WAVE SOARING OVER FLAT TERRAIN – INVESTIGATIONS ABOUT THE STRUCTURE AND ORIGIN OF THERMAL WAVES

By Joachim Kuettner, NCAR, Boulder, USA
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Many glider pilots have encountered wave-like updrafts upstream of cumulus clouds (or blue thermals) and have been able to climb slowly, but consistently outside the cloud to well above cloud tops (Fig. 1). Such pilot reports are widespread in the aviation literature but, strangely enough, they have not entered the scientific literature. The reason is probably the qualitative or "anecdotic" nature of these reports which, if not documented by precise quantitative measurements, are generally not acceptable as scientific evidence in professional journals.

At our institute, the National Center for Atmospheric Research (NCAR), we have made a serious attempt to change this situation by investigating this phenomenon systematically through aircraft observations and numerical models. These studies were guided by earlier glider observations as described by Jaeckisch (1968, 1972), Rovesti (1970), Kuettner (1970), Lindemann (1972), etc. and summarized in the "Handbook of Meteorological Forecasting for Soaring Flight" (1978). As is well known, this type of lift is usually called "Thermal Wave" (= wave over thermals).

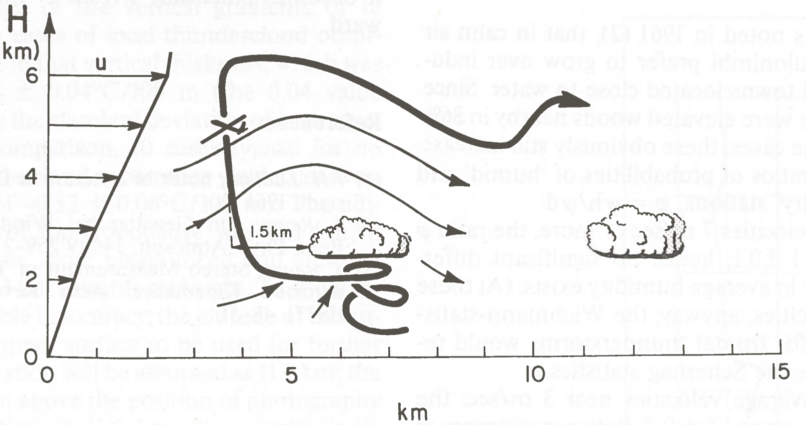
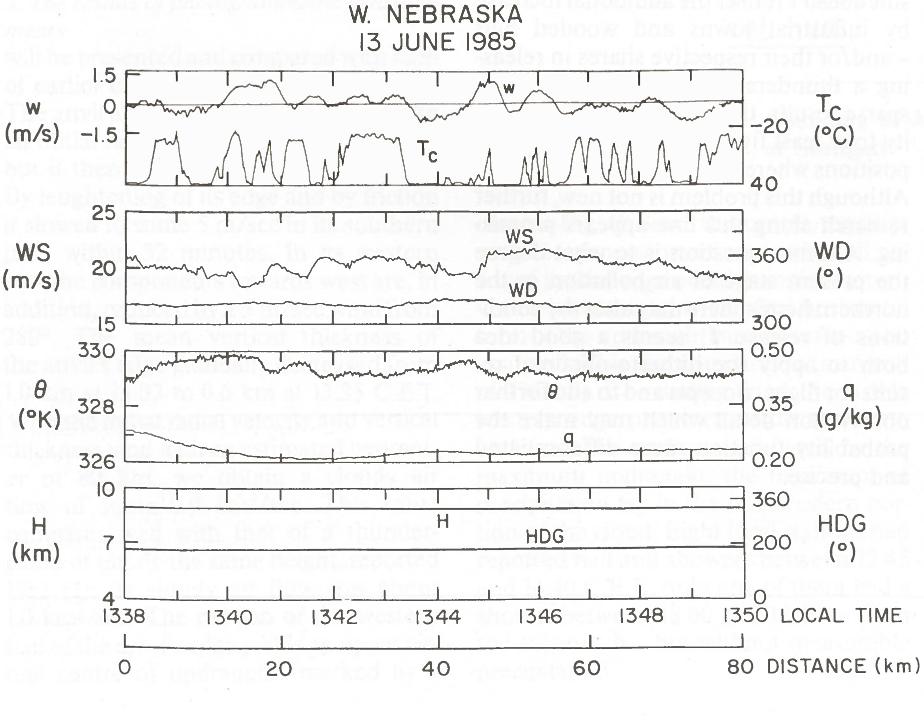


Fig. 1. Flight technique of sailplane pilot penetrating from cloud base into a thermal-wave upshear of cumulus. Note that the vertical increase of wind speed u extends from the ground through the stable layers above the cumulus clouds.



It should be made clear in the beginning that there is a certain similarity between the lift in thermal waves and that in front of rotor clouds connected with lee waves. Therefore, observations in mountainous terrain are always ambiguous. We have avoided this uncertainty by operating our instrumented aircraft, a two engined turbo-prop (King Air) - later to be augmented by jet aircraft - only over flat terrain, 300 to 400 km away from the Rocky Mountains.

The aircraft systems recorded all important atmospheric parameters and displayed them during flight on airborne television screens. The most important parameter is the vertical air motion (w) measured by the "gust probe" system. It clearly shows the wave motion as the aircraft overflies the cumuli while a down-looking infrared radiometer records the clouds underneath (see Fig. 2-4). It does so by measuring the cloud top temperature (T_c) or, in the absence of clouds, the much warmer ground temperature. In this way the clouds are marked and can be correlated with the waves (see also Kuettner et al., 1987).

1. Convection Waves

On an average-looking day with sunshine and fair-weather cumuli drifting in a moderate breeze, we were surprised to find most of the atmosphere on top to be filled with waves. There was little doubt that these were thermal waves, but they were really part of a larger phenomenon which we called "Convection Waves", i.e. waves associated with convection in general. The convective activity is usually limited in height by an inversion, but also deep convection can produce such waves. These waves, like mountain waves and ocean waves, are "gravity waves"; that is, gravity provides the restoring force that

Fig. 2. Thermal waves as measured by the NCAR King Air near 9 km altitude, about 4.5 km above cumulus tops. Wavelengths 10 to 15 km.
w = vertical air motion; T_c = cloud top temperature (cloud marker); WS = wind speed; WD = wind direction; θ = potential temperature; q = specific humidity; H = altitude of aircraft; HDG = heading of aircraft. The peaks in T_c indicate cumulus clouds underneath the aircraft. See also Fig. 8.

allows a stably stratified atmosphere to oscillate like a pendulum, once it has been excited by convective plumes.

As already observed by soaring pilots a necessary ingredient for such waves is the existence of *vertical shear,* i.e. an increase of horizontal wind with height, both in the convective layer and in the stable layer on top. The observed average shear is about 3 to 7 m/sec per km vertical distance (= 2 to 4 knots wind increase per 1,000 ft. altitude difference).

2. Obstacle Effect

Already 30 years ago, Joanne Malkus (1952) had concluded that a thermal rising in a wind shear layer will arrive at the top of the layer with a large differential in horizontal velocity, because it tends to conserve part of its (low) momentum from the surface layer. This also explains the down-wind-sloping of cumulus clouds under such conditions. With today's instrumentation we were able to measure directly this differential velocity and found that the cloud tops penetrated were traveling 6 to 10 m/sec slower than their environment. Thus, they form an obstacle to the environmental flow, just as ships do in a water stream or mountains in an air stream. And just like ships and mountains these convective obstacles are able to produce waves in the surrounding medium.

The process of wave formation however, is more complex because convective clouds or thermals are flexible obstacles, they are "pourous" and have a limited lifetime. It was therefore surprising to us to find thermal waves to exist at over 30,000 ft., the ceiling of our turbo prop aircraft (Fig. 2). Of course, at this altitude the waves are not as strong and regular as they are at lower levels (Fig. 3, 4) and not as well correlated with the clouds underneath, but it still raises the question how the wave motion gets to these levels if the cumulus clouds in the convective layer below live, typically, only 30 to 60 minutes.

One can estimate the vertical propagation speed of gravity waves from the airstream characteristics of the atmosphere and one finds values of 6 to 10 km per hour. Therefore, under favorable circumstances, a cumulus cloud topping at 10,000 ft. may indeed send waves to the 30,000 ft. level or higher during its lifetime.

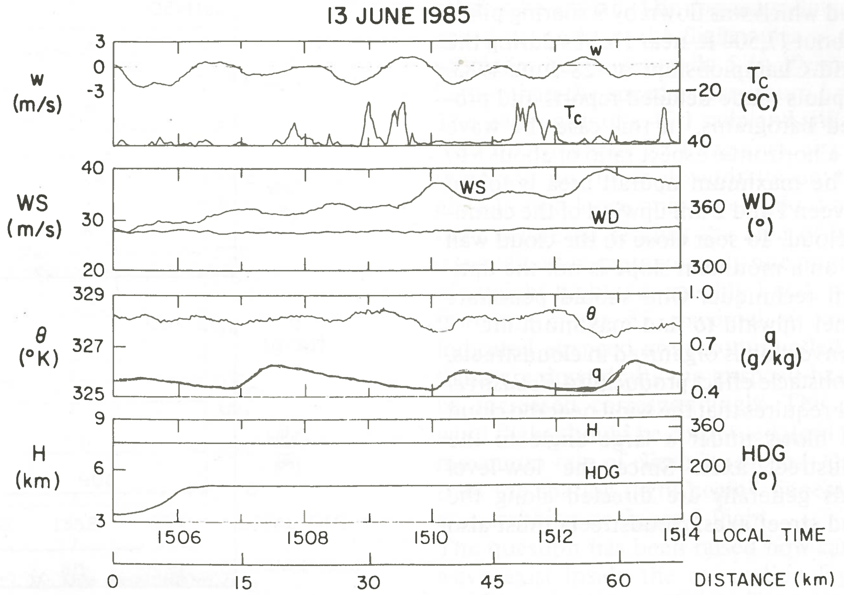


Fig. 3. Thermal waves measured on the same day as in Fig. 2, but 1,200 m lower. See also Fig. 8.

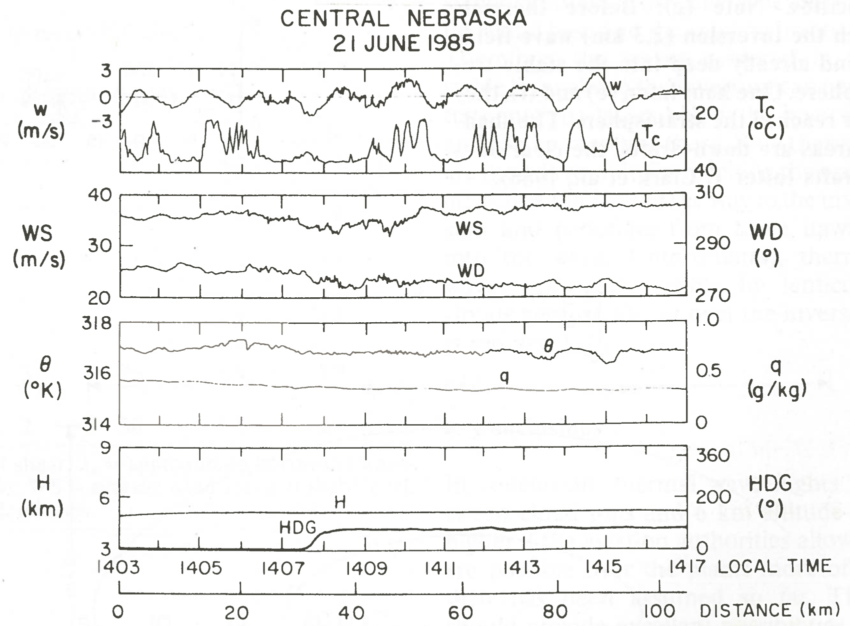


Fig. 4. Thermal waves measured at 2 km above cloud tops. Wavelength about 12 km. See Fig 2. for explanations.

3. Numerical Simulations

There is, however, another possibility. Mathematical models using the temperature and wind profiles measured in our flights indicate that there may be a "feedback" mechanism at work (Clark et al., 1986). Once the gravity waves have been formed in the upper layer they begin to organize the cumulus activity in the lower layer and adjust the spacing of the clouds (or thermals) to their own wavelength. The waves "tune their source", because a stable shear layer has a preferred wavelength. This may lengthen (or shorten) the lifetime of the cumulus clouds and produce a "cooperative" wave/convection system of long duration. The numerical models also indicate that, even before the thermal plumes reach the inversion, they already send "fingers" of wave lift into the troposphere aloft, which later on may penetrate into the stratosphere (Fig. 5). The simulations show that vertical shear in the convection layer is not sufficient; it must extend into the stable layer above in order to produce good waves.

4. Cumulus Waves and Cloudstreet Waves

There are two types of thermal waves, those connected with random (3-dimensional) convection and those over-organized (2-dimensional) convection. One may call them the "cumulus wave" and the "cloudstreet wave" (Kuettner, 1972). Over a field of individual cumulus clouds the *cumulus wave* appears to be 3-dimensional, i.e. its lateral extension is limited. An example is shown in Fig. 6. It depicts a thermal wave upstream of a cumulus cloud which was flown by 9 soaring pilots to about 17,500 ft. near Hobbs during the World Championships on 28 June 1983. All pilots made detailed reports and provided barograms. In this case the wave had a horizontal aspect ratio of about 5 to 2. The maximum updraft area is found between 1 and 2 km upwind of the cumulus cloud. To soar close to the cloud wall like on a mountain slope is not the optimum technique. One should penetrate farther upwind to find maximum lift.

If convection is organized in cloudstreets, the obstacle effect producing a *cloudstreet wave* requires that the wind near the cloud tops blows under a large angle to the cloudstreet axes. Since the low-level winds generally are directed along the cloud street axes, cloudstreets must also have directional shear (change of wind direction with height) to produce wave lift. If that is the case the lift area is like a highway paralleling the clouds, though displaced somewhat upwind of the street. It allows fast cruising along and over the cloudstreets with the possibility to hop from street to street, as is usually done beneath the cloud base. Although the rate of climb in the wave is less than under the cloud, the high altitude effect on true airspeed and the excellent view on the field of cloudstreets below may provide a more efficient way of cross-country soaring. Furthermore, the wave motions over cloudstreets are very regular as our research flights have shown (Fig. 7). Under these circumstances, a modified dolphin technique will allow the pilot not only to soar along the streets but to cross them with excellent glide ratio over ground.

Table 1 gives the results of our flight measurements on various days. Surprisingly, waves were encountered on every flight day. As can be seen, maximum updrafts in waves generally range from 2 to 3 m/s (air motion), wavelengths from 5 to 15 km (averaging 9 km) and vertical wind shears from 3 to 10 m/sec per km height. Note that such wind shear is quite common. The rate of climb of a sailplane in a thermal wave will generally not exceed 2 m/sec. Typical wind and temperature/humidity profiles for days with cumulus and cloudstreet waves are shown in Fig. 8 and 9.

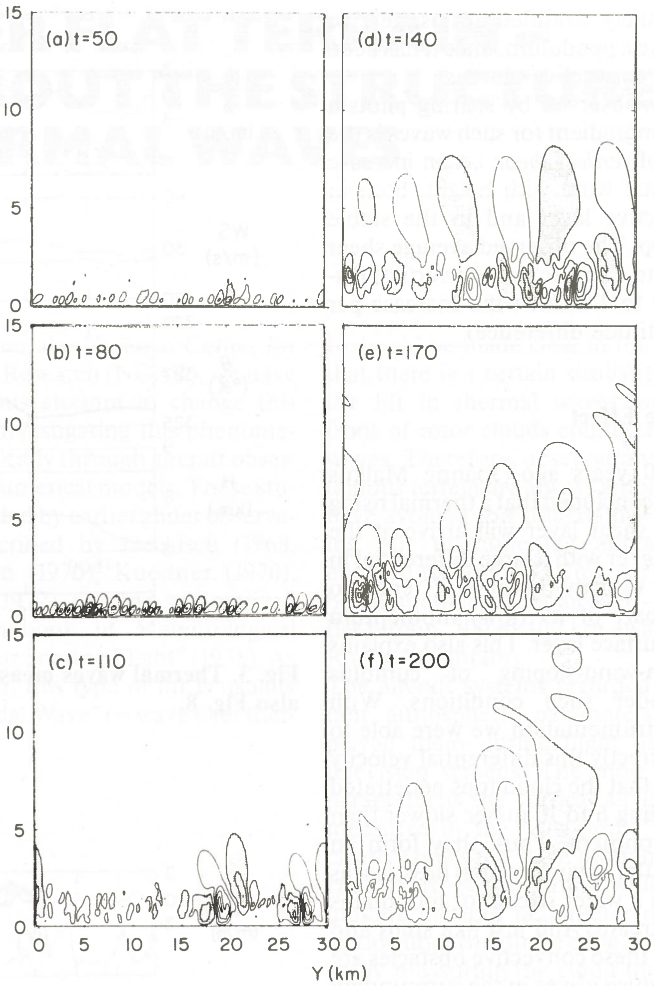


Fig. 5. Numerical simulations of thermal waves over heated ground in steps of 30 minutes, beginning at 50 minutes (a) and ending at 200 minutes (b) after start of heating. The contours show vertical air velocities. Note (c): Before thermals reach the inversion (2.3 km) wave fields extend already deep into the stable troposphere. One hour later, (e) and (f), they have reached the stratosphere. The shaded areas are down-drafts, the clear ones updrafts (after T. Clark et al., 1986).

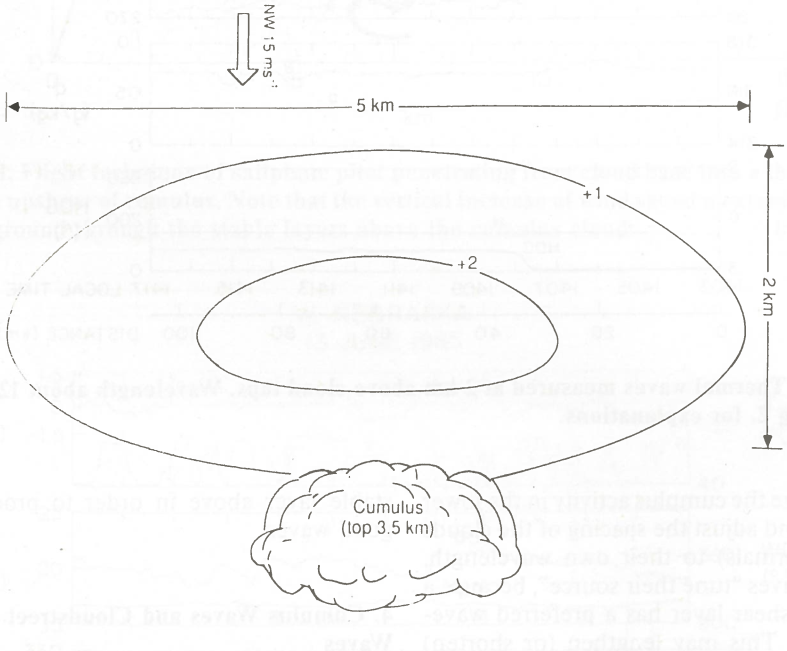


Fig. 6. Plane view of updraft field (m/sec) upwind of cumulus cloud as observed by 9 soaring pilots during World Championship in Hobbs on 28 June 1983.

5. Flight Techniques

The question remains how to catch the wave from underneath the cloud base. It has been done many times, but apparently it is not easy. Since the cloud drifts about 10 to 20 knots slower than the surrounding air, the sailplane has to penetrate against a relative head wind of 10 to 20 knots to reach the updraft area. To do so with minimum loss of altitude he has

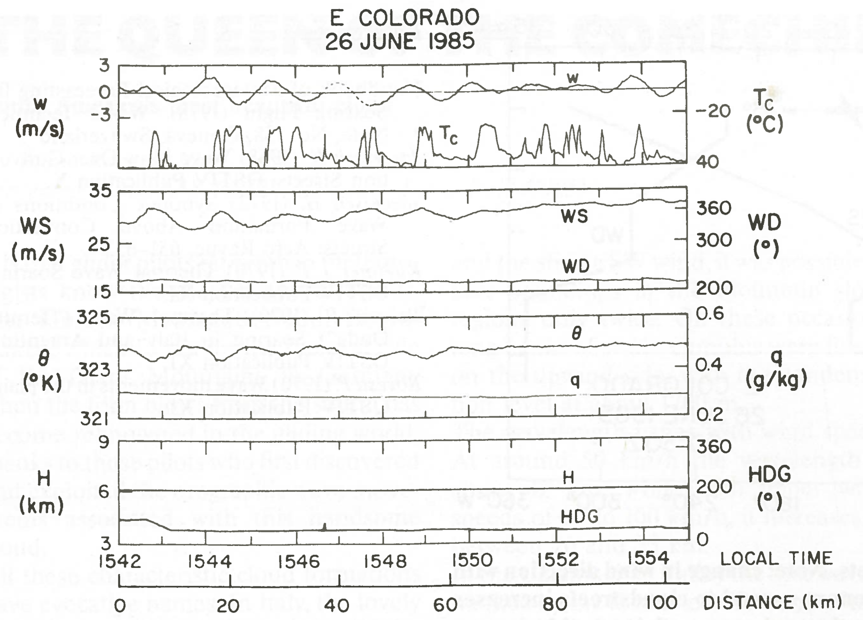


Fig. 7. Aircraft traverse normal to cloud streets at 6 km altitude, about 3 km above cloud tops. Wavelength 11 to 12 km. See Fig. 2 for explanations.

Table 1. Thermal-wave characteristics as derived from research flights.

Date	Location D_m (km)	S_z (m/sec per km)	λ_x (km)	w_{max} (m/sec)	WS (ms^{-1})	H (km)	h (km)
12 June 84	W. Nebraska 320	7	5-6	3	10	4.5	1.5
26 June 84	W. Nebraska 350	4	6	2	12	7.6	3.6
3 July 84	W. Nebraska 350	4	8	2	12	5.3	2.5
13 June 85	W. Nebraska 350	3-5	11	2	20	8.8	4.5
21 June 85	C. Nebraska 450	10	12	3	35	5.9	3.9
26 June 85	E. Colorado	10	11-12	2	30	6.0	2.8

D_m = distance form mountains; S_z = mean vertical shear; λ_x = approximate horizontal wavelength; w_{max} = maximum vertical velocity amplitude; WS = average wind speed at flight level; H = altitude of highest traverse; h = height over cloud tops.

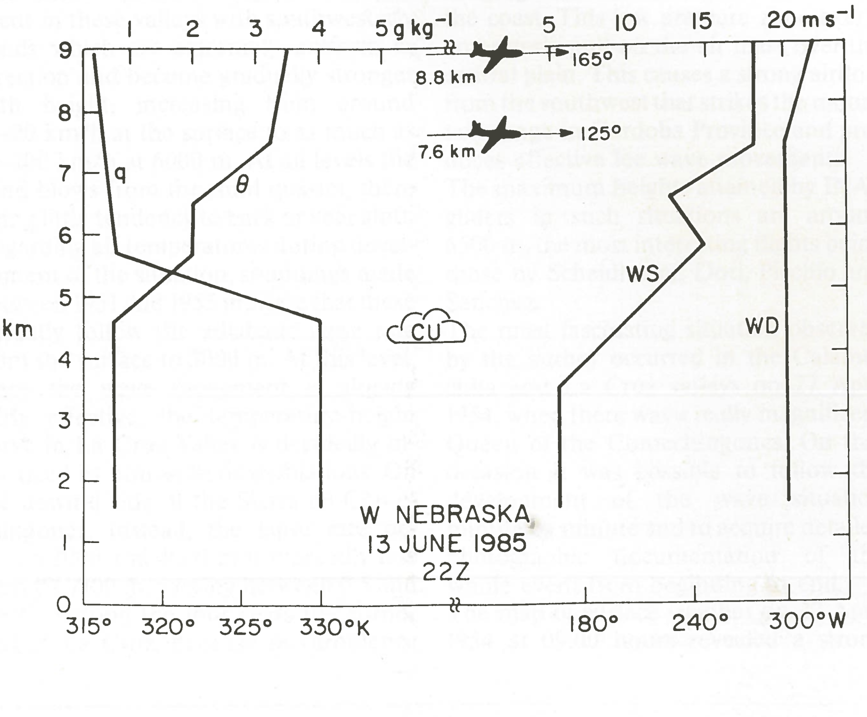


Fig. 8. Aircraft sounding on day with random distribution of cumulus clouds. WS = wind speed; WD = wind direction; q = specific humidity; θ = potential temperature (the potential temperature is constant along the dry adiabates). Note: inversion at 4.6 km; wind direction fairly constant with height; moderate vertical windshear (3.5 m/sec per kilometer). For thermal-wave activity on this day see Fig. 2 and 3.

to fly with best glide ratio for the given relative headwind. The corresponding air speed depends on the flight polar of the sailplane, but is generally 5 to 10 knots higher than the speed at maximum L/D. The glide ratio of a 40:1 sailplane will be reduced to about 25:1 (against air). If there are no up or downdrafts on this glide he will loose only about 200 ft altitude before he reaches the area of best wave lift, after approximately one minute of straight flight, i.e. roughly 1 stat. mile from the cloud. 55, maximal 60 knots indicated airspeed are recommended. If there are downdrafts the airspeed has to be increased correspondingly. The upwind flight should be continued until the maximum rate of climb is reached. Only then the soaring flight begins, generally, as a crabbing or figure-8 flight.

The question has been raised how can a wave exist inside the convection layer, considerably below the capping inversion, if it is known that waves can occur only in a stable atmosphere. Here we have to remember that the air is only unstable inside and under the cloud, but that around the cloud the clear air is usually stably stratified, especially at levels near the cloud base and the capping inversion. Therefore, the waves centered in the stable layer above the inversion can penetrate into the layers below the inversion and can be snatched there. Blue thermals are most favorable for reaching the wave-lift as one can soar all the way to the inversion and penetrate from there upwind into the wave. Unfortunately, thermal waves are rarely visible by lenticular clouds because the air over the inversion is too dry.

6. Conclusions

In conclusion, thermal wave flights between cloud tops and 6 km altitude (or higher if the aviation authorities allow it) are possible over the plains more often than has been assumed so far. They should provide excellent possibilities for cross-country soaring flights using widespread wave lift over flat terrain, provided there is moderate to strong vertical windshear under *and* above the capping inversion.

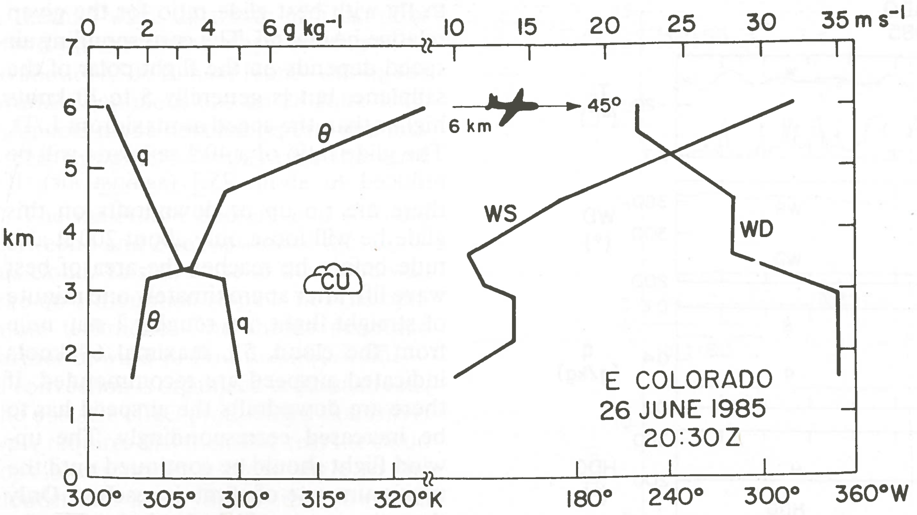


Fig. 9. Same as Fig. 8 but for day with cloudstreets. Note: change in wind direction with height and fairly strong windshear; wind component normal to cloudstreets increases 10 m/sec per kilometer. Inversion at 3.2 km. For thermal-wave activity on this day see Fig. 7.

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