From airflow separation to thermal updraft

# HOW WORKABLE THERMALS ARE CREATED

It is well known that birds of prey are able to rise directly from treetops into thermal updrafts, and model aircraft can do the same. However, the updrafts are too small for gliders to fly out of them, even if it were not impossible for safety reasons. This raises the question of how turbulent movements close to the ground and narrow updrafts can give rise to updrafts at least 650' – 1,000' wide that are large enough for gliders to use.

TEXT AND ILLUSTRATIONS Detlef Müller and Christoph Kottmeier, PHOTO Jen Davis

In our article "Thermals influenced by the ground and vegetation" (segelfliegen 04/2023, *additional information at the end of the article*), we discussed the factors that influence the formation of thermals at ground level (energy balance and ground). Here, we explained how dry soils and sealed surfaces, including forested areas, can become a significant source of thermals.

The article "Factors influencing thermal strength" (segelfliegen 06/2023, *additional information at the end of the article*) describes what thermal strength depends on (mainly base height and cumulus cloud thickness).

We also discussed the stratification of the convective boundary layer: on average, superadiabatic stratification (where the lapse rate is steeper than the dry adiabats) near the ground, above that, almost dry-indifferent stratification up to the cumulus condensation level, then the cumulus cloud level. A moisture-stable layer then terminates all convective processes. Without cumulus clouds, the boundary layer in the upper part is already dry-stable.

In this article, we will now discuss the organization of air parcels heated near the ground into thermals that can be worked.

The classic representation of the temperature measurements taken by Gerhard Fritsche and Rudolf Stange at the Leipzig radio tower in the early afternoon hours of a thermal day (***Fig. 1a***) clearly shows a very large temperature gradient in the lower 50' or so, with significant temperature fluctuations near the ground. We have added the mean temperature curve and the standard deviation as well as the temperature gradients over a 33' or 10-m-altitude-interval to the diagram: the extremely increasing temperature gradient towards the ground is clearly visible. It is well above the value for "autoconvection" (-3.42 °C/100 m), at which point denser air lies above less dense air and density instability occurs ("critical temperature gradient").

Actually, convective redistribution should occur spontaneously due to buoyancy instability, and the critical temperature gradient should be established. The fact that this is not the case is mainly due to the constant supply of heat from the ground on the one hand and "turbulent viscosity" on the other: Heat transport upwards is mainly achieved by the "flow of sensible heat," i. e., on days with radiation, by individual thermal updrafts.

The heat exchange between the initially slow-rising updrafts and the surrounding, stationary air through edge mixing causes a reduction in horizontal temperature and density differences. The rising air cools down not adiabatically, but superadiabatically. A rapid "tipping" is prevented, even if the autoconvective temperature gradient is exceeded.

The interaction between rising air parcels and the surrounding air, as well as turbulent mixing, results in a temperature profile in the lower 100' – 165' at which the temperature gradient decreases sharply with height near the ground but remains superadiabatic at

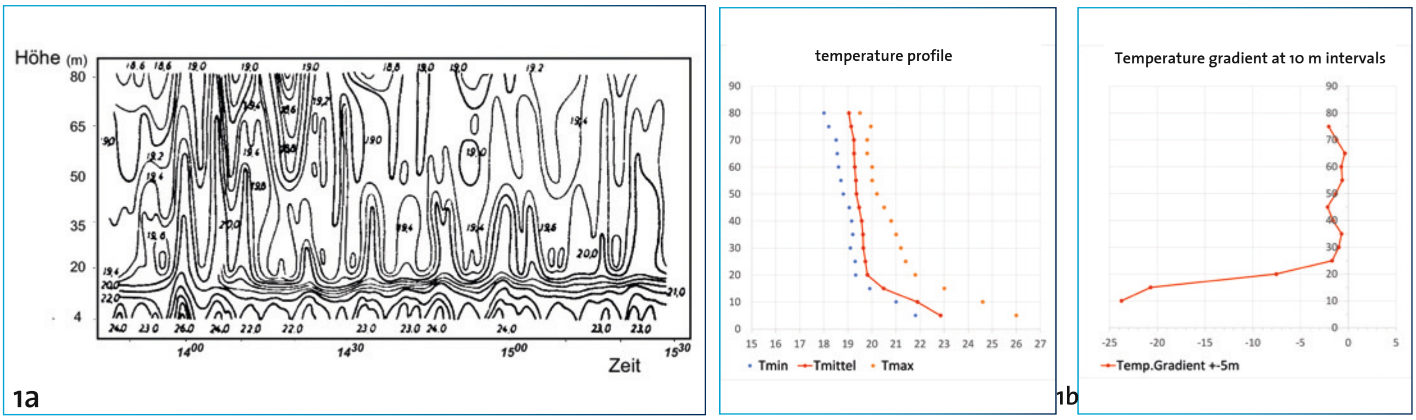



**Fig. 1a** Temperature profile over time at a height of 80 m. (Gerhard Fritzsche, Rudolf Stange: Vertical temperature profile over a large city. Beitr. Phys. fr. Atmos 23, 95-110, 1936). **Fig. 1b** Average temperature profile with temperature variance and temperature gradients over a 10 m altitude interval relative to **Fig. 1a**.

higher altitudes (***Fig. 1***).

If a layer of air close to the ground remains undisturbed, the temperature gradient near the ground can exceed the autoconvective value without automatically leading to redistribution/convection. Nelson R. Williams published a paper on this subject in 1948, in which he showed that under realistic conditions, averaged over a depth of ten meters, a critical temperature gradient of -122 °F/1,000', i. e., 21 times the dry adiabatic temperature gradient, is possible. This fits quite well with the average gradient of the Leipzig measurements.

**Height of the superadiabatic layer**

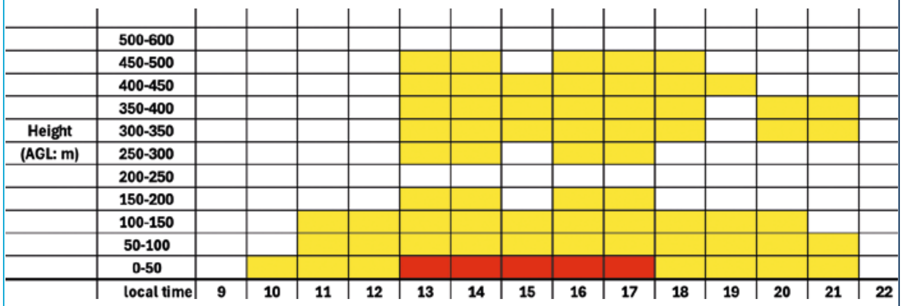
But how high does the layer with a superadiabatic temperature gradient actually extend? An example of this can be found in the literature in a series of measurements taken in Iowa, USA (***Fig. 2***):

The persistence of the autoconvective gradient between approximately 13 and 17 local time indicates an almost continuous supply of heat, as the heat is constantly transported upwards by convective updrafts.

In meteorological literature, the superadiabatic layer of the convective boundary layer is referred to as the "surface layer" and reaches a height of 10-15 % of the base/blue thermal height. It is the result of the interaction between the warming of the air near the ground, Archimedes' buoyancy, and turbulent mixing, and is characterized by a temperature decrease of more than 3 °C/1,000' m. Since the ground is the source of air humidity (evapotranspiration) and turbulence or convection transports air humidity to higher altitudes, the surface layer is also typically characterized by a decrease in air humidity with altitude.

How high the surface layer actually reaches in a day and how pronounced the superadiabatic temperature gradient near the ground actually is depends on the surface conditions, how much they warm up, and the wind speed. As the wind speed increases, the vertical temperature gradient near the ground decreases because the turbulence near the ground causes the heated air parcels to be "removed" prematurely.

Only above the surface layer, in the so-called mixed layer, do we have an approximately dry adiabatic stratification, which is characterized by large-scale convection/upward and downward wind distributions with typical diameters of several hundred meters. On days with high solar radiation, it grows during the course of the day due to the ever higher updrafts, which penetrate into more stable air layers and, through compensatory sinking, carry warmer and drier air into lower layers.

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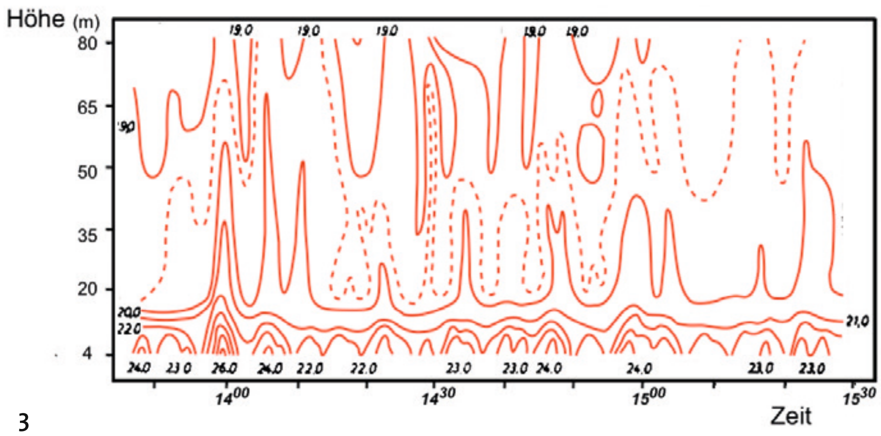


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The air humidity (the mixing ratio) is almost constant on average.

**From separation to flyable thermals**

As the measurements taken in Leipzig (***Fig. 1***) show, eruption-like bursts of warm air occurred periodically every 5 minutes or so due to the continuous supply of heat from the ground, but most of the vertical movements appear to break off at a height of about 50' due to mixing with the surrounding air. We feel these bursts of warm air on the ground as brief "detachments."

***Fig. 3*** shows a processing of the Leipzig measurements, in which only integer isotherms are plotted with solid lines. The 20 °C isotherm and the dashed 19.5 °C isotherm clearly show that even above 65' altitude there is still a regular

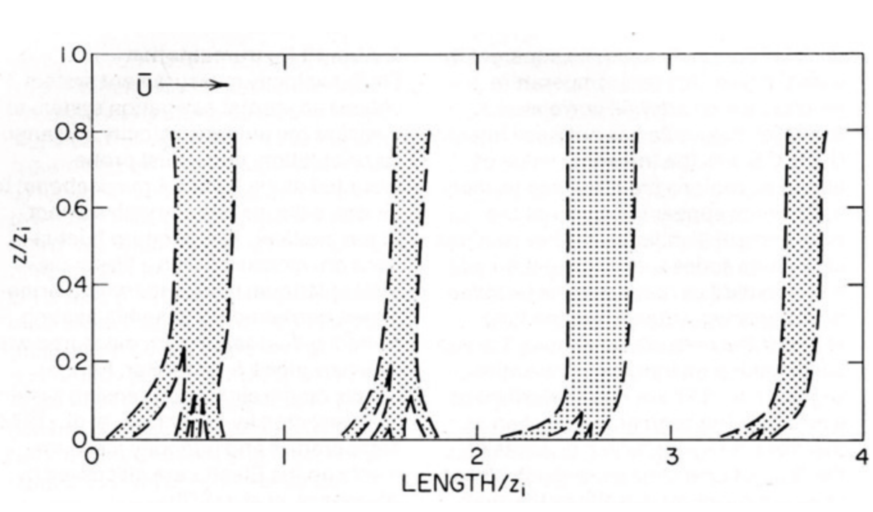


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**Fig. 2** Height intervals with superadiabatic stratification (yellow shading) and gradients greater than the autoconvective gradient (red shading) between 9:00 a.m. and 10:00 p.m. local time, measured with a microwave radiometer on August 25, 2011, over northern Iowa, USA. (ALAN C. CZARNETZKI: Persistent Daytime Superadiabatic Surface Layers Observed by a Microwave Temperature Profiler).
**Fig. 3** As in Fig. 1a, but reduced to the integer isotherms (solid lines) and the 19.5 °C isotherm (dashed line).
**Fig. 4** Schematic cross-section of the boundary layer showing a thermal field based on the size and number of thermals observed along the flight routes. (Airborne Measurements of the Structure of Thermals, D. H. Lenschow and P. L. Stephens, Presented at XVI OSTIV Congress, Châteauroux, France (1978).

heat flow (albeit characterized by smaller horizontal temperature differences) from the turbulent-viscous lower layer up into the upper layers.

Only particularly heated air pockets have sufficient buoyancy to continue rising despite the mixing processes (shown in the illustration at around 2:00 p.m.). The maximum temperature variance values show 4 °C at a height of 13'. Apparently, this temperature (and thus density) gradient was sufficient to allow the heated air parcel to continue rising on this windless day. At a height of 165', the temperature was already less than one degree Celsius.

The "outbreak" at around 2:00 p.m. lasted only about three minutes, similar to the other detachments. This was followed by two more weakening detachments, which apparently made their way to higher altitudes. However, when we consider the air volumes required for good updrafts in the mixed layer, this simply does not add up – neither in terms of diameter nor the duration over which the air rises here! Not every one of these detachments can result in a strong updraft above.

The explanation for these contradictions was provided by meteorological measurement campaigns in the 1970s, which included detailed aircraft measurements (Jagadish Chandran Kaimal and Joost Businger, Donald Lenschow, and Pamela Stephens). ***Fig. 4*** shows a schematic cross-section of the thermals based on a large number of flight routes in an extensive area with thermals over the sea.

The flight measurements showed that up to an altitude of about 0.2 times the height of the convection layer—i.e., in the "surface layer"—individual smaller updrafts merge to form larger ones.

In the early 1990s, Alastair Williams and Jörg Hacker from the Flinders Institute for Atmospheric and Marine Sciences at Flinders University in Adelaide published the results of flight measurements over Australia that dealt precisely with the transition from updrafts near the ground to flyable thermals. Fig. 5 is based on illustrations from their presentation at the OSTIV conference in Uvalde, Texas, in 1991.

Williams and Haker distinguish between "plumes" in the surface layer and 'thermals' in the mixing layer. In the surface layer, the ground-level updrafts not only accelerate, but also merge into larger, stronger "thermals" or are suppressed.

Air parcels rising locally from the turbulent, viscous lower layer enter the area of influence of updrafts and downdrafts or circulation systems with their cross-currents from the mixing layer. Convergences form, into which plumes are drawn/pushed together and merge. As a result, at the upper edge of the layer near the surface, the thermals finally become what glider pilots see, namely more or less extensive areas of updrafts with vertical speeds that can lift a glider into the air.

If you look closely, you can also see the sinking and horizontally moving air above the turbulent viscous base layer in the measurements taken at the Leipzig radio tower based on the temperature variations (***Fig. 1 and Fig. 3***).

We also see a clear influence of the interaction between updrafts in wind on the merging of several small updrafts into a larger one. If a strong updraft moves with the horizontal wind over comparatively slower young updrafts near the ground, the strongest of them are given an easier path upwards and are "collected" and receive the primary updraft that can be flown out.

We also find evidence of individual detachments merging into broader updrafts in Oliver Predelli's illustrations (***Fig. 6***). Above 260', the structures with horizontally varying humidity and potential temperature decrease, indicating that the detachments near the ground are "growing together" to form flyable thermal updrafts.

From a gliding perspective, we suggest subdividing the convection layer into four sublayers – above the molecularly viscous sublayer of a few millimeters in thickness:

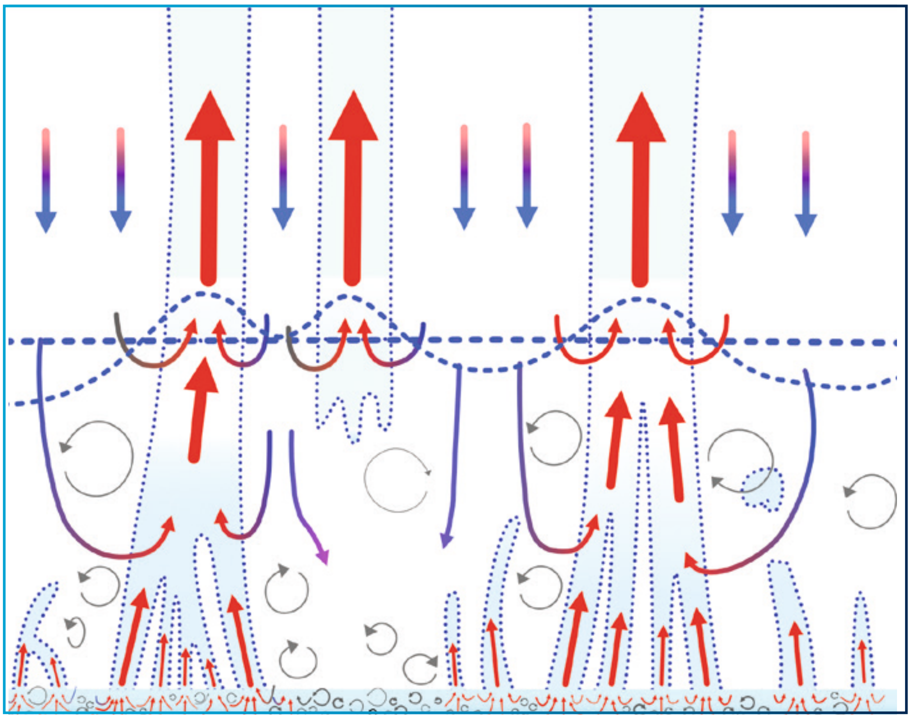

**Fig. 5** The transition from plumes in the near-surface layer to thermals in the mixed layer that can escape. Warm air flows from the near-surface layer into the wider updraft areas of the mixed layer, which extend through the entire depth of the convection zone. The descending parts of the mixed layer vortices penetrate from the free atmosphere down into the lower near-surface layer. Cross-flow between neighboring upward and downward arms of mixed layer vortices occurs in the middle of the near-surface layer. Convergences form, into which plumes/ground-level updrafts are drawn/pushed together and merge. (Modified representation according to A.G. Williams and J.M. Hacker: Inside Thermals, XXII. OSTIV Congress, Uvalde, Texas, USA 1991).

- The lower layer near the surface ("turbulent-viscous sublayer"). The lowest layer, which is the source of the ground-level updrafts (according to Williams and Hacker: "plumes"). It is characterized by very high temperature gradients, partly due to autoconvection. Height: a few decameters.
- The upper layer near the surface ("orientation layer"). Middle and upper areas of the superadiabatic/near-surface layer. The descending air from the mixing layer penetrates into the near-surface layer up to this point. There are cross-currents between neighbouring upward and downward arms of mixing layer vortices in the middle area of the surface layer, which lead to convergences into which the "plumes" are drawn/pushed together and combine to form flyable thermal updrafts. Height: approx. 10-20% of the base/blue thermal height.
- The mixing layer. It is (almost) dry adiabatic and encompasses the area with updrafts (according to Williams and Hacker: "thermals"). More detailed observations show that, on average, the upper half is slightly dry stable.
- The entrainment zone. Here, the updrafts penetrate a dry, stable layer of the free atmosphere, and compensating air from the free atmosphere—usually drier—is mixed into the

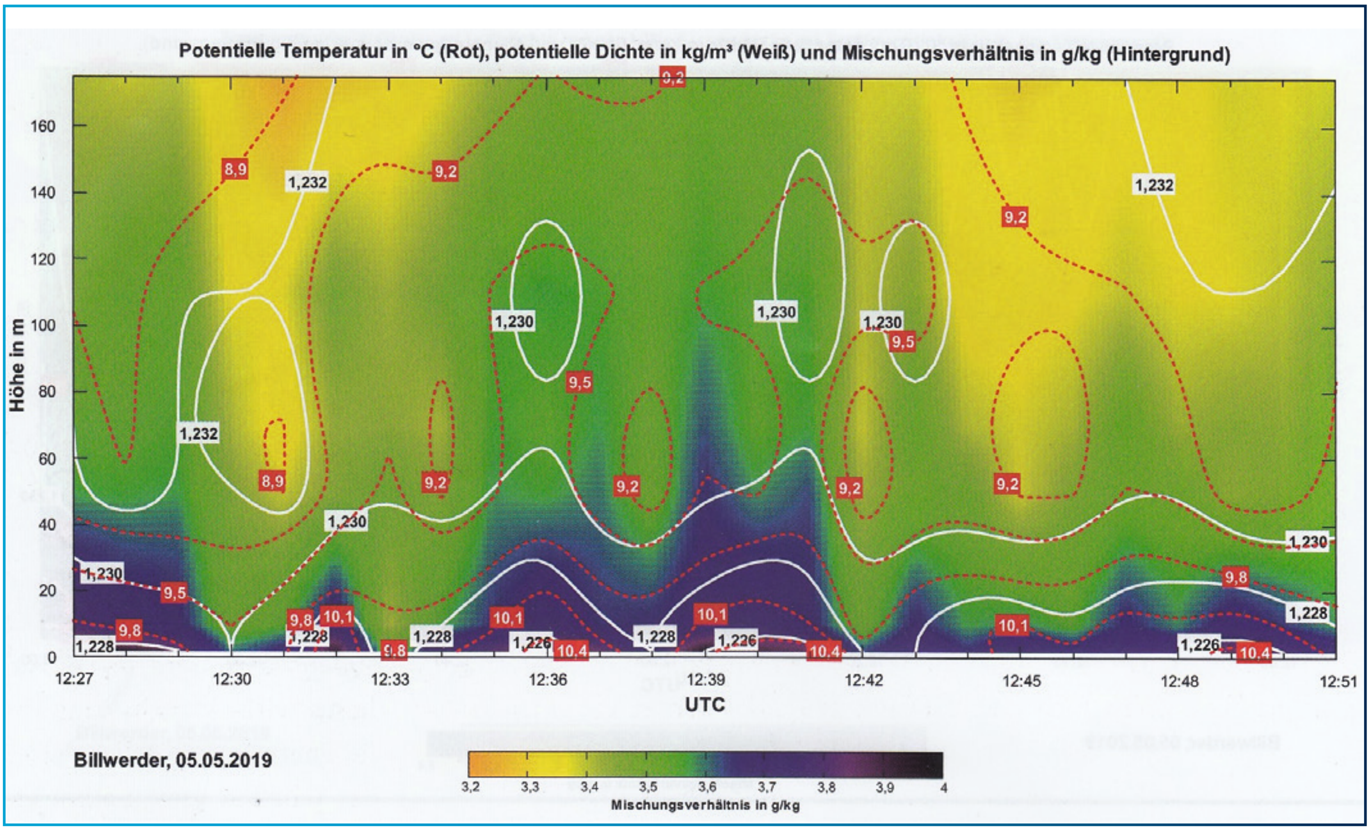


**Fig. 6** Graphical representation of meteorological measurements taken at a mast in Billwerden, Hamburg.
(from "The formation of thermals at ground level" by Oliver Predelli, segelfliegen 03-2023, additional information at the end of the article)

mixed layer. Above this is the free atmosphere.

**For practical flying,** it is very important to have a clear idea of how flyable thermals are formed, as shown in the pictures. Especially over flat and slightly hilly terrain and at lower altitudes (650' –1650'), exploiting updrafts often requires multiple shifts because the organization into a few strong updrafts is still taking place.

**In our next article,** we will illustrate the described image of the updraft structure with new evaluations of lidar and mast measurements taken at the 200-meter measuring mast of the Meteorological Institute in Karlsruhe.
We will then take a closer look at the controlling structures in the mixing layer. We will show which larger convective rearrangements in the boundary layer ensure that the location with a flyable updraft and the distribution of updrafts do not depend solely on the characteristics of the Earth's surface. ♦

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