Glider Flight in the Lower Stratosphere above Cumulonimbus Clouds

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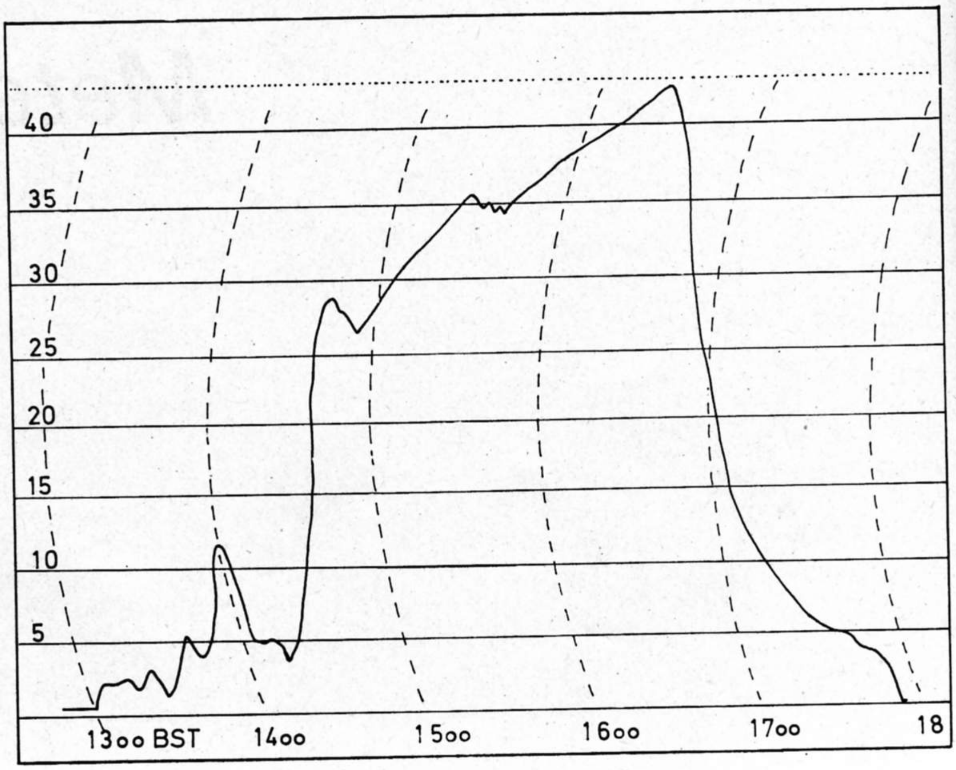
Summary

On 9 May 1972, Mr. Michael Field, flying an 18 m span glider, climbed to nearly 8,700 m in a cumulonimbus cloud between Swinden and Oxford. He then flew upwind out of the cloud and climbed in wave lift to 12,960 m, about 4 km above the tropopause. Radar observations showed no sign of lee waves in the troposphere below 5 km and it appears that the high level waves used by the glider were caused by the convective clouds extending up into a layer of strong winds near the tropopause.

Account of the Flight

Mr. Field, flying a Slingsby Skylark 4 glider, left Booker airfield at 13.00 BST on May 1972 and was aero-towed upwind to an area clear of the airways radiating from London. At about 14.00 BST he reached 11,520 ft (3,510 m) in a large cumulus and was then able to fly further upwind to a large bank of cumulonimbus cloud. He reached this cloud at Cricklade (about 5 miles NNW of Swinden) and, after penetrating some distance into cloud, located the region of upcurrents. This part of the climb began at about 3,100 ft (945 m) and continued up to 28,520 ft (8,690 m).
When the rate of climb decreased to zero and the cloud became lighter Mr. Field steered WSW to reach clear air. The outside of the glider was by then covered with ice. Inside the cockpit the condensation had frozen covering canopy and instruments with hoar frost. The artificial horizon had been kept clear by constant scraping of the glass but other instruments were obscured at this time and as a result the pilot at first misread his height as about 18,000 ft when in fact it was 28,000 ft.
The canopy ice prevented the pilot from observing just when clear air had been reached. The glider has clear vision panels but the ice was too thick for these to be opened. As a result the pilot could not give any description of the appearance of the clouds, nor could he note his position in relation to them. This lack of visual observation is a severe handicap in analysing the remainder of the flight.
When the glider had descended to 26,000 ft (8,000 m) it reached an area of smoothly rising air which the pilot recognised as wave lift. He then began a series of wide «S» turns keeping to an average heading of WSW. This is a pattern of flight commonly used in wave soaring when the forward speed of the glider is greater than the horizontal wind speed. Since the air speed indicator was not functioning then the pilot trimmed the glider to a speed which seemed comfortably above the stall.
At 30,000 ft the true airspeed is estimated to have been between 80 and 90 knots (40 to 45 m/sec), which was much more than the environmental wind at that level.
At 36,000 ft (nearly 11,000 m) the pilot lost the area of lift and began a search to regain it. During this search he descended to 34,000 ft (about 10,500 m). At this level he experienced about a minute of severe cobblestone turbulence. The true airspeed at this level was probably between 90 and 100 knots (45 to 50 m/sec). When the turbulence ceased the glider entered strong lift. The rate of climb seemed rapid at first, but soon decreased to a slower rate than before. When the rate of climb became negligable the pilot abandoned the ascent at a height which was later confirmed as 42,520 ft (12,960 m) above sea level.

Fig. 1 Copy of barograph trace supplied by Mr. Field. Calibration lines for time and height have been added.



During the descent, but while still above the freezing level, the tailplane was twice struck by pieces of ice which, it is assumed, had broken off the wings. The airbrakes were in use to increase the rate of descent and it may be that the buffeting and vibration they caused shook off some of the ice. The freeing level was about 4,000 ft (1,220 m) and consequently the ice did not clear completely before landing. Since the forward view was still too poor for a return to the airfield the pilot made a landing, in a field at the foot of the Chilterns several miles north west of Booker.

Vertical Currents Encountered during the Climb

The rates of climb achieved by the glider have been calculated from a copy of the barograph trace provided by Mr. Field (figure 1). The original trace shows only the pressure curve; heights and times have been superimposed after calibration.
The vertical velocity of the air currents has been derived by adding the calculated sinking speed of the glider to the mean rate of climb. The sinking speed of a Skylark 4 at various airspeeds has been measured by several independant test groups in recent years and the curves show a satisfactory measure of agreement. Figure 2 shows the calculated sinking speed of a Skylark 4 flying straight at an indicated airspeed of 55 knots at altitudes from sea level up to about 55,000 ft. The full curve is for a glider in clean condition, the pecked curve is the result of adding

50% to the sinking speed to allow for the effect of ice. No figures being available for gliders in this condition. Various glider pilots were consulted and this estimate was thought reasonable. In view of the uncertainty of the ice correction no additional correction was made for the change of Reynolds number; it has been estimated that this would only amount to about 5% decrease in glider performance at levels near the tropopause.

The average rate of climb for the ascent inside the cumulonimbus works out at about 9.5 knots, indicating vertical currents of at least 13 knots (6.5 m/sec). However the rate of climb was less than this at the beginning and end of the cloud climb. Between the heights of 10,000 and 25,000 ft (3,000 to 7,600 m) the rate of climb was about 15 knots (7.5 m/sec) suggesting up currents of at least 19 knots (9.5 m/sec). These rates of climb are not remarkable for the size of cloud and suggest that the glider was not in the strongest lift.

In clear air the vertical currents were much less. From 26,000 to 36,000 ft (8,000 to 11,000 m) the rate of climb averaged 3 knots (1.5 m/sec). This probably represents a vertical current of about 8 knots (4 m/sec).

The final part of the climb from 34,000 ft (10,360 m) to the top showed an average rate of ascent of 1.8 knots (0.9 m/sec) but allowing for the greater rate of sink the vertical velocity of the air was probably again about 8 knots (4 m/sec).

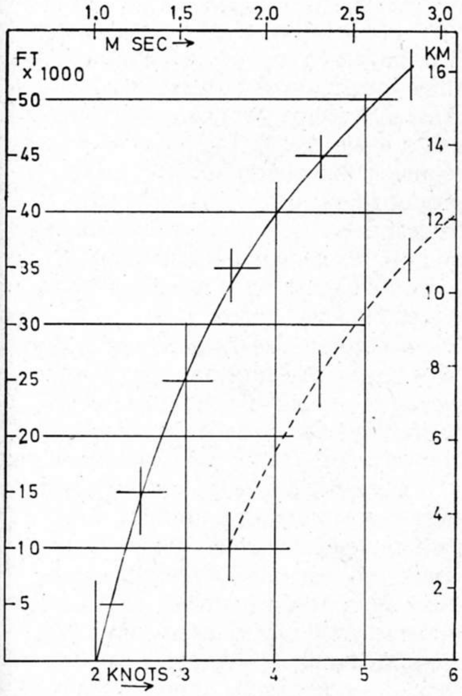


Fig. 2 Calculated sinking speed of Skylark 4 Glider at various altitudes. Full curve for glider in clean condition, pecked line shows estimated performance when ice had formed.

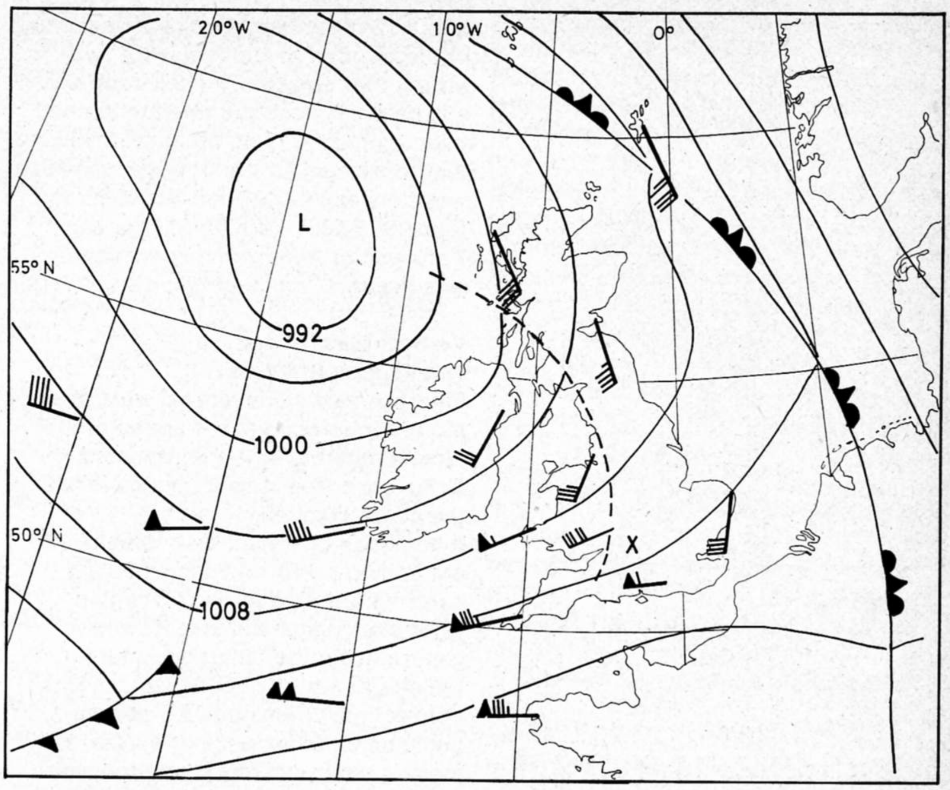


Fig. 3 Midday chart for 9 May 1972 with 300 MB winds added.

Meteorological Conditions in the Area of the Flight

The midday chart (fig. 3) shows a depression west of the Hebrides with an unstable southwesterly airflow over England. Minor troughs were moving north east across the country and one of these troughs produced a continuous line of shower cloud which may be seen in the satellite photo (fig. 4). Arrows showing the winds reported at 300 mb have been added to the surface chart to indicate the presence of a jet stream which was extending toward Brittany. Figure 5 shows cross sections of the upper winds along a line from Long Kesh in Northern Ireland to

Fig. 4 Satellite photo of cloud pattern over British Isles at midday 9 May 1972.

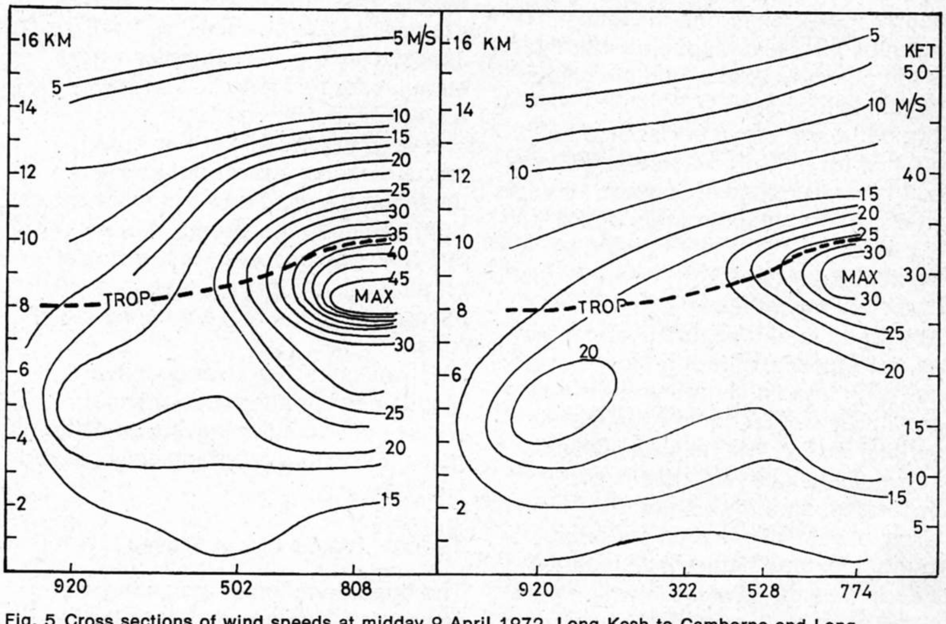


Fig. 5 Cross sections of wind speeds at midday 9 April 1972. Long Kesh to Camborne and Long Kesh to Crawley.

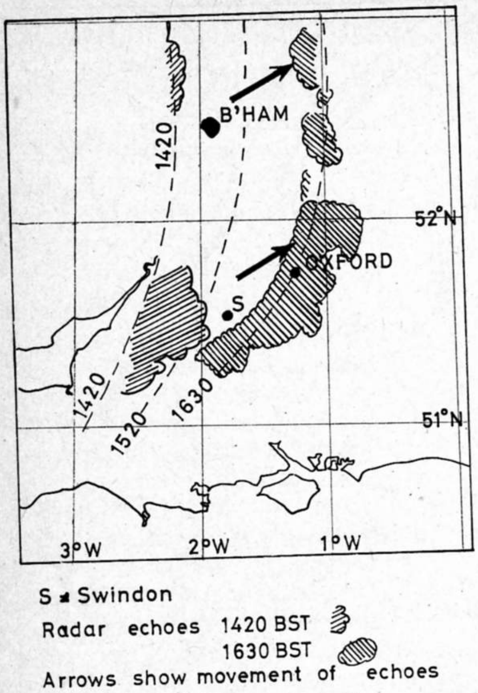


Fig. 6 Movement of Cumulonimbus belt during the period of the glider's climb, as shown by Malvern radar. Hatching shows the eastern edge of the cloud echo at 1420 and the entire area at 1630 BST. Letter S denotes Swindon.

Camborne in Cornwall, and also from Long Kesh to Crawley in Sussex. These cross sections are approximately at right angles to the wind, and show the edge of the jet stream. The mean winds for the climb were estimated from these cross sections.

Movement of Shower Clouds

Malvern radar recorded the pattern and movement of numerous showers which occurred over the Midlands and southern England that afternoon. The long band of cloud shown on the satellite photo appeared on the radar as a number of separate showers. The cloud mass visible over Devon and the Bristol Channel on the photo was later tracked by radar. Its movement is shown in figure 6. From the times given by Mr. Field it appears that this is the cloud mass in which the glider began its big climb.
The pattern of cloud cells could be tracked for up to two hours and showed that the average speed was 24 knots (±2 knots) from a direction of 240°.

Vertical Extent of Cumulonimbus Clouds

Although cloud tops had been measured by radar that morning there were no height readings for the afternoon and it was necessary to estimate the vertical extent. The height to which convective clouds can rise is partly dependant on their distribution [1]; large masses of cumulus are often found to extend higher than isolated clouds. The cloud mass in which the glider climbed formed part of a very active system several miles wide and about 70 miles long. The radar echoes photographed at Malvern were so strong that a number of cells could still be seen when the attenuation had been increased to 40 db. It seems likely that tops reached the tropopause which was between 28,000 and 30,000 ft (approx. 8,500 to 9,100 m). Figure 7 shows the Aberporth ascent which was the most representative sounding.

Vertical Wind Shear and «Thermal Waves»

Figure 8 shows the vertical wind shear plotted in relation to the speed of the clouds together with the assumed airflow over the cumulonimbus in which the glider climbed.
It has been observed that cumulus containing powerful convective up currents are able to rise through a layer of stronger winds aloft without experiencing the tilting or distortion of the clouds which occurs with weaker convection. When such a vigorous cumulus cloud extends into a faster moving airstream aloft the upcurrents act as an obstruction to the horizontal flow aloft. Some of the surrounding air is probably entrained into the expanding cloud but the rest of the flow is deflected round or over the cloud. Kuettner [2] suggests that for a vertical wind shear of 3 knots per 1,000 ft (5 m/sec per km) a glider may be able to ascend in clear air close to the upwind side of a cumulus at about 2 knots (1 m/sec). The technique used is very similar to hill soaring.
When the air between and over the cumulus clouds is relatively stable one would expect most of the flow to be deflected round rather than over the clouds. This seems to be confirmed by glider pilots observations that it is rarely possible to climb much above the top of scattered cumulus. Long lines or «streets» of cumulus clouds appear to influence the air flow to greater heights however.
Jaeckisch [3] gives examples where cumulus formed long streets beneath an inversion with stable air above. The wind at cloud level was parallel to the cumulus streets but above the inversion the wind had a component at right angles to the streets. A wave like flow was observed in the stable air aloft and gliders were able to climb several thousand feet above the cloud tops.
This wave like flow over cumulus clouds has been termed «thermal waves» or «cumulus waves» to distinguish it from the orographically caused lee waves.

Thermal Waves or Lee Waves?

The conditions under which thermal waves can form are similar to those for the development of lee waves and it may be difficult to separate the two processes. There are many observations of the effect of lee waves on the distribution of convective clouds. These show that cumulus clouds are suppressed in wave troughs and enhanced under wave crests. There are at present relatively few observations of waves produced exclusively by the underlying thermal activity. However Townsend [4] has shown that convective currents can produce wave motion in the stable layer above.
The great depth of instability on 9 May 1972 makes the development of lee waves seem unlikely. The possibility cannot be excluded for that reason alone because there are now a number of observations of large cumulus and even cumulonimbus extending up through levels at which gliders were soaring in lee waves. These observations show that lee waves can occur in close proximity to large convective clouds. The likelihood of lee waves on this occasion can be ruled out from the report by Malvern.
The high powered radar at Malvern is able to detect waves in the troposphere

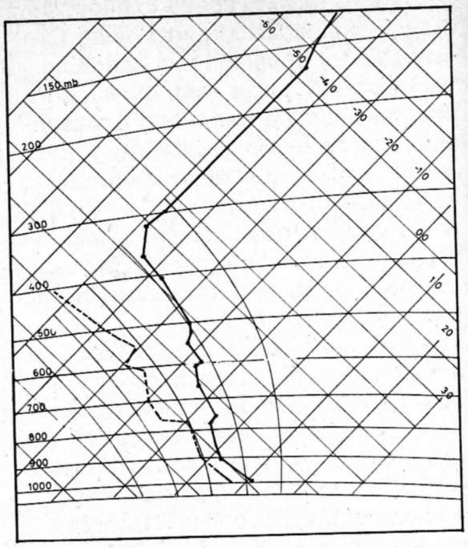


Fig. 7 Tephigram of the Aberporth sounding at 1200 BST on 9 May 1972.

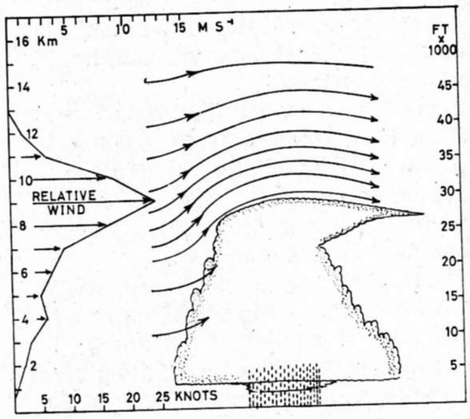


Fig. 8 Vertical wind shear in relation to the cumulonimbus with assumed pattern of airflow over it.

[5]. A few hours before the glider began its climb the Malvern radar had been scanning the sector upwind towards Wales. The range/height pictures showed more than one quasi-horizontal layer in the mid troposphere and if wave flow had occurred it should have been visible as an undulation in one of these layers. The radar records show the development of convective clouds, with one top reaching the 5-km level, but no sign of wave flow.

Other Gravity Waves

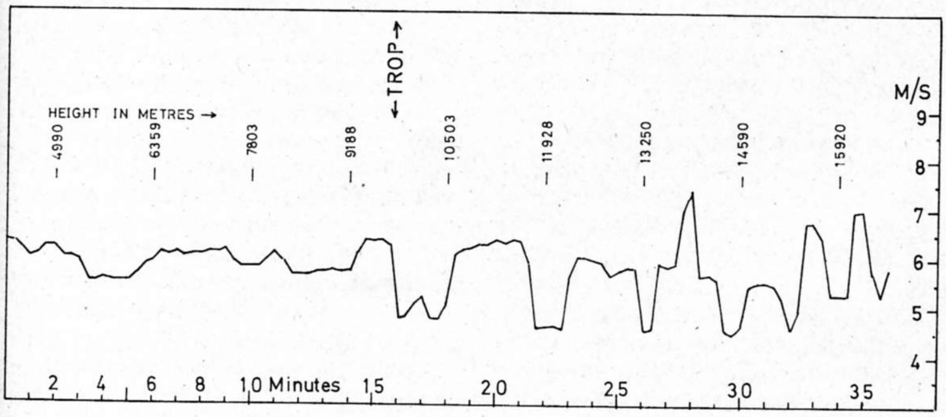
Where jet streams exist the conditions of stability and vertical wind shear often favour the development of gravity waves. Kuettner [6] considered the possibility of such waves being used by a glider. Satellite photographs have revealed a number of examples of transverse waves on the long bands of jet stream cirrus. Roach [7] has given examples of waves at high level far out over the Atlantic in regions where there was a strong upper flow ahead of a developing depression.
The situation on 9 May 1972 showed some similarity to the examples quoted by Roach. The Pershore sounding was therefore examined to see if the balloon showed any periodic variations in the rate of ascent which might indicate wave motion.

Indications of High Level Waves from the Balloon Sounding

A radiosonde was launched from Pershore about two hours before the glider took off. The height of the balloon was measured at 20-second intervals and from these values the rate of ascent was plotted. Figure 9 shows the variations observed from about 5 km upward. Values below 5 km are not included here because it was considered that convective currents influenced the upward velocity.
In the diagram time is plotted on the x axis and the rate of ascent on the y axis. The actual height at four minute intervals is written above the curve. The results are summarised below.
Mean rate of ascent from 5 to 9 km = 5.93 m/sec (below the tropopause), variation ±0.4 m/sec.
Mean rate of ascent from 9 to 13 km = 5.69 m/sec, variation ± 1.0 m/sec.
According to Scrase [8] the decrease in the rate of ascent above the tropopause is not uncommon. The increased range of oscillations and their period may however be significant. The period of the first oscillation is about 320 seconds; subsequent periods grow shorter with increasing altitude. These oscillations may represent weak waves in the lower stratosphere, but if so the associated vertical currents are very much less than those found by the glider a few hours later.

Fig. 9 Variations in the rate of ascent of the Pershore radiosonde from 1100 to 1135 BST on 9 May 1972. Actual height at four minute intervals written above the trace.

Rate of ascent of balloon (averaged over 20 sec intervals)



Stratospheric Wave and the Underlying Cumulonimbus

While the glider was ascending in the lower stratosphere its average cross country speed was not much less than the speed of the cumulonimbus beneath. It is probable that the two stages of the ascent above the tropopause used two different waves which moved in phase with the clouds beneath.
If one may assume that the period of 320 seconds was close to the natural period of oscillation of the air just above the tropopause and the wave kept in phase with the cloud below moving at 24 knots (12 m/sec) then the wave length would be nearly 4 km.

Clear Air Turbulence

It is not unusual to experience clear air turbulence (CAT) close to areas of wave flow particularly if there is strong wind shear in the vertical. Radar studies [9] revealed that clear air turbulence developed when large amplitude Kelvin-Helmholtz billows with wavelengths up to 4 km broke down.
The glider experienced about one minute of severe «cobblestone» turbulence at about 34,500 ft (about 10,500 m) after which the air was found to be rising rapidly. It seems possible that the glider flew through a breaking wave at this stage. The Richardson Numbers, calculated for layers of 200 and 400 m depth from the Pershore sounding a few hours earlier, showed no sign of the very low values of R_i normally associated with this class of turbulence. There were however no strong vertical currents when the balloon ascended into the lower stratosphere. The development of these strong upcurrents may have produced local concentrations of wind shear which did not exist at the time of the sounding.
A special investigation into clear air turbulence was being undertaken this day and a large number of aircraft reports were available. There was only one report, from a large military jet, which coincided fairly closely in time and height with the glider observation. The jet flew from west to east at 35,000 ft just north of the area of the climb. No turbulence was observed there although light turbulence had been encountered when climbing through the tropopause further west. This negative report, together with the fact that the glider only once encountered turbulence, suggests that the CAT was a very local phenomenon, probably associated with the altered airflow above the cumulonimbus.

Conclusions

A jet stream was extending eastwards over Brittany and the strengthening upper winds on the northern side of this jet passed over an irregular line of cumulonimbus clouds. The tops of these clouds extended up to the base of the stratosphere and acted as a partial barrier to the strong upper winds. As a result the air on the upwind side of the clouds was forced to rise over the cloud tops producing a vertical component of air of at least 8 knots (4 m/sec). The disturbance to the flow in the upper troposphere also extended into the lower stratosphere producing a wave like motion at least 4 km above the tropopause.
By flying out of the cumulonimbus cloud at high level and on the upwind side the glider entered a region of ascending air and was able to climb through the tropopause and well into the lower stratosphere.
This is the first report of such a phenomenon at high level but there have been a number of observations of a similar phenomenon on a smaller scale when cumulus develop in a vertical wind shear.
The turbulence encountered in clear air above the cumulonimbus cloud suggests a localised breakdown of the wave flow. This type of CAT may be a regular occurrence when wave flow

develops over cumulonimbus clouds but if so it probably only affects small areas.

Acknowledgements
I should like to express my gratitude to the staff of the Meteorological Research Unit at Malvern who provided a very large number of tracings from radar PPI photographs, worked up a radiosonde of exceptional detail, and supplied a series of range/height photographs showing airflow over and to lee of the Welsh mountains.

I am also grateful to Mr. S. G. Cornford, Meteorological Office Bracknell, who provided data from reports of clear air turbulence, and to Dr. J. P. Kuettner, WMO, for information on «Thermal Waves».

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