Thermal Waves

Carsten Lindemann
Institut für Theoretische Meteorologie der Freien Universität Berlin

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Ten cases of thermal waves experienced by glider pilots in Germany were collected in the past three years and among these there are five reliable enough to group them under the category of 'cumulus waves'.

The other cases fall either under 'cloud street waves' according to Jaeckisch [3] or thermals beneath classical lee waves, taking the term 'thermal waves' in a more general way. The thermal waves connected with cloud streets have been much discussed; the most important question to my knowledge is what the whole system is triggered by, even if the wind profile in the convection layer is not as much curved as it should be for cloud streets to exist. The distance between two cloud streets may approximate the natural wavelength of the more stable layers above thus amplifying its oscillation up to heights of several kilometres.

Thermals connected with lee waves occur generally in mountainous terrain during summer. I only have one case of this type, probably because of lack of higher mountains in our area, but in this case there are some indications that lee waves and thermal waves near isolated cumulus clouds may co-exist in the same area.

This happened on 14 August 1971 when I flew a Falke near Oerlinghausen. There were $^1/_8$ cu hum with 1800 m cloud base over ground, the cu having a vertical extent of about 400–500 m, mostly capped by lenticular clouds. The whole system drifted slowly away. Additionally, there was a bigger cu med of about 1200 m vertical extent stationary in the lee of the 200 to 250 m high Teutoburger Wald. The Falke was primitively instrumented for recording temperature and vertical velocity (figure 1).

Below this cloud, in about 2000 m, the updraft was 3 to 4 m/sec (figure 2) while upwind of the cloud 1.5 m/sec were found. However, the whole system seemed to be weakening because of decreasing convective activity in the late afternoon, the cu becoming smaller. It was very interesting that there was no special cloud formation above the hill range itself, whose slopes were situated sunward and windward at that time. No convective circulation with updraft above hill and downdraft above valley was to be seen in this area as could be expected with amplifying cumulus growth above hills.

The distance from the crestline of the hillrange to the 'wave crest' approached $^3/_4$ of the natural wavelength of lee waves. Thus, it seems that lee waves at higher levels only enhance normal convection underneath the wave crest. Lee waves up to 4000 m over ground were flown near Kassel at that day, as Thielemann [2] mentioned.

However, cloud street waves and thermals connected with lee waves are not the theme I want to speak about. We are primarily interested in thermal waves induced by isolated cumulus clouds. Intentionally I do not say isolated thermals, because I think that these waves must be connected with moist convection to create sufficient vertical velocity usable by gliders.

These waves are independent of mountains, as indicated by their non-stationary behaviour. Most of the cases known are only found by chance. There are no measurements of streamlines, temperature, and pressure outside and inside clouds available except those by Malkus [4, 5, 6] and Pastushkov and Shmeter [9], who did not find reliable wavelike pattern outside cloud. Therefore, the first investigation can only look for characteristic synoptic situations giving the larger-scale framework for these mesoscale or convective scale phenomena. Within the limits of representativity of radiosonde and pilot balloon ascents, which are often more than 100 km away from the area of interest and up to two hours earlier or later as the time of event, five cases of thermal waves yield the following conditions:

Positive vertical wind shear with a minimum value of 0.0025 sec^{-1} (2.5 m/sec increase per 1000 m) from the ground to the cumulus tops and a maximum value of 0.020 sec^{-1} within the wave layer itself. Change in wind direction in this layer did not exceed 35°. The thermal stratification was nearly dry adiabatic below the cloud layer and a little more stable than moist adiabatic in the cloud layer. This layer was topped by slightly more stable layers or even inversions, thus limiting the vertical extent of the clouds. Because of these special synoptic situations an error in wind shear of approximately 50 per cent may be possible.

Since there were not thermal waves connected with each cumulus cloud, a temporary acceleration of the horizontal wind field may have happened in the area, but cannot be proven.

In all cases there were normal to excellent thermal conditions, the updraft below cloud exceeding the wavelift on the upwind side of the cloud by more than 100 per cent. The combined systems of thermal updrafts and thermal waves were not stationary – as lee waves ought to be – but were drifting with some velocity in the direction of the synoptic wind; however, with one exception it was not possible to determine this velocity. The maximum wave lift of 2.5 m/sec was found at a distance of about 500 m upwind of the edge of the cloud.

As there were no special measurements, one can try to construct the ability of the atmosphere to form thermal waves from synoptic parameters such as vertical wind shear $\partial\bar{u}/\partial z$, static stability above cloud base $(g/\Theta) \cdot \partial\Theta/\partial z$,
and the averaged thermal vertical velocity $\bar{w}_{Th}$, which can be estimated by

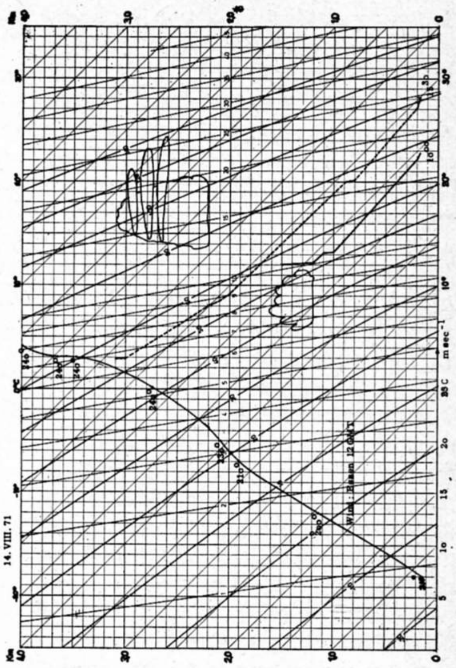

Figure 1
Temperature and vertical velocity measurement of motor glider 'Falke' near Oerlinghausen and wind sounding of Essen on 14 August 1971.

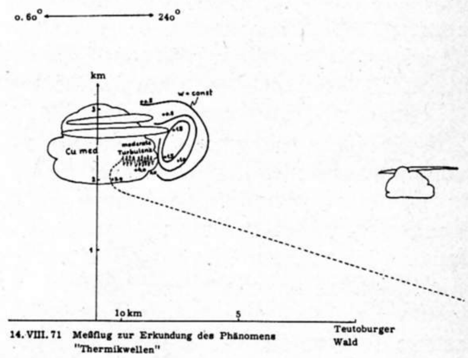

Figure 2
Flight investigation of the 'thermal wave' phenomena.

Lindsay's method [7], involving additional orographic influences. Combining the dimensions of these parameters with the amplitude A of thermal waves in a linear fashion (which may reduce the validity of this concept) and introducing a non-dimensional factor β, one may obtain

$$A = \beta \overline{w}_{Th} \cdot \partial \overline{u}/\partial z \,/\, (g/\Theta) \cdot \partial \Theta/\partial z \qquad 1$$

Unfortunately β varies from three to fourteen, thus making this simple concept doubtful, even if the error of all parameters may be quite large. Along these lines it may be better, according to a conversation with Dr. Kuettner, not to take the amplitude but the vertical velocity w of the streamline pattern and to combine it in a non-linear fashion with the abovementioned parameters. For the amplitude A a wavelength corresponding to the horizontal cloud size in the direction of the wind should be taken into account.

In view of this doubtful test one may instead consider the probable streamline pattern inside and outside the cloud and look for reasons why these special streamline patterns exist. To all pilots the thermal wave resembles slope lift, the cloud being the obstacle to a faster air flow outside.

The exchange of momentum within the vonvective updraft is much larger than in normal shear conditions, where there is mainly non-convective turbulence. For this reason the vertical wind shear of the convective updraft inside the cloud, where the air accelerates due to release of latent heat, is smaller than outside.

Observations by Byres and Battan [1] show that the reduction in shear within the cloud can be up to 50 per cent, depending on the horizontal extent of the updraft area. Newton [8] estimated horizontal velocity differences between air inside and outside of cloud up to 10 m/sec, which is also a realistic value for slope winds.

How the trajectories or streamlines look in reality cannot be said with certainty. I shall try to construct a streamline pattern relative to the cloud from my best case, that of 30 April 1972 near Oerlinghausen (figure 3). Flying a Libelle I reached cloud base in 1800 m above ground in excellent updraft of about 3 to 4 m/sec. In order not to be sucked into the cloud I flew upwind, finding weak lift immediately after leaving the lower edge of the cloud. The cloud had a horizontal extent of about 1 km perpendicular to and 500 m parallel to the wind.

It was possible to climb in a slopelike manner from 1800 to 2300 m up to the top of the cloud. Maximum climb was about 1 m/sec corresponding to more than 1.5 m/sec vertical velocity of the air. The cloud wall had a nearly vertical

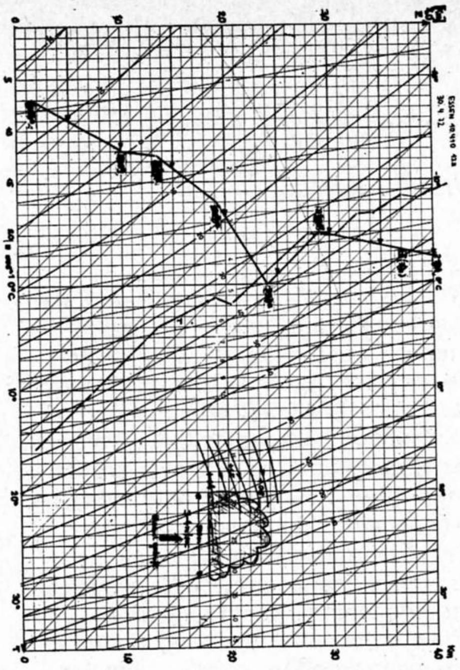

Figure 3
Thermal wave near isolated cumulus on 30 April 1972 at Oerlinghausen and wind and temperature sounding of Essen.

slope so that the streamlines must have entered the cloud itself. During 25 minutes the whole system, convection and wave pattern including the glider itself, drifted 21 km corresponding to an average drift velocity of about 14 m/sec = 28 kts. That is a smaller value than could be found by the Essen 12 z pilot balloon ascent of 16 to 25 m/sec in that layer (figure 3).

How does one get a relative velocity between non-convective free air and convective cloud air?

There are two different 'hydrodynamic' systems, the first being the convective current containing the whole cloud, the second being the surrounding shear flow controlled by the large-scale pressure gradient. Due to large transport and convective mixing of horizontal momentum, there can be differences in horizontal velocity between inside and outside of the convective current of up to 10 m/sec – depending, according to Malkus [5], on the vertical velocity of the thermal updraft. This leads to a zone of horizontal convergence on the upwind part of the cloud. The convergence itself results in a flow going up or down or around the cloud.

We estimate the convergence, negleting the flow around the cloud – that is neglecting $\partial \overline{v}/\partial y$ which may only be done with clouds having a large horizontal extent. Taking for this special case $\Delta \overline{u} = 3$ m/sec over a horizontal distance $\Delta x = 300$ m approximately we obtain a convergence of 0.01 sec^{-1}

Integrating over a vertical extent of 500 m and taking the vertical velocity at cloud base $z_0 = 0$ m/sec, one gets a vertical velocity at cloud top of 5 m/sec. This value is too high, mainly due to the effect of neglecting $\partial \overline{v}/\partial y$ and setting the vertical velocity

$$W = \int_{z_0}^{z_l} \partial w/\partial z \cdot \delta z = - \int \partial \overline{u}/\partial z \cdot \delta z \qquad 2$$

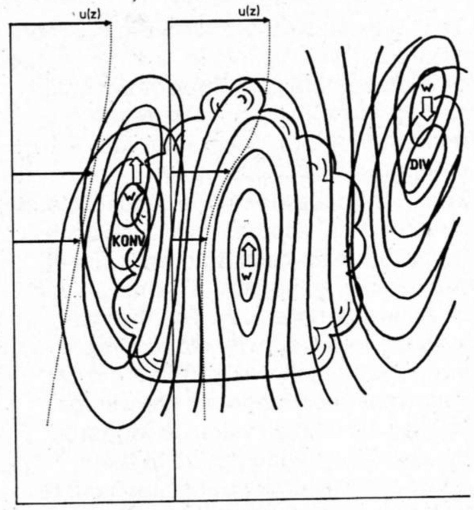

Figure 4
Model of thermal wave surrounding a cumulus cloud. Vertical velocities, w, and convergence and divergence pattern are indicated. The vertical profiles of the horizontal wind inside and outside the cloud are also shown.

To take the vertical velocity at $z_0 = 0$ does not restrict the value of these considerations because even with a negative vertical velocity at this level the lift will become positive some distance higner up. To get large positive vertical velocities in front of the cloud it is necessary that the direction of wind does not change to a great extent (figure 4).

Behind the cloud, on the downwind side, there must be a zone of divergence at a distance from the cloud which may be larger than that of the convergence centre in front of the cloud because of inertia.

Given the zones of convergence and divergence it is possible to construct streamlines, isolines of vertical velocity, and the axis of maximum vertical velocity assuming appropriate boundary conditions. The streamlines inside of clouds may be averaged because of turbulence in cloud, but to be sure one would have to have measurements of the character of turbulence within these areas.

If there is a stable layer above the cloud, which is capable of oscillations, such that the dimensions of the cloud match the natural frequency of the upper flow, the wave flow may reach to greater heights.

This seems to be the normal case in cloud street waves, as Jaeckisch [3] pointed out. Finding a new cumulus cloud with thermal waves in the lee of the first may indicate a larger oscillating pattern.

Regarding the exchange of horizontal momentum inside and outside the cloud – the two 'hydrodynamic' systems are not separated from each other by a solid wall – let me speculate a little:
The horizontal difference in horizontal momentum seems to be larger than the vertical difference of horizontal momentum ($\Delta\bar{u}/\Delta x > \Delta\bar{u}/\Delta z$) even under extreme conditions. It may be possible that the exchange of momentum between the air inside and outside the cloud is small because of a small eddy coefficient of viscosity, if this concept can describe the mechanism in any way.
One could think of a smaller eddy coefficient due to the effect of evaporation of cloud particles at the cloud edges. Considering the cloud wall as something like a semipermeable wall, free air can penetrate it more easily from the outside than cloud droplets do from the inside because heat must be transported to the particles to evaporate them. In this case the eddy coefficient must be inversely proportional to the liquid water content.
But even if there is a strong exchange of momentum, due to a normal or even higher coefficient of eddy viscosity, one can expect a strong gradient of horizontal momentum at the edges of the cloud because there is a very large vertical transport of slower horizontal momentum by the strong updrafts inside the cloud.
It is necessary to construct a model of thermal waves based on the obstacle effect of the cloud. This must include the aerodynamic drag due to a difference in horizontal momentum which in turn depends on the vertical momentum transport of updrafts and the momentum exchange with an unknown coefficient of eddy viscosity.

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Thermische Wellen

Zusammenfassung

Im Verlaufe der drei letzten Jahre haben Segelflieger fünf verschiedene Fälle von Wellen in Deutschland beobachtet, die im Zusammenhang mit dem Vorhandensein von Cumuluswolken standen. Messungen, die mit Hilfe von Radiosonden oder Ballonen durchgeführt wurden, zeigten eine vertikale Windscherung von mindestens 0,0025 sec^{-1} (Zunahme von mindestens 2,5 m/sec pro 1000 m Höhenunterschied) unterhalb der Cumuli, und höchstens 0,020 sec^{-1} in der Schicht, in welcher die Wellen beobachtet wurden; die Richtungsänderung des Windes betrug höchstens 35°. Die Bedingungen für die Entwicklung von thermischen Aufwinden waren ausgezeichnet. Die Wellen waren nicht stationär, aber das ganze System verschob sich in Richtung des synoptischen Windes.
Die Amplitude der Welle kann anhand der Formel Nr. 1 berechnet werden, welche die vertikale Windscherung, die statische Stabilität über der Wolkenbasis und die durchschnittliche Aufwindgeschwindigkeit in der Thermik berücksichtigt. Immerhin ist der Faktor β nicht eine Konstante; er schwankte zwischen 3 und 14, was die Anwendung der Formel für die Vorhersage von thermischen Wellen in Frage stellt.
Man kann aber den Verlauf der Stromlinien in Betracht ziehen. Er gleicht demjenigen, der beim Vorhandensein von Hangaufwind beobachtet werden kann; die Wolke ersetzt hier den Hang. Zwei verschiedene «hydrodynamische» Systeme sind vorhanden: das erste umfasst die Thermikströmung und die Wolke; das zweite die umliegende und umfliessende Strömung, die mit dem Druckgradienten in Zusammenhang steht. Abb. 4 zeigt ein Strömungsmodell, das sowohl den horizontalen Wind wie die Konvergenz- und Divergenzzonen darstellt.
Ein gutes Beispiel eines Fluges in einer Thermikwelle wird in Abb. 3 wiedergegeben. Der Aufwind erreichte 3 bis 4 m/sec unter der Wolke und 1,5 m/sec in der vorgelagerten Welle. Die Verschiebung des Systems betrug 21 km innerhalb 25 Minuten.
Die in Abb. 1 und 2 dargestellten Flüge entsprechen nicht thermischen Wellen, aber eher thermischen Aufwinden unterhalb der klassischen Leewellen.

Ondes thermiques

Résumé

Au cours des trois dernières années, cinq cas d'ondes liées à des cumulus ont été observés en Allemagne par des pilotes de vol à voile. Les mesures faites par radiosondes et ballons indiquaient une variation verticale du vent d'au moins 0.0025 sec^{-1} (augmentation de 2,5 m/sec par 1000 mètres) au-dessous du cumulus et ne dépassant pas 0.020 sec^{-1} dans la couche où se trouvaient les ondes; le changement de direction du vent dans cette couche ne dépassait pas 35°. Les conditions pour vol thermique étaient excellentes. Les ondes n'étaient pas stationnaires, mais tout le système se déplaçait dans la direction du vent synoptique.
L'amplitude de l'onde A peut être déduite théoriquement de l'équation 1, à partir de la variation du vent sur la verticale, de la stabilité statique au-dessus de la base des nuages et de la vitesse moyenne de l'ascendance thermique. Toutefois, le facteur β n'est pas constant, mais varie entre 3 et 14, ce qui rend problématique l'application de la formule lors de la prévision des ondes thermiques.
En lieu et place, on peut prendre en considération les tracés des lignes de flux. Ils ressemblent à ceux qu'on observe lors d'ascendances de pente, le nuage remplaçant ici la pente. Il existe deux systèmes «hydrodynamiques» différents, le premier représenté par le courant de convection et contenant tout le nuage; le second constitué par les variations du flux environnant, correspondant au gradient de pression à grande échelle. La figure 4 représente un modèle d'écoulement, mettant aussi en évidence le vent horizontal et les zones de convergence et de divergence.
Un bon exemple d'un vol dans une onde thermique est représenté par la figure 3. L'ascendance au-dessous du nuage était de 3–4 m/sec et celle due à l'onde précédant le nuage était de 1,5 m/sec. Le système s'est déplacé de 21 km en 25 minutes.
Les vols représentés par les figures 1 et 2 ne correspondent pas à des conditions d'ondes thermiques, mais plutôt à des courants thermiques au-dessous d'ondes de ressaut classiques.