



Thermals made visible

— but what does it
look like now?



For a long time now, it has been possible to measure the daily development of temperature, humidity, and wind at frequent intervals using radiosonde ascents.

Thanks to modern variometers, supplemented by wind calculation software such as “HAWK” or the live display system “Anemol,” it is now possible to measure many details of thermal currents in gliders during flights or circles at different locations and at different altitudes. However, this is naturally only possible at the location of the aircraft, never simultaneously across the entire altitude range of the thermals and at any location. This means that fairly simple questions about the size and shape of updrafts, their movement with the wind, and their frequency have so far only been answered approximately.

This is where lidar technology offers a major advantage. In its most common application, it enables the measurement of updrafts and downdrafts above the installation site from approximately 165’ above ground level to the upper edge of the boundary layer, with a measuring distance of approximately 200’ and typically every 20 seconds as a complete profile. Many different measurement

methods have also been developed, e.g., using several lidars simultaneously, measuring downwards from a research aircraft, or successfully combining wind lidars with other measurement systems. Lidar technology is also used for wind energy studies and investigations of wake vortices behind commercial aircraft. Here, we will limit ourselves to vertical wind measurements, which are supplemented by stored measurements of the horizontal wind. The horizontal wind is determined by the differently inclined emission direction of the laser pulses.

Measurement location and measurement procedure

At the Karlsruhe Institute of Technology (KIT) Campus North (formerly the Karlsruhe Research Center), meteorological measurements have been carried out in a forest area for decades using a highly sophisticated 650’ high mast.

Among other things, all three wind components are measured with ultrasonic anemometers at four heights, the temperature with platinum sensors at eight heights, and the humidity with dew point mirrors at five heights.

With a measurement frequency of 20 Hz, the convective movements, i.e., the thermals, can be made very visible at the

What new insights can we gain from data obtained using modern wind measurement technology such as Doppler lidar? This technology provides a much more complete picture of thermals than other methods.

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Modern lidar methods make thermals “visible,” even without clouds. KIT measurement setup for the “Swabian MOSES” measurement program near Rottenburg, 2021, with Doppler lidar in the foreground and cloud radar in the middle.

mast (**Fig. 1**). In combination with Doppler lidar measurements, they provide fairly complete information about the temporal development of the wind over the entire altitude range of the thermals. To achieve this, the Doppler lidar was operated for several weeks in July 2020 in a small clearing about 650' away from the base of the mast. Vertical wind measurements were taken by aligning the lidar beam in the zenith direction, while horizontal wind was determined by measurements in all four cardinal directions (N-E-S-W) at an elevation of 75 degrees. Vertical profiles of the vertical and horizontal wind are available at intervals of 165'. The temporal resolution is 4 s for the horizontal wind and 20 s for the vertical wind

A day with great thermals

To illustrate a typical diurnal development of the convective boundary layer, we have taken July 21, 2020 as an example. On this day, it was almost cloudless at noon in the Upper Rhine Graben (**Fig. 2**). Nevertheless, the thermals were strong, and four flights of over 1,000 km and over a hundred flights of over 500 km were flown in Germany, some of which also crossed the Upper Rhine Graben (www.weglide.org).

The thermals during the course of the day as seen by the lidar are shown in **Fig. 3**. At 6 a.m. (all times in CET) – i.e., shortly after sunrise at 5:45 a.m. – the horizontal wind speed at altitudes between approximately 300' & 3,000' is around 12 – 14 kt (**Fig. 3b**). At an altitude of around 4,000', however, there is almost no wind. The area up to an altitude of 100 m is the stable layered night-time boundary layer. The layer above it up to 4,000' (residual layer) marks the area of the previous day's thermals. Only very weak vertical movements can be observed in this layer at night (**Fig. 3a**). A temperature inversion separates the residual layer from the free atmosphere above it, where the horizontal wind

speed is significantly higher (**Fig. 3b**). The conditions in the residual layer change after sunrise. Around 8:00 a.m., i.e., after the ground-level inversion has dissipated (**Fig. 4**), the first small convective cells (plumes) penetrate it from below (**Fig. 3a**). From 10:00 a.m. onwards, as the ground warms up and an unstable layer of air forms near the ground (**Fig. 4**), convective vortices are triggered, which are associated with significant fluctuations in the horizontal wind (**Fig. 3b**). The temperature data show how the potential temperature continues to rise in pulses (**Fig. 4**). It is clearly unstable, especially up to an altitude of 300'. Before 3:00 p.m., there are even signs of weak instability up to an altitude of 650'.

As with temperature, pulsations can also be observed in convective vortices. With increasing radiation, they advance to ever greater heights and around 1:00 p.m. they reach the height of the residual layer from the previous day (**Fig. 3a**). Since the inversion at 4,101' m is weak, the convective boundary layer rises to about 5,750' in the course of the afternoon due to the rising warm air parcels. On this day, it is therefore about 1,650' higher than on the previous day. The updrafts reach 8 – 10 kt and have also enabled good thermal flights in the Rhine Rift Valley. The downdrafts can reach up to 6 kt. The horizontal wind also varies in the vicinity of updrafts (**Fig. 3b**), as was also determined by wind-measuring variometers.

The measurements thus impressively confirm our knowledge of the convective boundary layer on undisturbed thermal days. In the early afternoon, the convective boundary layer has the typical vertical structure: above the unstable layer near the ground (Prandtl layer) is the well-mixed, highly turbulent mixing layer. This is capped by an entrainment layer with an embedded inversion. Above this lies the free atmosphere. As the evening cools, the updrafts and

Fig. 1 The 200 m high meteorological measuring mast of the Karlsruhe Institute of Technology (KIT) on the North Campus (49° 5' 33" N, 8° 25' 33" E, 110.4 m above sea level).

Fig. 2 Satellite image (natural colors) on July 21, 2020, at 1 p.m. CET.

Fig. 3 (a) Time series of the vertical wind and **(b)** the horizontal wind on July 21, 2020. The dashed line shows the mean boundary layer height, z_i , and the dotted line shows the height of the residual layer, RL. The white bars mark periods with data failure. The lower scale bar marks the time window, which is discussed in more detail below.

Fig. 4 Potential temperature at the 650' mast on July 21, 2020. The temperature shows a superadiabatic (unstable) layer approximately in the lowest 300' and good mixing above that, i.e., rather adiabatic layering.

downdrafts weaken, first near the ground and later also in the upper boundary layer, and are no longer flyable.

Downwinds, even from the very top to the very bottom

We want to limit ourselves to a few interesting phenomena that are particularly well visible in Doppler lidar measurements and may be of importance to glider pilots. To this end, we chose a period in the early afternoon when the thermals were well developed (**Fig. 3a**). The first of the two hours was characterized by several shorter-lasting (and therefore narrower) thermal structures, and the second by a longer-lasting thermal structure. What questions about thermals should we address now:

- What does the vertical structure of the updraft tubes look like?
- What vertical extent and sink rate are typical for the downdraft areas?
- What happens at the upper edge of the turbulent boundary layer, the so-called entrainment layer?
- How variable are the horizontal winds?

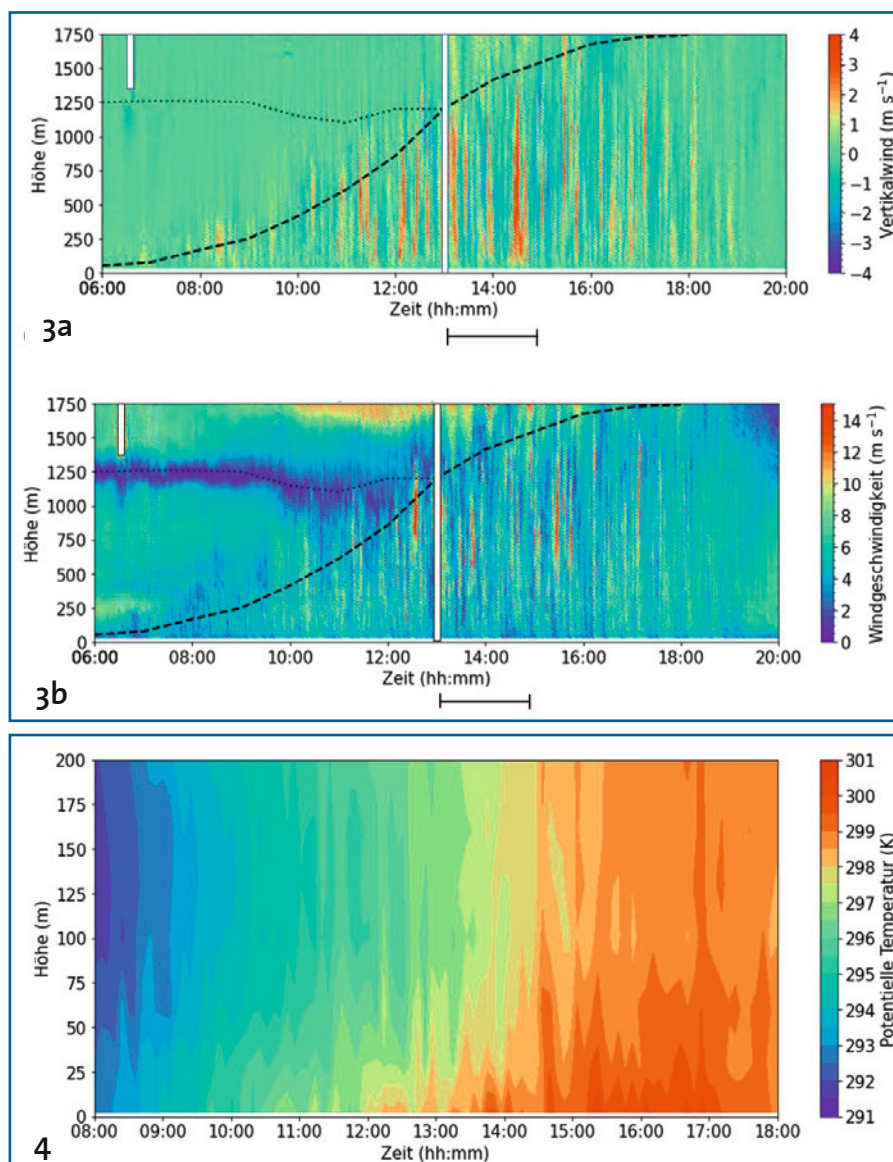
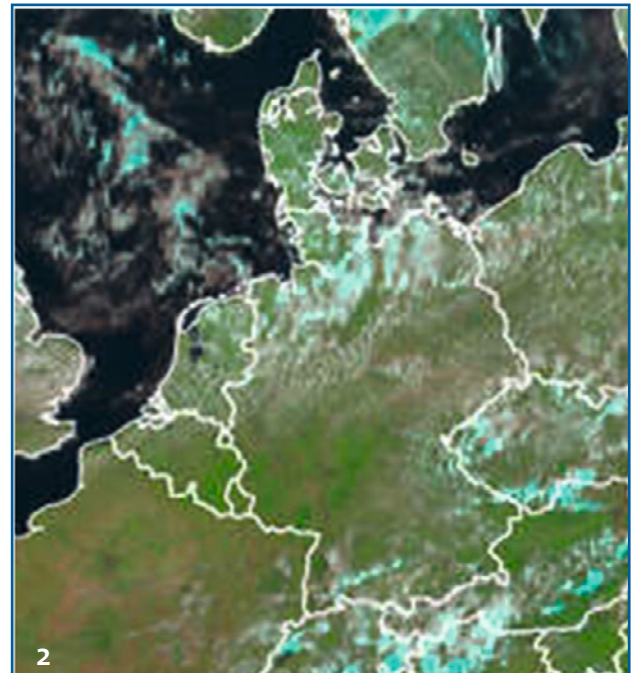
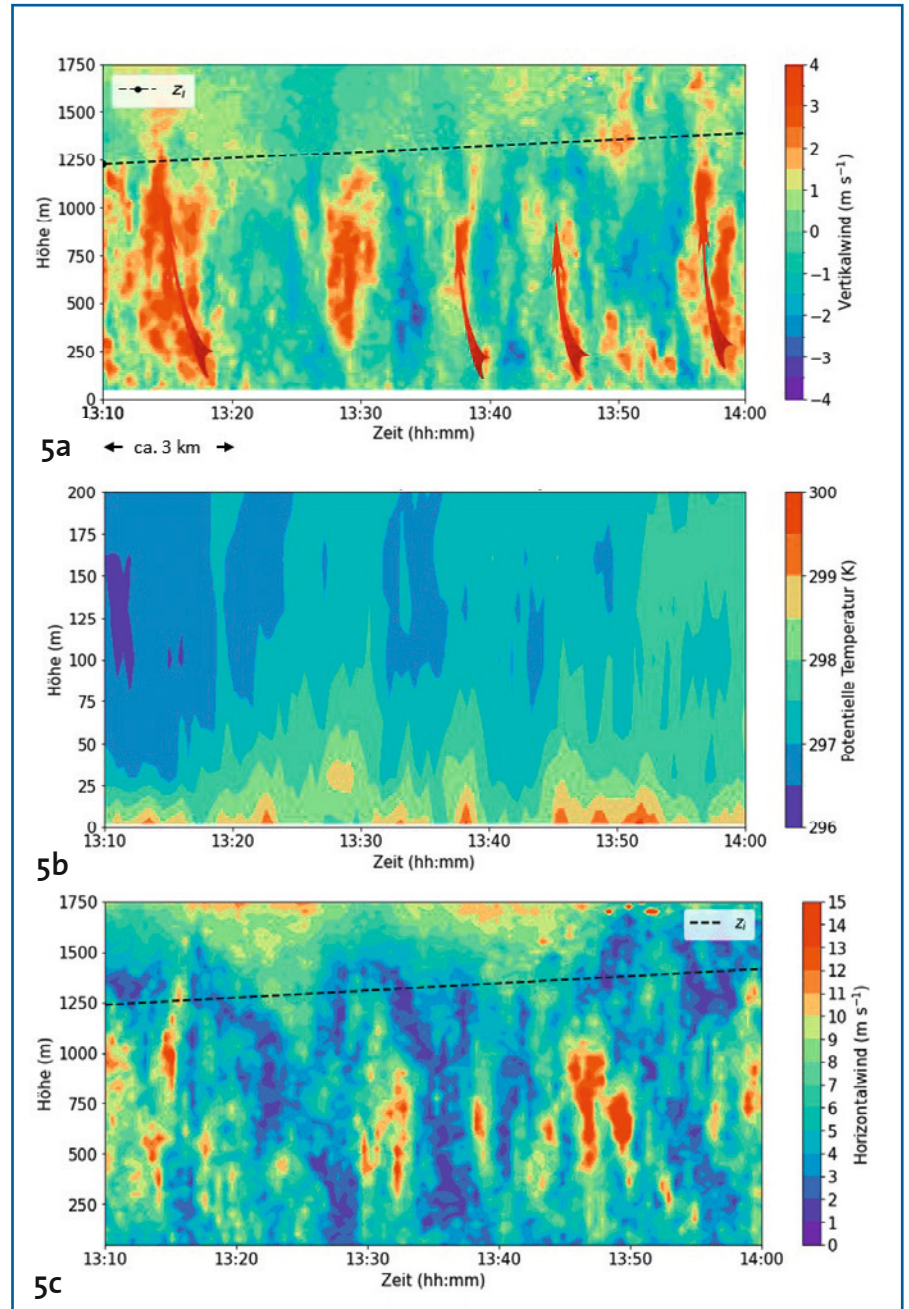


Fig. 5 (a) Vertical wind, (b) potential temperature, and (c) horizontal wind between 1:10 p.m. and 2:00 p.m. The dashed line in (a) and (c) indicates the upper boundary layer limit, z_i . The arrows in (a) indicate the direction of the updrafts and downdrafts.

Let's look at the first period from 1:00 p.m. to 2:00 p.m., which is characterized by strong temperature fluctuations near the ground (**Fig. 5b**). During this hour, approximately five thermal tubes of varying durations (between two and eight minutes) can be seen above the Doppler lidar (**Fig. 5a**). Some of them extend from near the ground to the upper boundary layer, z_i , or collide with the entrainment layer. Their further ascent is slowed down in the inversion. The maximum vertical wind speed typically occurs in the middle of the boundary layer.

Another interesting aspect is the non-exact vertical alignment of the thermal tubes near the ground. In the lowest approx. 250 m, the "foot" of the thermal tube lags behind its position above it. The time lag of the thermal tube can be explained by the lower wind speed in the layer near the ground due to friction and is indicated in the graph by the curved lines. Above this, they are more vertical, as Oliver Predelli also found. Between all passing thermal tubes, there are phases with downward movements (**Fig. 5a**). If the phases are longer, the downdrafts are weaker; if they are shorter, they can reach speeds of 6 kt/s^{-1} . In general, all downdrafts extend like tubes across the entire boundary layer. They are triggered at the upper boundary layer limit when updrafts penetrate the entrainment layer as compensating downdrafts and transport both dry, warm air and momentum from above into the boundary layer. This is clearly



shown in **Fig. 5a** by the blue areas. The decrease in specific humidity measured between 10:00 a.m. and 4:00 p.m. even at an altitude of 650' is certainly also a consequence of this mixing process of dry air and its downward transport by the downdrafts. The downdrafts also reach their highest speed on average in the middle of the boundary layer and become weaker

towards the ground (**Figs. 3a, 5a**). There, the descent is deflected into horizontal motion, which contributes to small-scale convergences and promotes the detachment of new updrafts. Secondly, in the vicinity of thermal tubes, a brief increase in horizontal wind must always be expected. Wind peaks above 20 kt in the middle of the boundary layer are obviously not uncommon (**Fig. 5c**).

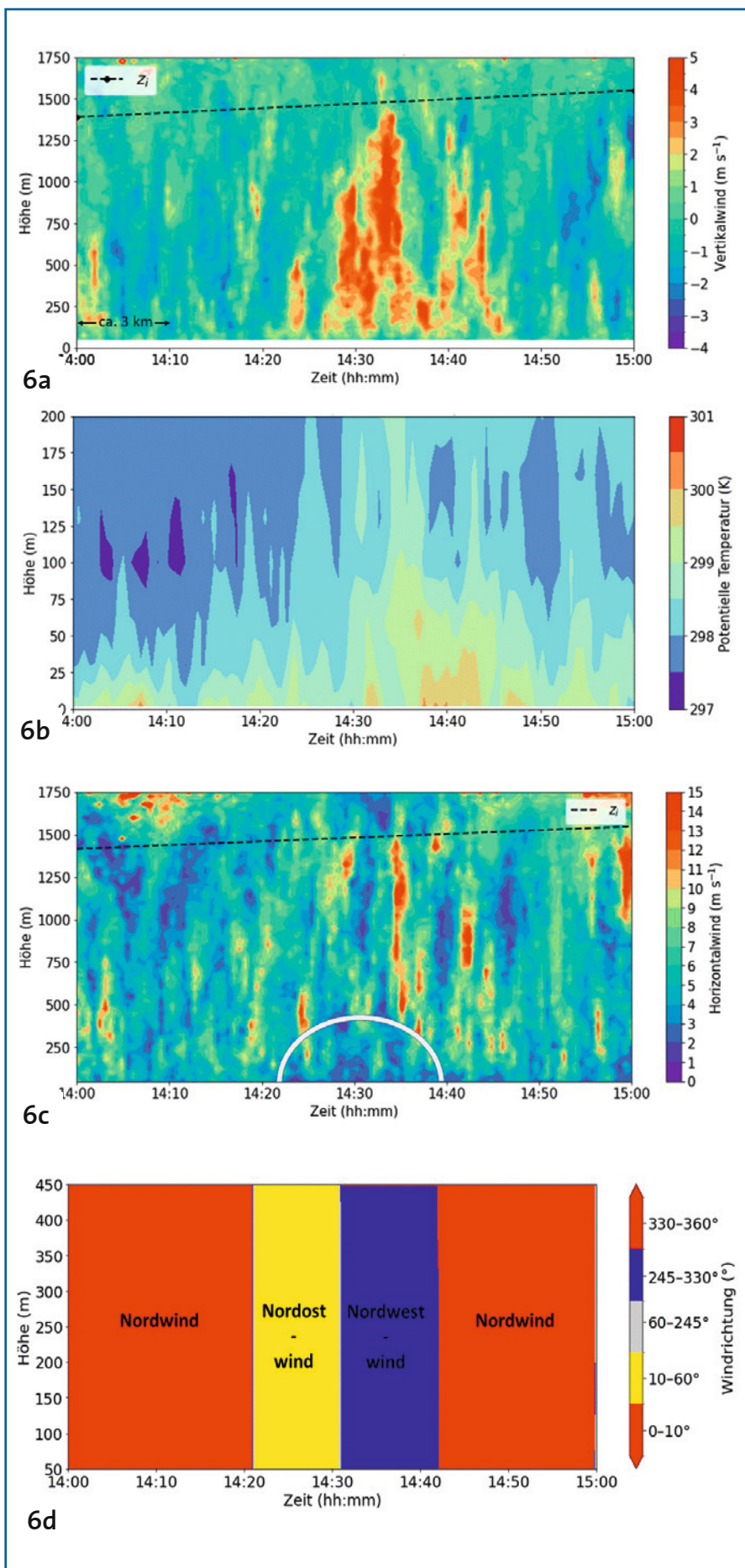


Fig. 6 (a) Vertical wind, **(b)** potential temperature, **(c)** horizontal wind, and **(d)** wind direction on July 21, 2020. The dashed line indicates the boundary layer height, z_i . In (c), the curved line indicates an area up to an altitude of 1,350' where the horizontal wind is lower than in the periods before and after.

These are surprisingly high values, but they should also be found with wind-measuring variometers.

Strong thermal

Let us now turn to the next hour, in which the temperature near the ground continues to be unstable and exhibits strong pulsations (**Fig. 6b**). The thermals are characterized by a single prolonged updraft phase of approximately 15 minutes, preceded and followed by a 20-minute descent (**Fig. 6a**). The updraft area, i.e., the strong updraft at 2:30 p.m. from an altitude of about 1,350', is "fed" by several narrow updrafts below it – conditions that have already been described above. Assuming a shift of the approximately 15-minute thermal tube with an average horizontal wind speed of about 5 m/s⁻¹, it has a horizontal extension of approximately 3 miles. Another strong updraft just a few minutes later is likely to be related to the first thermal tube (**Fig. 6d**).

Since the doppler lidar only provides measurements from a height of 165', we can also refer to the mast measurements for this event. This allows us to assess how well neighboring measurements – the mast and lidar are approx. 650' apart – correlate with completely different measurement methods and to observe the appearance of the thermal tube down to the ground.

Upwinds that can be flown out

The three periods of weak thermals

Fig. 7 Vertical winds on July 21, 2020 (a) from the Doppler lidar and (b) at the 650' mast. The altitude range below 150' is not covered by the lidar.

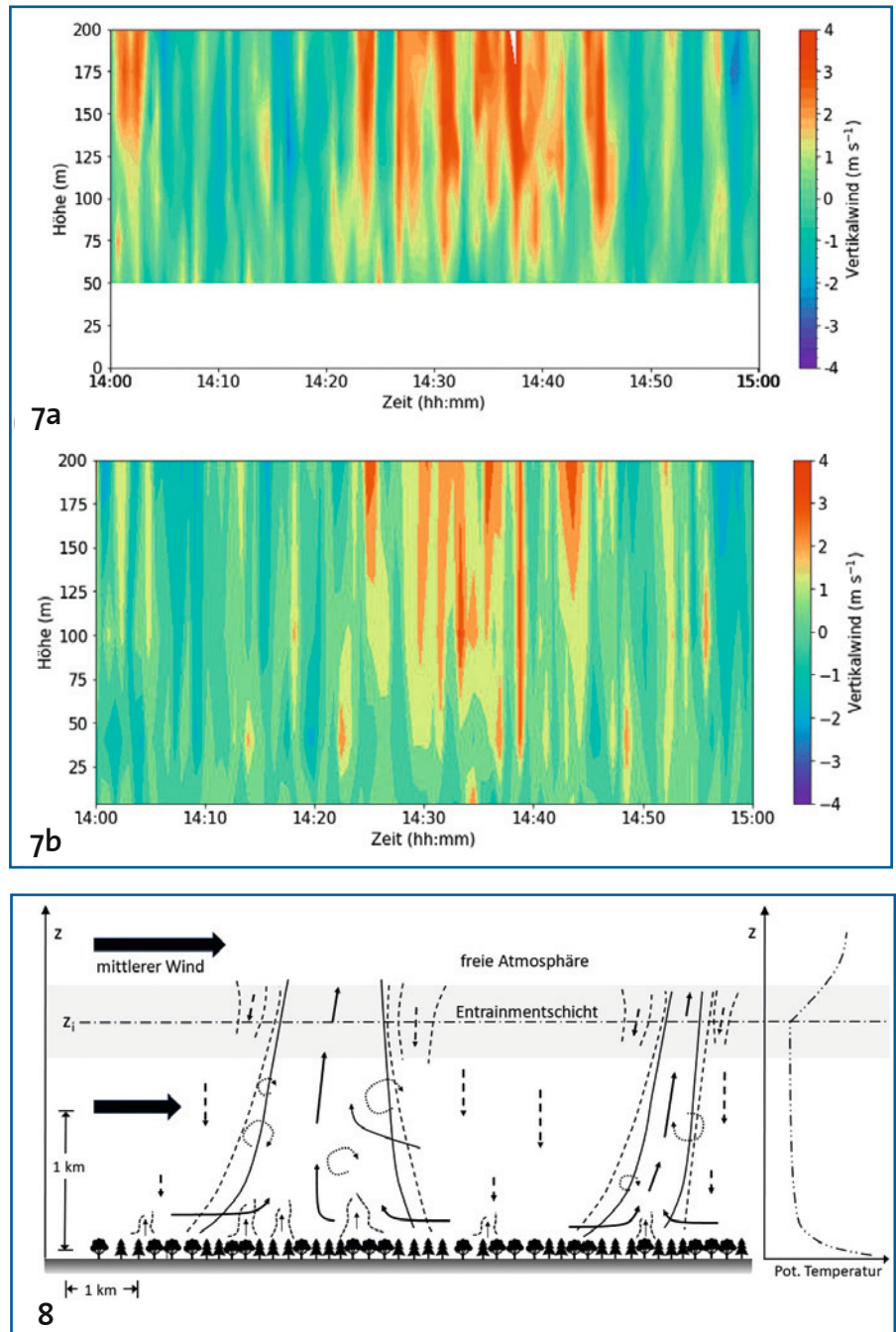
Fig. 8 Schematic representation of convection in the boundary layer. z_i indicates the boundary layer height. Areas with updrafts are indicated by solid arrows and lines, areas with downdrafts by dashed arrows and lines.

(2:05 p.m. to 2:25 p.m. and 2:45 p.m. to 3:00 p.m.) and stronger updrafts (2:25 p.m. to 3:45 p.m.) can be seen at both locations (**Fig. 7**), even though the structures are not entirely the same. The details in the middle phase show slightly more and stronger updrafts on the lidar, and they are not entirely simultaneous. Due to the distance of 650', the updrafts do not drift “identically” over the locations. In addition, the mast data clearly show that the updrafts and downdrafts are even weaker near the ground.

The joint measurements clearly show that the updrafts only stabilize and become strong enough to fly at around 300' to 500'. This is entirely consistent with previous findings, as described by Müller and Kottmeier 2025. The powerful thermal tube shown here is fed by warm air near the ground, which significantly reduces the superadiabatic temperature gradient in the lowest 300' from 3:00 p.m. onwards (**Fig. 4**).

This is probably also one of the reasons why no more convection cells are triggered locally for the rest of the hour. The wind changes in the vicinity of the thermal tube are also striking. During the updraft phase (2:25 p.m. to 2:45 p.m.), the horizontal wind in the lowest approx. 1,350' is weaker than during the downdraft phases, i.e., before and after (**Fig. 6c**).

As in the previous hour, conditions are extremely gusty in the vicinity of the thermal tube, i.e., in the middle of the



boundary layer. No preferred spatial correlation with the updraft can be identified. The greatest fluctuations in the horizontal wind appear to occur at the rear of the updraft (e.g., between 2:35 p.m. and 2:45 p.m.). According to the theory of turbulent flows, both dynamic and thermal generation are possible causes of the turbulent beha-

vior of the horizontal wind, especially the high wind peaks. However, the exact cause has not yet been explained. As regards the wind direction near the ground in the vicinity of the thermal tube, very marked changes can be observed in the passage of the cell (**Fig. 6d**). Here, the strongly fluctuating wind directions were grouped into four

sectors: north wind (red), northeast wind (yellow), northwest wind (blue), and all other wind directions (gray, did not occur here).

What do the results show us? Before the arrival of the thermal tube, we can see the synoptically prevailing north wind on this day. With the arrival of the thermal tube, the wind turned to the northeast, and with the passage of the center, it turned just as abruptly to the northwest until its end. After that, it blew from the north again. Considering that the thermal tube moved from north to south across the lidar, the wind measurements clearly confirm the wind convergence in the lower part of the thermal tube (inflow). This wind behavior is also known from other observations and is consistent with the lower horizontal wind speeds in the lower part of the thermal tube (*Fig. 6c*).

New insights

Let us now briefly summarize the results, also using the schematic representation in *Fig. 8*:

Due to wind shear, updraft tubes often have a downward slope near the ground

up to an altitude of about 500'. In addition, several small and weaker updrafts (plumes) near the ground form in the well-mixed layer into a few strong updraft tubes, which then often reach the upper edge of the boundary layer and even into the entrainment layer, causing the boundary layer to grow. Maximum speeds and turbulent fluctuations of the vertical wind up to 10 kt usually occur in the middle of the boundary layer.

At the upper edge of the boundary layer, the entrainment layer, dry, warm air and momentum from the free atmosphere are mixed into the boundary layer. Since the wind speed in the free atmosphere is often higher than in the boundary layer, increased horizontal wind speeds associated with downdrafts must be expected in the entrainment area.

The downdrafts usually extend continuously across the entire boundary layer, i.e., from the entrainment layer to

the layer near the ground (Prandtl layer). Here too, the highest values of up to 6 kt usually occur in the middle of the boundary layer.

Strong fluctuations in horizontal wind often occur in the vicinity of the updraft tubes. Lidar measurements showed values of over 10 m/s in the middle of the boundary layer. This phenomenon is not yet fully understood. A new aircraft-borne lidar developed at KIT is expected to provide further insights.

In the lower part of the updraft tubes, i.e., from the lowest point to approx. 1,350', a convergence in the horizontal wind was observed. This inflow into the updraft tube is also to be expected for reasons of mass conservation.

The results from lidar and mast measurements confirm much of what glider pilots and meteorologists already know about thermals with new and more complete data. However, they also provide new insights into the fascinating world of updrafts and downdrafts. ♦

ADDITIONAL INFORMATION
THERMAL ARTICLES:

