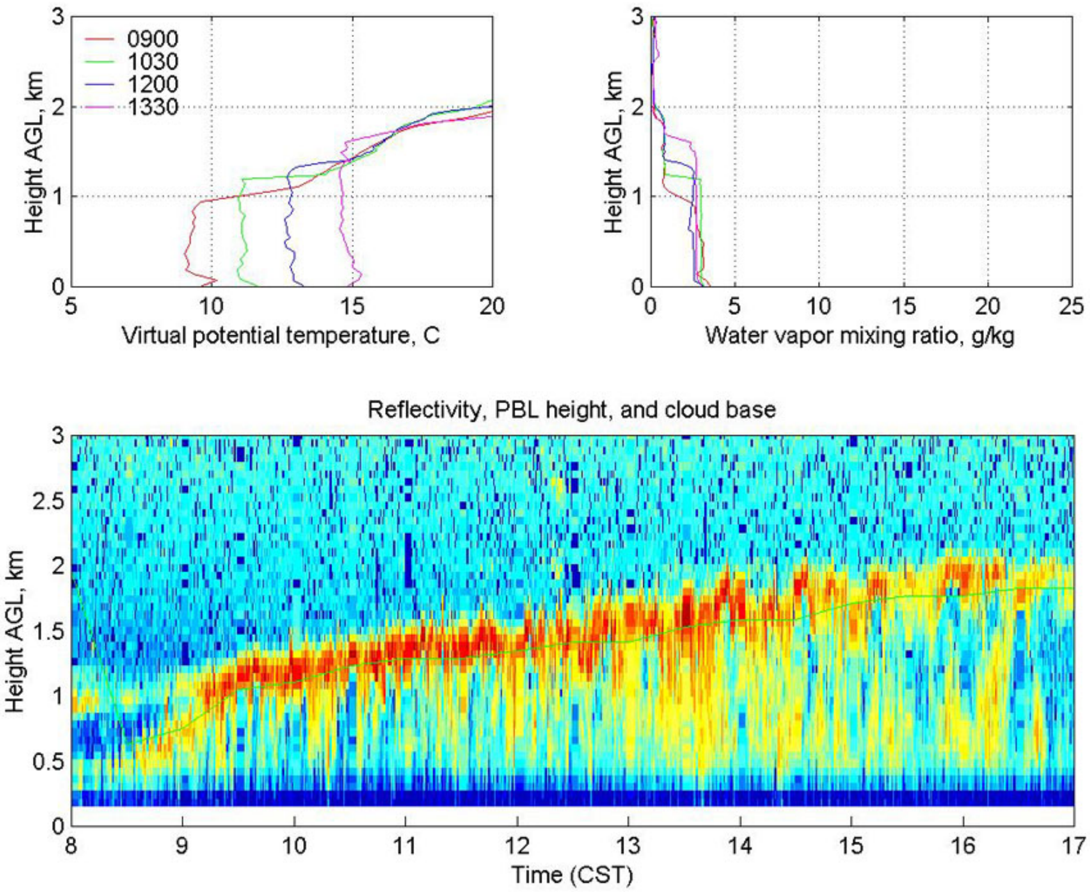

Figure 1: Boundary layer structure as shown by a radar wind profiler and sounding balloons on September 23, 1995 over Illinois.

The boundary layer has three important sublayers, the surface layer, mixed layer, and entrainment zone. The surface layer is the lowest 100-200 m, so it's where model sailplanes fly a lot of the time. The mixed layer extends from the top of the surface layer to near the BL top. This is where cross-country models and full-size sailplanes spend their time. The wind speed is zero right at the ground, increases through the surface layer, and is roughly constant with height in the mixed layer. In fact, the mixed layer is called that because turbulent mixing causes all quantities (potential temperature, wind speed, water vapor, pollutants) to be uniformly mixed throughout the layer on average. That doesn't mean that differences don't exist at the scale of individual blobs; if everything were perfectly uniformly mixed there wouldn't be any thermals and we might as well stay home! The entrainment zone is the interface between the BL and the free atmosphere above, and is where clouds form. The surface layer is unstable, the mixed layer is neutral, and the entrainment zone and the atmosphere above are stable.

Thermals and plumes

The sun warms the ground, and the ground in turn warms the layer of air nearest to it. As soon as a parcel of air is warmer than its surroundings, it starts trying to rise. Air has mass and momentum and it's immersed in other air, so it can't just go to its desired level instantly. Furthermore, the ground is not uniform, some parts are darker and/or drier and heat up faster, and some parts are moister or lighter in color. The result is that there are blobs (parcels) of air forming, rising, and pushing other parcels out of the way. Some of those parcels end up at the ground, get warmed up, and want to rise themselves. All of this turbulent motion leads to small plumes of varying shapes and sizes of rising and sinking air. Some of the rising parcels meet up with others and form larger blobs; others get torn apart by turbulence and lose their identity. The size of parcels in the surface layer is roughly proportional to their distance from the surface. The air within a plume is rising, but it is also turning in all three dimensions, its motion depending in a completely unpredictable way on the small-scale shape, color, and moisture of the ground and the motion of all the other parcels in its vicinity. Plumes start out at the surface with no *average* horizontal speed. They pick up bugs, seeds, and sometimes trash, all of which help us to see where the air is rising.

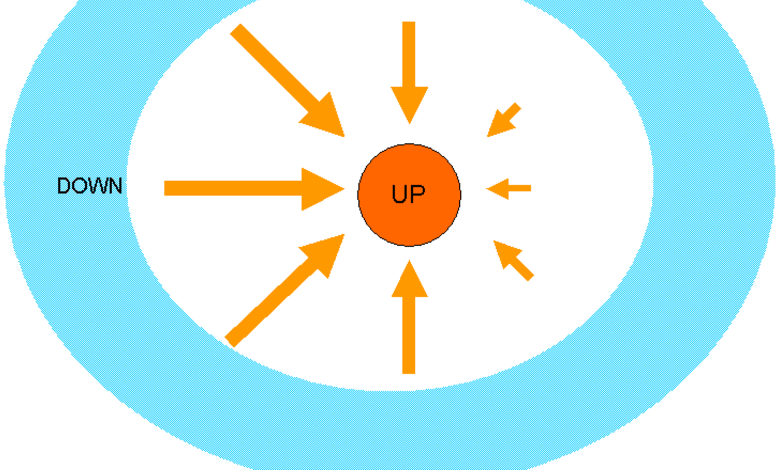

Figure 2: Plumes (orange) and sinking air (blue) in the surface layer.

The plumes converge as they rise (figures 2 and 3). By the time they reach the top of the surface layer, 100-200 m above the ground, they have joined into relatively large columns of rising air. The size of thermals in the mixed layer is roughly proportional to the BL height, so the columns are a few hundred meters to as much as a couple of kilometers in diameter. We could think of the thermal as a tree with a trunk in the mixed layer and roots in the surface layer. The air within the thermal still has horizontal and turning motions as well as rising, and those motions depend on the motions of the surface layer plumes that formed its roots. Remember too that these are fat trees, roughly as wide as they are tall (figure 4). Thermals are a degree or two Celsius warmer than the surrounding air, and they rise at 1-3 meters per second. The air in thermals moves horizontally more slowly than the surrounding air because it "remembers" being near the surface where it was moving very slowly.

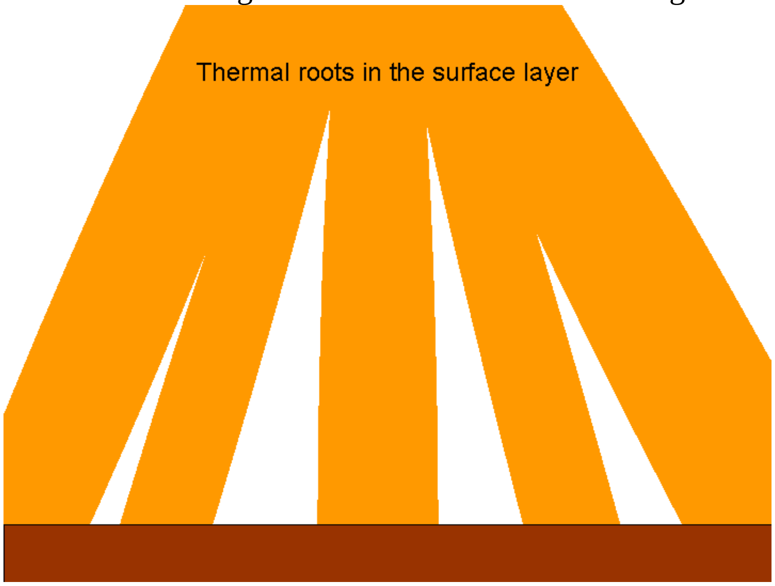

Figure 3: Side view of thermal roots (plumes) in the surface layer. The vertical extent of this figure is 100-200 m. Real plumes are much more ragged and chaotic than this schematic drawing.

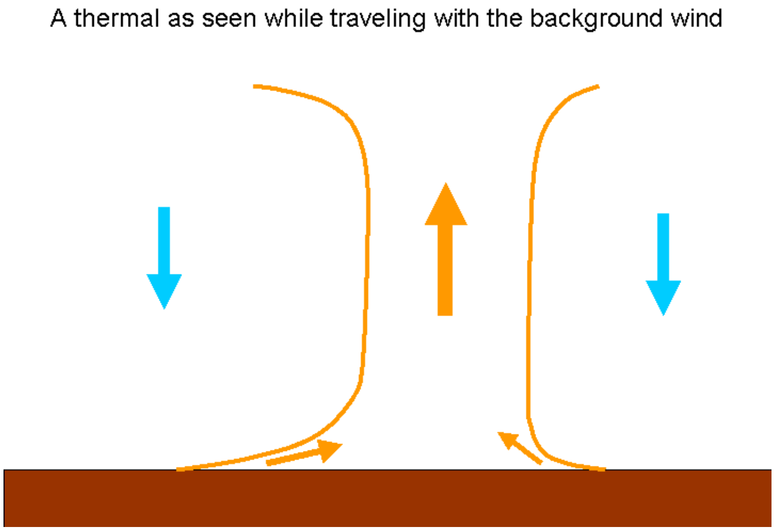

Figure 4: Side view of a thermal. Rising air is inside the orange outline.

When rising air reaches the top of the BL, it spreads out, again like the top of a deciduous tree. The air is now more dense than its surroundings, not because it has changed but because the air around it is warmer. You may remember from high school physics that a gas cools when its pressure is reduced, and that's true of rising air in the atmosphere as well. Scientists often work with potential temperature, which corrects for that change. In any case, the air at the top of the BL is warmer in potential temperature than the air rising from the surface. In fact, that's what defines the BL top. If the air in the thermal were still warmer (less dense), it would continue to rise, and wherever air from the surface can reach in a short time is, by definition, part of the boundary layer. Sometimes the tops of thermals are visible as cumulus clouds. Because the rising air has momentum, it actually overshoots its level of neutral buoyancy before falling back. If the stable layer (sometimes called the inversion) atop the BL is weak, the clouds may build up and it may rain. Looking again at figure 1, we can see the tops of the thermals as rises in the reflectivity plot.

All of the parcels and their motions also have time scales, which can be thought of as the lifetime of a parcel, the time it maintains a recognizable identity. The time scale is related to the parcel's size and therefore to its place in the layered structure of the BL. Surface layer plumes have short lives before they merge into thermals or mix with other air and lose their identity. Thermals live about as long as it takes them to move from the bottom of the mixed layer to the top. Since they are rising at a few meters per second and the BL is 500-2000 meters deep, thermals last several hundred seconds or 10-20 minutes. So our tree analogy is at best a snapshot in time. It would be more realistic to think of thermals as fat logs. By the time the top reaches the BL top, the bottom of the thermal may have changed or moved. The log or tree analogy is also good because the sides and edges of thermals aren't smooth, they are complex just like the bark of an old tree. Around the edges, the thermal air mixes with the surrounding air in chaotic swirls and eddies.

While we've been focusing on a bunch of plumes that got together to make a thermal, the rest of the boundary layer hasn't just been sitting idly by. Any time a parcel of air moves, other parcels have to move as well to accomodate it. Two parcels of air can't occupy the same space any more than solid objects can! Furthermore, conservation of mass requires that when one parcel rises another has to fall to keep the total amount of air at any level roughly constant. We've also been thinking of the thermal as an isolated individual, when really it's part of a field of thermals. They may be organized roughly hexagonally or in horizontal lines, and they occupy somewhat less than half the horizontal area at any height (except at the very top of the BL). In between the thermals is cooler, sinking air. That's right, there's more area of sink than lift! The good news is that it's generally not as strong. Again, conservation of mass applies; if the thermals are smaller than the sink, they must be stronger to move the same amount of air. As a thermal reaches the top of the BL, it spreads out and finally loses its identity, becoming part of the sinking air. Individual molecules may reach the surface, be warmed again, and become part of another plume and another thermal, and so on.

Observations and Simulations

How do we know about thermal structure? There are several ways to "see" what the air is doing in the boundary layer. Sometimes we can get clues visually. Clouds often mark the top of the thermals; on a polluted day we can see the dirty BL as we look down from an airplane or a mountain. Dust devils are particularly strong surface layer plumes.

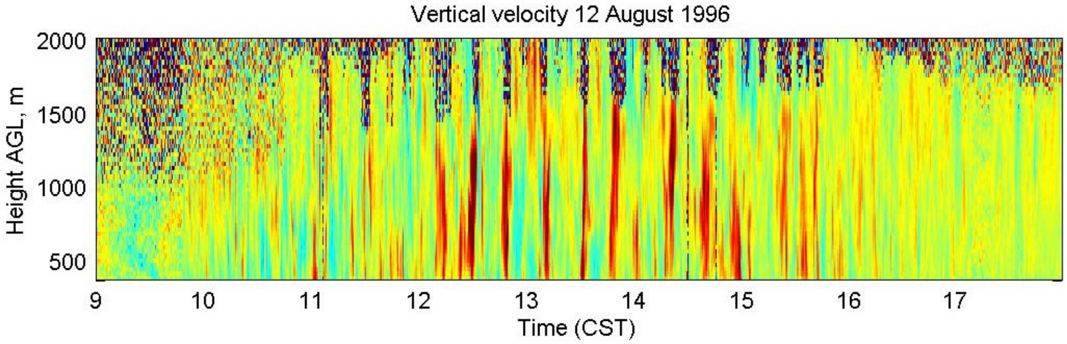

Figure 5: Thermals shown by a lidar on August 12, 1996 over Illinois. Upward velocities are in red, downward in green and blue. Random colors near the top of the figure are low signal above the BL.

Scientists have developed more sophisticated techniques. Water tanks in laboratories have been used to visualize atmospheric flows. More recently, remote sensing instruments have been developed for use in the real atmosphere. The boundary layer wind profiler radar that made figure 1 is one example. I've used profilers to study BL turbulence. The best pictures of thermals come from lidars (laser radars). Figure 5 is from a vertically-pointing lidar showing thermals moving over a site in Illinois. You can see that in the morning, the thermals gradually get stronger, larger, and farther apart. They are largest and strongest in the middle of the day, and then get weaker, smaller, and closer together in the afternoon.

Another way to "see" thermals is with numerical models. Even with modern computers it's still too difficult to simulate the BL with full resolution. Large Eddy Simulation models (LES) resolve the main features of the BL. Figure 6 is a 3D rendering of LES output for the sort of day we're talking about. We can see the thermals as blobs of rising air of various sizes and shapes. The surface layer plumes are not resolved by the model. A newer, more finely resolved LES result is shown in figure 7. This version begins to resolve the surface layer plumes. Horizontal cross-sections at different heights from the same simulation are shown in figure 8.

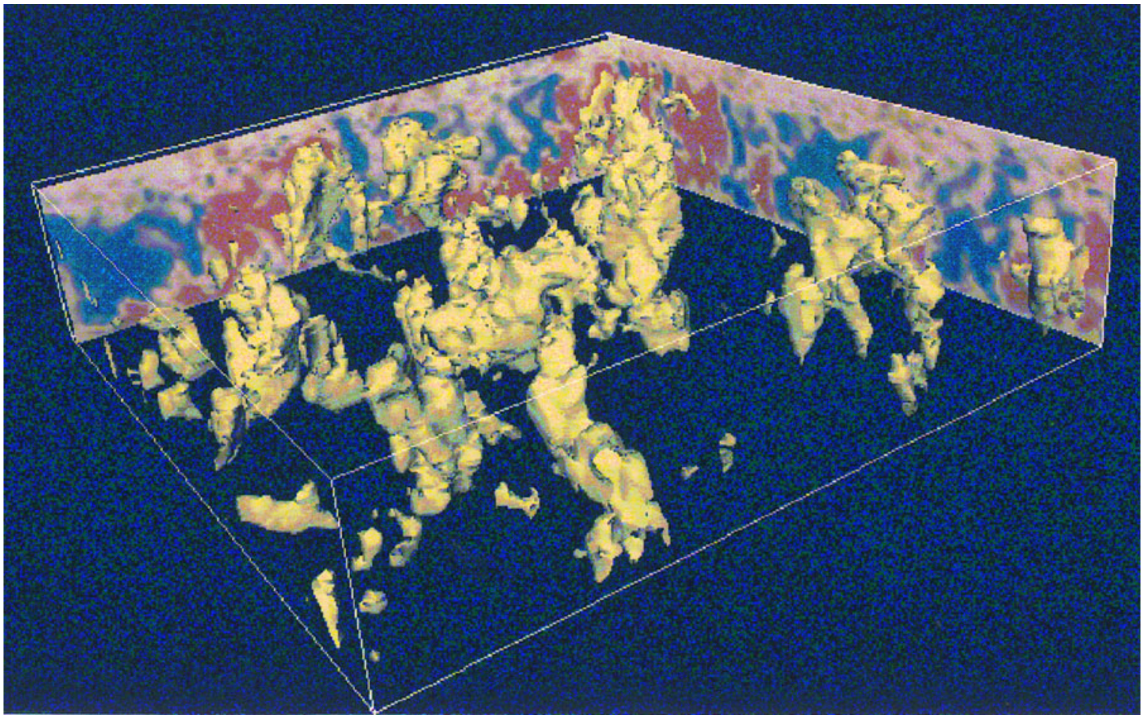

Figure 6: Perspective rendering of thermals in a computer model. Volumes enclosed by yellow surfaces are thermals. On the back and side walls, upward motion is in red and downward in blue. The box is 5 x 5 x 1.25 km. Graphic copyright 1998 Peter Sullivan / National Center for Atmospheric Research, used by permission.

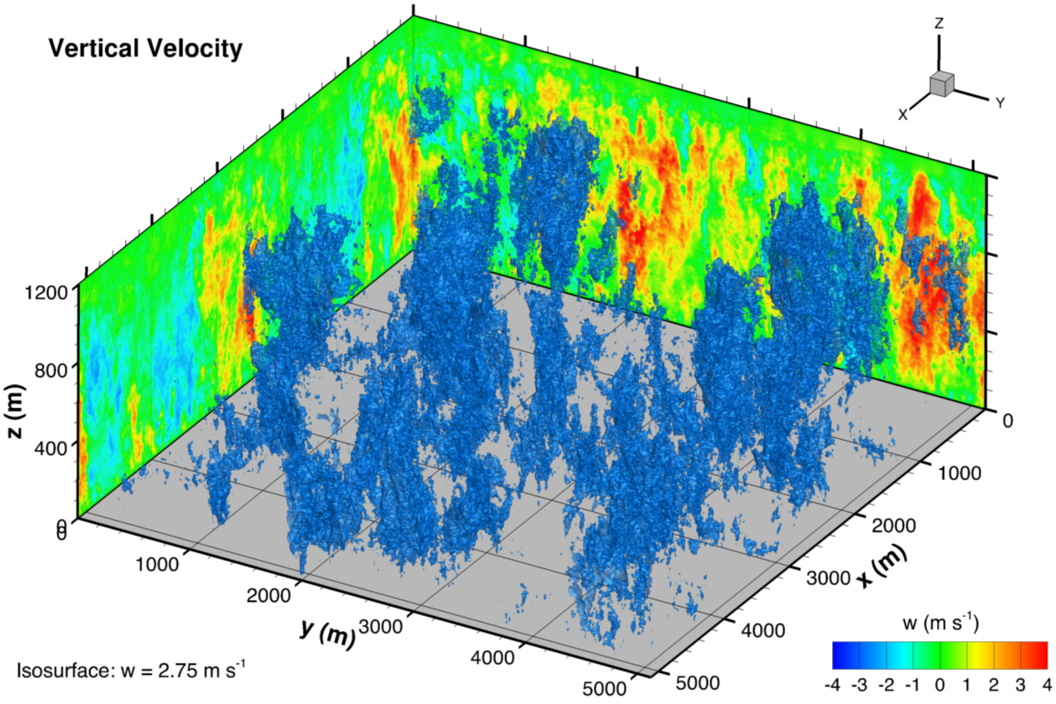

Figure 7: Perspective rendering of a more finely resolved LES. Air rising at more than 2.75 m/s is in blue in the body of the volume. Velocities in the cross-sections on the walls are colored according to the colorbar in the lower right corner. Graphic copyright Ned Patton / National Center for Atmospheric Research, used by permission.

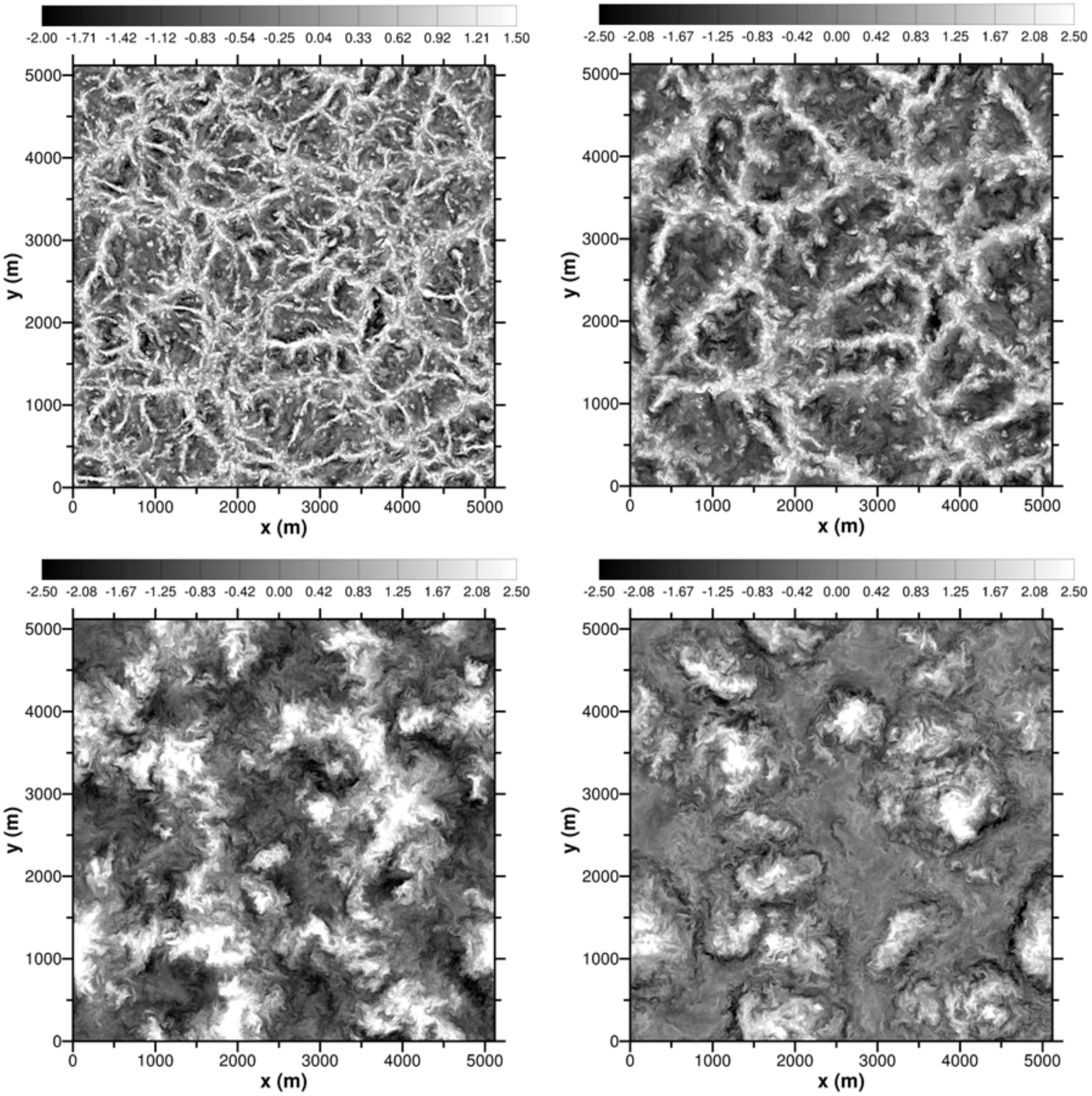

Figure 8: Horizontal cross-sections from LES at four heights. Upper left, 4% of the BL height, upper right 10%, lower left 50%, lower right 90%. Vertical velocity is in gray scale as shown in each plot, note that the scale is smaller in the upper right. Small, relatively weak, and roughly linear surface layer plumes combine as they rise to make larger and stronger thermals. From Sullivan and Patton (2011), The Effect of Mesh Resolution on Convective Boundary Layer Statistics and Structures Generated by Large-Eddy Simulation, Journal of the Atmospheric Sciences, copyright 2011 American Meteorological Society, used by permission.

Movement, tilt, relationship to ground features, bubbles, etc.

Over flat, smooth terrain, thermals move with the wind. The measurement site in Illinois where the figures were made was specifically chosen to be as simple as possible, in fact, we called it the Flatland site. If stronger terrain features (hills, for example) or changes in surface characteristics (lakes, large parking lots) are present, plumes may tend to form over hotter or higher spots. This can make it easier to find a thermal. The tendency isn't perfect, though, because other physical phenomena still play a role. For example, thermals may be kicked off by an obstacle that causes warm air to break away from the surface. Even over large hot patches of ground, a vigorous thermal may suck up all the warm air, bringing in cooler air from the sides, and the thermal will disappear while the ground warms the air again. What happens depends on details of the patch size, wind speed, and temperature contrast.

The wind in the mixed layer is roughly uniform with height, so thermals over uniform surfaces tend to move as columns with little or no tilt. Thermals kicked off by terrain features, on the other hand, move downwind as they rise.

Model sailplane pilots, standing still on the ground, have a different perspective than full-size pilots who are immersed in the moving air. The local wind at the surface is the vector sum of the background wind and the flow into the thermal. A thermal upwind will reduce the local wind speed, or even reverse the direction if the background wind is light enough. A thermal downwind will increase the wind speed. Figure 9 is like figure 4, but it shows the wind vectors (in two dimensions) from the point of view of a stationary pilot. A nice simulation of this effect by Mike Fantham is available at the time of writing (November 2014) here: http://www.flyquiet.co.uk/smf/index.php?topic=1134.msg10501#msg10501

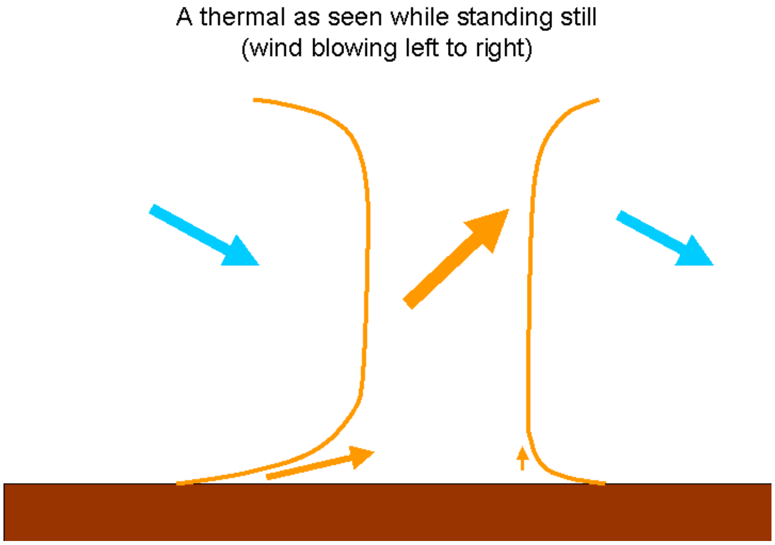

Figure 9: Thermal outline and wind vectors (in the plane of the picture) from the point of view of a model pilot standing on the ground.

Thermal myths

People naturally try to explain what they observe, often by making analogies, and sometimes those explanations grow into persistent myths. Probably the two most persistent myths about thermals are that they rotate in a particular direction because of the Earth's rotation, and that they are doughnut-shaped (toroidal). Neither is true of observed or modeled thermals. The Coriolis force due to Earth's rotation is much too weak to act significantly on small, short-lived flows like thermals. Thermals have rotation, due to the differing momentum of the plumes that make them up, but they don't rotate in any predictable direction or at a predictable rate. Not even dust devils have a preferred direction of rotation. As for doughnuts, the only way that air can recirculate is by going down to the surface and being reheated there. In dry BLs, the strongest sink is usually far away from the strongest lift. However, there is some evidence that clouds can produce toroidal circulations, and that there is a strong descending shell of air around some clouds.

Weak thermals

As the wind gets stronger or the sun weaker, buoyancy due to heating at the surface becomes less important. Thermals become smaller and less well-defined. It's hard to state a simple rule of thumb for when the wind is strong enough to have a major effect, because that depends on the strength of the sun and the surface moisture. On overcast or very windy days, turbulence is produced by the wind shear, that is, the change in wind speed or direction across a layer. Shear-driven turbulent motions are small compared to thermals, and can't usually be taken advantage of to keep a sailplane up. When surface heating is less, other factors become more important. For example, thermals can have a more significant tilt with height and wind speed and direction can vary more with height when surface heating is relatively weak.

Conclusions

I hope this article has been helpful in explaining thermals and showing some of the latest methods of observing them. Remember that the atmosphere is very complex and almost anything can happen, but what I've described here is what happens in the simplest case.

References

The best current textbook on the boundary layer is *An Introduction to Boundary Layer Meteorology* by Roland B. Stull. It's quite readable at least in the introductory parts, and should be available in any decent university library. Dennis Pagen's *Flying Conditions* is a good small book written from the perspective of a hang-glider pilot. The classic text on soaring meteorology is C.E. Wallington's *Meteorology for Glider Pilots*. Both appear to be out of print, but could probably be found with a little searching. My article in the March 1998 Bulletin of the American Meteorological Society entitled *The Flatland Boundary Layer Experiments* shows several more examples like figure 1 of different boundary layers. It should also be in libraries.

Acknowledgements

Shane Mayor and Steve Cohn of the National Center for Atmospheric Research made the lidar measurements shown. Peter Sullivan and Ned Patton, also of NCAR, provided the simulation figures.