# Some Characteristics of Thermal Convection as Measured by a Powered Sailplane

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**Summary**
Measurements of the convective boundary layer by means of a powered sailplane are presented. They refer to the vertical flux of sensible heat and vertical velocity. The temperature excess and, to some extent, the humidity excess in thermals in relation to vertical velocity and height are measured. Thermal activity over different kinds of surfaces are investigated and give a hint to sailplane pilots how to qualify different soaring areas.

**Introduction**
The characteristics of thermal convection in the boundary layer (the lowest 1000 m, approximately) are measured by a simplified, but highly sensitive system of temperature and humidity measurements, as well as vertical velocity measurements, which give reliable results when additionally corrected by vertical acceleration. This report consists of three parts: First, some statistical properties of thermal convection, especially the relation of vertical velocity to vertical flux of sensible heat; second, the vertical variation of vertical velocity and temperature excess; lastly, the connection between the vertical velocity and properties of the underlying surface.

**1. General Statistical Properties of Thermal Convection**
Figure 1 shows how frequent certain values of vertical velocity were observed under conditions of thermal convection at about 300 m above ground. The maximum negative vertical velocity is only about half as much as the maximum positive vertical velocity, suggesting that updrafts may be the generators for vertical circulations in the convective boundary layer, with downdrafts being mostly due to mass compensation. The positive skewness (asymmetry) of the vertical velocity distribution in Fig. 1 supports this view.
Figure 2 shows, for part of this flight, the potential temperature (°C), vertical velocity (m/s), and vertical flux of sensible heat (W/m²). The largest amount of heat (lowest curve) is transported by what the sailplane pilot will normally call "thermals" having a measurement length (diameter) of more than a hundred meters. There are only a few high heat flux values outside the thermals, which barely change the total amount. These seem partly to result from differences in response time of the instruments.
The distribution of measured values of sensible heat flux is presented in Figure 3. It is to be noted that the maximum value of positive heat flux is about double that of the maximum value of negative heat flux while a very high percentage of the atmosphere transports negligible heat flux or nearly nothing. This is underlined by the steepness ("Kurtosis") of the curve.

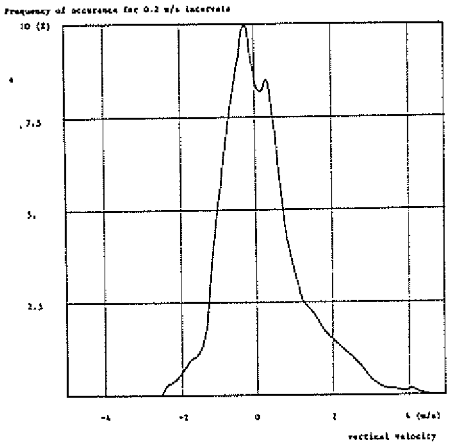



Figure 1: Frequency of occurrence of vertical velocity intervals Meppen, 25th of April, 1974, 16.02–16.18 in 300 m above ground (standard deviation $\sigma_w$ = 1.02 m/s, skewness = 0.74, kurtosis = 0.82).

These functions for themselves give no information about the magnitude of the thermals and their distance from each other. Statistically this information can be gained from a plot of spectral energies in relation to wavelength, although the meaning of wavelengths in a turbulent atmosphere must be interpreted cautiously. Figure 4 shows the spectral energies of vertical velocity for a flight at about 300 m above ground on the 25th of April, 1974, under conditions of thermal convection of medium strength. There are two different maxima of energy: The main maximum is at a wavelength of about 1400 m, while the smaller one is at about 400 m. The analogue flight data give an average distance between two "Thermals"* of 1620 m referring to the main maximum, while the mean measurement length of

* Definition: More than 1.5 m/s over a distance of more than 100 m.

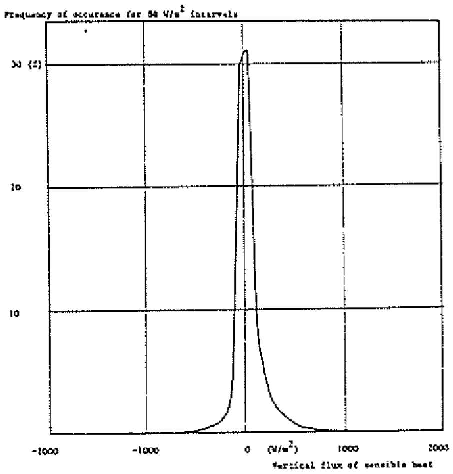
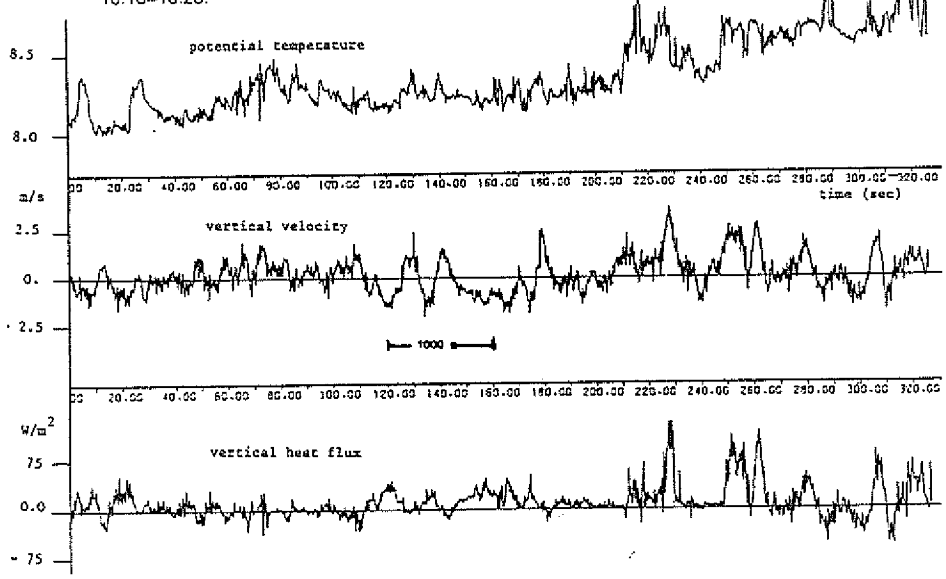



Figure 3: Frequency of occurrence of vertical heat flux intervals Meppen, 25th of April, 1974, 16.02–16.18 in 300 m above ground (standard deviation $\sigma_{wT}$ = 209 W/m², average = 60 W/m², skew = 2 W/m², kur = 16 W/m²).

Figure 2: Plots of potential temperature, vertical velocity, and vertical flux of sensible heat computed out of digital data. Flight: Meppen 4/25/74 16.18–16.23.



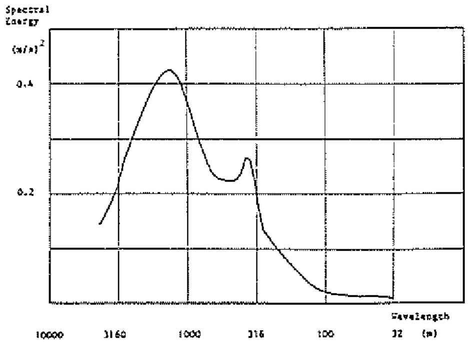



Figure 4: Spectral energy of vertical velocity $(m/s)^2$
Meppen, 25th of April, 16.02–16.18 in 300 m above ground.

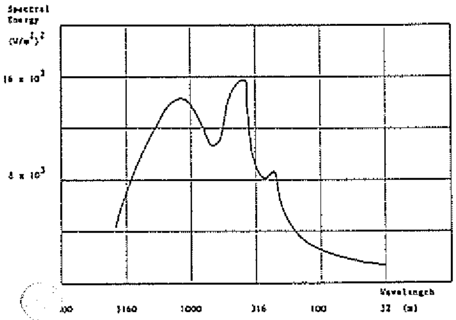



Figure 5: Spectral energy of vertical flux of sensible heat $(W/m^2)^2$
Meppen, 25th of April 1974, 16.02–16.18 in 300 m above ground.

a single convection cell of 480 m refers to the smaller second maximum. In other words, the distance between thermals is of the order of 3.5 times the diameter of the thermal.
Figure 5 is a similar presentation of spectral energies of vertical flux of sensible heat. It shows that the effective heat flux works on the same scales as the vertical velocity, but the main maximum is now that of the scale length of thermals (400 m). In our experience, based on 100 analyzed flights, it is not possible in each case to distinguish between two different maxima of spectral energy, since there is not always such a clear separation as found here. In most cases, our flight and measurement path seems to have been chosen too short for this type of analysis.
The computed results of about 50 measurement intervals for vertical velocity give a good correlation between maximum vertical velocity and its standard deviation, $\sigma_w$, a parameter related to the intensity of turbulence. From these measurements it appears that the convective planetary boundary layer can be separated into three parts: the first from near the ground to 400 m, which may be called the "developing layer"; a medium layer from 400 to 800 m; and a "dissipating layer" above 800 m. (The inversions or stable layers inhibiting further vertical penetration of thermals were in these cases between 1100 and 1500 m.) The correlation coefficients between maximum vertical velocity and standard deviation for the three layers were 0.82, 0.76, and 0.97. The line of regression was about $w_{max} = 4\ \sigma_w$ for the two lower layers and $w_{max} = 3.4\ \sigma_w - 0.2$ for the upper layer, which means that the upper layer, having already a greater stability in the mean, reduces the maximum vertical velocity without reducing the degree of turbulence.

Figure 6 represents the percentage of total flight length covered by thermals (as defined earlier) at various heights. This analysis comprises six different flights over the same site during similar weather and stabile conditions. (The points above 50 percent of flight path belonged to cloud streets and have not been incorporated in the regression line.) The maximum is found at about 450 to 550 m, while the percentage values decrease upwards, probably because not all convection cells reach the same height due to differences in buoyancy and dimensions. Regarding the decrease downwards, it is reasonable to assume that smaller cells join each other while ascending and that they increase in diameter with height due to entrainment. At the height of the maximum, near 500 m, the curve suggests that the thermals are spaced in the average about four times their diameter, not much different from the value suggested by Figure 4. Further measurements including more than one powered sailplane have to prove this view.

## II. The Vertical Velocity and Temperature Excess in Relation to Height

Figure 7 is a presentation of vertical temperature and humidity soundings (center) in conjunction with horizontal soundings of vertical velocity and temperature and humidity excess at various altitudes. Maximum and mean values of vertical velocity are given on the right side and temperature and specific humidity excesses on the left side of the figure. Near the ground the atmosphere is superadiabatic, while it is dry adiabatic mostly in the rest of the convection layer. The vertical velocity remains nearly constant with height, but the temperature excess decreases with height. Qualitatively, this suggests a divergence of vertical heat flux indicating a heating of the layer by convection. Some measured temperature excesses are shown in the center of the figure near the mean lapse rate of environment. The crosses are those connected with positive vertical velocity (mostly thermals); the circles those with negative vertical velocities. As can clearly be seen, the "thermals" cool nearly adiabatically when penetrating into the stable layers above, thus losing their kinetic energy. The compensating descending air comes from the warm layers above and penetrates into the convection layer. The same physical principle of vertical penetration into stable layers was found in cooling tower measurements (Fortak, 1977) which have a much larger amplitude in the neighbourhood of the sources.

## III. Characteristics of Thermals as Influenced by Different Types of Surfaces

Every sailplane pilot knows that there are great differences in the intensity of thermals due to differences in surface characteristics. These differences are extreme between mountains and neighbouring valleys, where high, heated surfaces produce so many thermals that thermal activity is almost totally suppressed over the valleys. Similar differences in vertical heat can be measured over flat ground with varying vegetation.

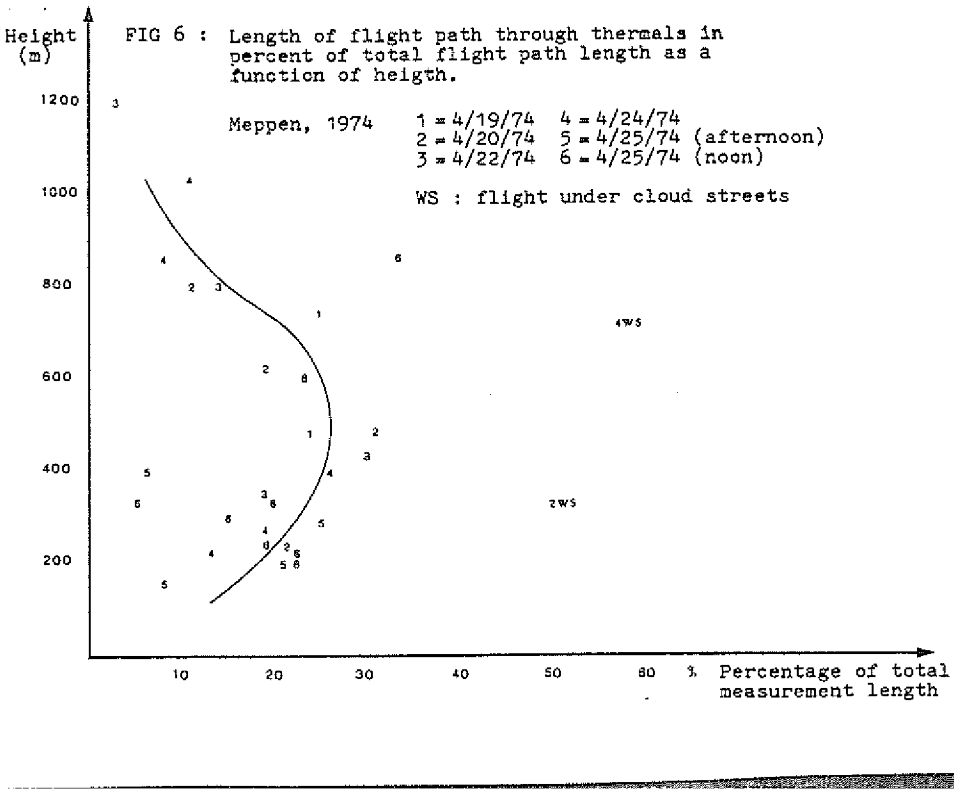



FIG 6 : Length of flight path through thermals in percent of total flight path length as a function of heigth.

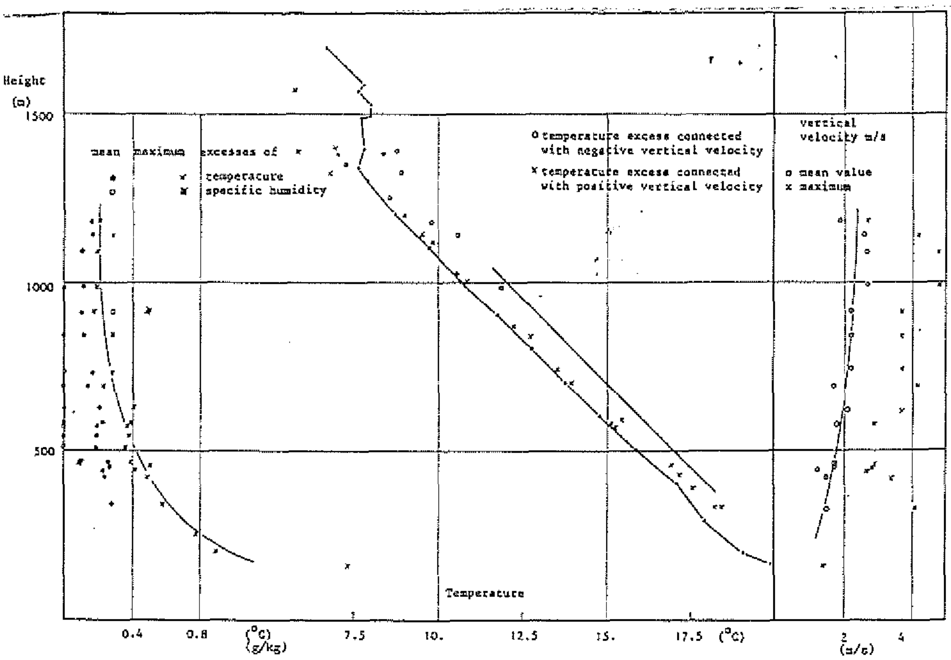


Figure 7: Vertical and horizontal soundings of parameters of thermal convection Oerlinghausen, 8th of September, 1975, 15.25–16.55.

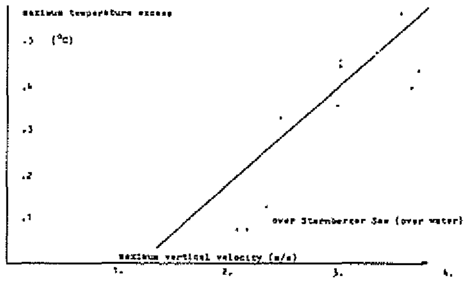


Figure 8: Mean maximum vertical velocity and mean maximum temperature excess of 13 different measurement intervals measured with D-KMET in a maximum height of 500 m above ground over Bavaria in May, 1976
Line of regression (without lake data)
$w_{max} = 4.5\ T_{max} + 1.2$ correlation coefficient = 0.83.

A comparison of a flight over sandy grounds and over moist meadows showed that positive vertical velocities reached 5 m/sec in the first case (with six measurement points of 4 m/s) while in the other case they never reached a value of 4 m/sec. The minimum (negative) values in both cases are only half of the maximum values, a relation similar to that mentioned already in Figure 1.

These differences in thermal activity occurred under the same synoptic condition; however, under different synoptic conditions the results seem to be similar. A measurement campaign made under the scientific leadership and pilotage of Prof. Fortak in Bavaria during May 1976 resulted in 17 flights over the same terrain but under varying synoptic conditions. The height above ground was between 100 and 450 m. Two flight legs were compared: the first one parallel to a small hill near the town of Murnau, the second one near the shore of Lake Starnberg (Starnberger See) representing a much moister surface. The average maximum vertical velocities measured over these two tracks were 3.53 m/s and 2.19 m/s, respectively, while the mean temperature excesses were .57°C to .18°C respectively, thus showing a consistent difference in spite of varying synoptic conditions.

Figure 8, finally, shows the value of maximum vertical velocity vs. maximum temperature excess. The three values far below the regression line were measured over Lake Starnberg where the temperature excesses were quite small. It seems possible that these thermals have been produced over land, but were transported over the lake by the mean wind where colder air from the lake entered the thermals reducing the buoyancy rapidly.

The figures presented here are only a small part of the total measurements. We will continue this program for lifetime studies of single thermals as well as for general statistics. The measurements and all the equipment have been funded by the Deutsche Forschungsgemeinschaft (German Science Foundation).