Observations of lee waves by high-power radar

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SUMMARY

A very high-sensitivity 107 mm radar has been brought into operation for meteorological studies of airflow within the optically clear (or cloudy) atmosphere. One application of this radar has been to observe the detailed three-dimensional structure of lee waves, using backscatter from both refractive index inhomogeneities and cirrus ‘clouds’ as means of tracing the pattern of airflow. This paper presents case studies showing how the radar has revealed the structure of lee waves downwind from the Welsh mountains. One of the case studies illustrates a steady-state wave pattern, another illustrates an unsteady pattern with waves varying in orientation and wavelength, another illustrates a strongly damped wave pattern, and a final one illustrates two families of waves co-existing at different altitudes. The radar method is shown to provide a direct and elegant technique for measuring lee wave properties. Although it depends on the presence of naturally occurring targets to trace the airflow pattern, such targets are found to be abundant in situations of strong lee wave activity.

1. Introduction

Naturally occurring targets such as precipitation particles are often distributed sufficiently widely to serve as tracers of whole fields of motion and by this means radar has been able to contribute significantly to our understanding of the detailed fields of air motion within a variety of frontal and convective cloud systems. Progress has been achieved both through incoherent (non-Doppler) and Doppler radar techniques, i.e. by inferring fields of motion either from the evolution of three-dimensional precipitation patterns or directly from the Doppler shift of the back-scattered energy. A major limitation in the use of these techniques is their restriction to situations in which detectable particles are present. However, the work of Hardy, Atlas and Glover (1966), and others, has shown that a radar operating at a suitable wavelength with a high transmitted power and a sensitive receiver can also detect echoes from naturally occurring inhomogeneities of refractive index in the optically clear (or cloudy) atmosphere. With the development of a high-power 107 mm wavelength Doppler radar, capable of detecting such clear-air echoes, we have been able to investigate, amongst other things, the structure of lee waves occurring in precipitation-free situations. Four case studies are presented in this paper. Previous quantitative studies of air motion within mountain lee waves, as reported, for example, by W.M.O. (1960) and Wooldridge and Lester (1969), have relied upon aircraft and/or balloon-borne measurements, with the inherent difficulty of reconstructing the three-dimensional field of motion from such data. In contrast, however, although the full Doppler capability of the high-power radar was not available at the time of the present studies (November 1969 – April 1970), the radar technique discussed in this paper is shown to provide a direct and elegant method of observing the three-dimensional lee wave pattern.

2. Nature of the data

The radar is located at the Royal Radar Establishment site at Defford, Worcestershire (02°09′W, 52°06′N), about 70 km east of the lee slope of the Black Mountains and neighbouring mountains, which will be referred to collectively as the south Wales mountains. The radar, which has been described in detail by Watkins (1971), is sufficiently sensitive to permit lee waves to be observed out to a range of 50–80 km under favourable circumstances. Two types of meteorological target were responsible for most of the echoes detected in the case studies reported here:

(i) clear air targets
(ii) cirrus ice crystals.
The clear air targets are due to refractive index inhomogeneities associated with shallow sheets within which there is a large mean vertical gradient of potential refractive index. Small-scale turbulence distributes the gradients over a range of scales and the radar detects inhomogeneities on a scale of half the radar wavelength. Humidity gradients have a dominating influence on refractive index in the lower troposphere; temperature gradients dominate in the upper troposphere.

In this paper stratified echoes are used simply as indicators of the pattern of airflow, especially where they are perturbed by lee waves. Whereas it is easy to justify this kind of treatment in the case of the generally rather shallow clear-air layer echoes associated with refractive index inhomogeneities this is more difficult in the case of echoes from cirrus. However, the cirrus often had a clear-cut base due to total evaporation in a dry layer, in which case the variations in the level of the cirrus base can be regarded as an indicator of the airflow there. This is confirmed by time-lapse movie films of radar data which show the height of the base of identifiable cirrus wisps rising and falling as they travelled through systems of lee waves. Layer echoes of one kind or another were often found to occur simultaneously at several altitudes. Thus the radar provided data on the lee waves simultaneously at several heights, sometimes to above 10 km. Knowledge of the horizontal winds permitted updraughts to be inferred from measurements of the slope of echo layers where these were perturbed by steady state lee waves. In the present studies horizontal winds were derived from radiosondes; in future studies the winds can be derived from Doppler measurements obtained with the same radar.

Two operational modes were employed in the case studies, the radar echoes being photographed for each scan on an R.H.I. (Range-Height Indicator) display.

*Mode 1*: Elevation scans (typically from 0° to 30°) in the upwind and/or downwind directions (i.e. in the mean direction of the wind above the planetary boundary layer), generally for a period of at least half-an-hour.

*Mode 2*: Elevation scans from 0° to approximately 30° elevation at 10° azimuth intervals, the time taken for 360° azimuth coverage being about three-quarters of an hour. The Mode 1 data were used to study the variation of lee wave amplitude as a function of height and time, and to establish whether the broad wave pattern tended to be in a steady state. Mode 2 data enabled the three-dimensional steady-state structure to be synthesized.

The interpretation of the lee wave pattern observed with the Defford radar was aided by data from radiosondes released sequentially from the Royal Radar Establishment site at Pershore, 8 km north-east of the radar site, and also by data from the noon soundings at Aberporth, 170 km towards 273° from the radar site and upwind of the Welsh mountains. These soundings permitted profiles of Scorer’s $l^2$ parameter to be derived, where $l^2 = s/u^2 - 1/u \beta u \delta s^2$ (Scorer 1949). Here $s$ is the static stability, defined as $(g/\theta) (\delta \theta / \delta z)$, where $\theta$ is the potential temperature and $u$ is the horizontal wind component resolved perpendicular to the (infinitely long) mountain ridge originating the lee wave train. In situations when the ridge orientation is not well defined, and particularly if the variation of wind direction with height exceeds 30° (excluding the surface wind), Corby (1957a) considers it necessary to use components of the wind resolved in the direction of the low-level winds, say at 300 m. However, in the case of the Welsh mountains there is a tendency for ridges to be oriented in a direction 190°–10°. Satellite photographs on the occasions studied showed that the lee waves were similarly oriented. Therefore, following Scorer, wind components, $u$, have been taken along 280°–100° for all of the case studies (for which the winds above the planetary boundary layer were between 250° and 300°).

3. Case studies

(a) 3 November 1969: steady-state lee waves

A satellite photograph taken at 1000 GMT on 3 November 1969 revealed two clearly defined trains of lee waves in a strong westerly airstream 180 km south of a quasi-stationary cold front. The wave trains extended 110 km downwind from the mountains of south and
central Wales, being detected by the satellite as a result of the thinning of the stratocumulus cover in the wave troughs. The Defford radar obtained information on the southern-most wave train from 1000 to 1534 GMT. Radiosondes were launched at 0958, 1428 and 1510 GMT from Pershore and at 1100 GMT from Abergavenny. At 1510 GMT the wind increased steadily from 245°/24 m s⁻¹ at 1 km to 275°/48 m s⁻¹ at 12 km. There were two marked temperature inversions, one between 1.5 and 1.7 km and the other between 2.6 and 2.9 km, with an approximately saturated adiabatic lapse rate above and below.

An example of the kind of R.H.I. data obtained is illustrated in Fig. 1. Three distinct clear air layer echoes occurred (at about 1-6, 2-2 and 2-8 km) and their relationship to sharp humidity gradients can be clearly seen from the accompanying profile. The intensity of the echo from cloud droplets in the low-level stratocumulus was probably weak compared with that from the clear air. Side-lobe echoes from the Malvern Hills gave rise to the pillar echo between 12 and 16 km range. The three clear air layers were perturbed by lee waves of wavelength 25 km (23-5 km when resolved along 280°) and (crest-trough) amplitude 300 m. Nearly vertical alignment of crests and troughs is evident from Fig. 1 and this proved to be a feature of all the case studies. Convective circulations in the planetary boundary layer are thought to have been responsible for the 2 km perturbations in the lowest echo layer (‘A’ in Fig. 1). The behaviour of these perturbations is clarified in Fig. 2(a) which is an x - t plot of the height of layer A, where x is distance upwind (towards 260°) from the radar and t is time. The fixed lee wave pattern can be seen in Fig. 2(a) with a distinct crest at range 25 to 30 km and an amplitude of up to 400 m. The smaller scale perturbations can be seen modulating the fixed pattern. From the slope of the isopleths in Fig. 2(a) it appears that the component of travel along 260° of the perturbations was 18 ± 2 m s⁻¹, corresponding to the component of the wind at 1 km as measured by the radiosondes. Individual perturbations were resolvable for up to 10 minutes. The small-scale perturbations extended with diminished amplitude vertically through the stable layer up to 3 km. Fig. 2(b) shows that, on a longer time scale, neglecting the short term modulation due to the 2 km perturbations, the lee wave pattern retained a remarkably steady state, with crests and troughs remaining geographically fixed over the entire five hour observational period.

Fig. 3, synthesized from Mode 2 data between 1252 and 1320 GMT, shows the overall lee wave pattern at the top of the low-level convective layer. Two major areas of high ground are also illustrated; namely the mountains of south Wales at the western edge of the figure and the Cotswolds, south-east of the radar. A single, well-defined wave-train with wavelength 20 km and amplitude 400 m dominates the pattern in Fig. 3. The orientation of the waves (190° - 010°) is parallel to the lee-slope of the south Wales mountains. The waves extend from these mountains from approximately 250° (corresponding to the wind direction above the planetary boundary layer) and they persist with virtually undiminished amplitude for at least 110 km downwind.

Crest-trough wave amplitude $A_m$ is plotted as a function of height in Fig. 4. Apparently $A_m$ decreased with height from a maximum of about 500 m within the low-level inversion below 3 km to 200 m at 7 km where a sharply-defined cirrus base served as a useful tracer of the wave motion. Vertical air velocity may be inferred from the slope of the echo layer at levels where the amplitude of the travelling 2 km perturbations was small. The layer at 2-8 km (Fig. 1) has a maximum slope of 1 in 10. Radiosonde measurements showed that the wind component along 260° was 30 m s⁻¹ at this level, thereby implying a maximum vertical velocity, $W_m$, of up to 3 m s⁻¹. Measurements of the vertical motion of radiosondes, as demonstrated by Corby (1957b), also permitted the vertical air motion to be inferred at the time of passage through the layer. This technique gave values of $W_m$ at 1510 GMT which decreased from 1 m s⁻¹ near Pershore to 0.5 m s⁻¹ at 12 km height some 60 km downwind of Pershore. These values are less than those inferred from Fig. 1 since they apply to a time and place where the amplitude of the wave pattern was relatively small. The wavelength inferred from the radiosonde data was, however, similar to that given by the radar observations.

The $l^2$-profiles derived from two soundings at Pershore and one at Aberporth are
Figure 2. Height of echo layer 'A' on 3 November 1969 plotted in an x-t plane, where x is distance from the radar towards 260° and t is time, (a) from 1411-1429 GMT and (b) from 1900-1530 GMT. Isopleths in (a) are at 100 m intervals with heavy stippling above 1.8 km, medium stippling above 1.6 km and sparse stippling below 1.4 km. Isopleths in (b) are at 200 m intervals with stippling above 1.8 km and hatching below 1.6 km. Heavy lines in (b) indicate the positions of crests, broken lines those of troughs. Arrows indicate times of data.
shown in Fig. 5. The Aberporth profile was very similar to those derived from the Pershore soundings. The constancy of the $T^2$-profiles throughout the day is consistent with the steady-state nature of the observed wave pattern; all profiles show $T^2$ decreasing with height from a maximum in some lower layer, considered by Scorer (1949) to be necessary for lee wave formation. Also, as predicted by Scorer (1949), the observed values of wavelength $\lambda$ fell between the maximum and minimum values of $(2\pi/l)$.

(b) 3 February 1970: unsteady lee waves

The lee waves on 3 February 1970 occurred in a strong westerly airstream about 300 km north of a frontal wave. Mode 1 and 2 data were obtained with the Deford radar throughout the period 1125 to 1520 GMT. Special radiosondes were released from Pershore at 1030, 1243 and 1453 GMT and an ascent from Aberporth was made at 1146 GMT. Both the ascents revealed a roughly isothermal layer at 5·5 to 6·3 km, (less marked in the 1243 GMT ascent), the static stability above and below tending to be stronger than in the 3 November 1969 study. Winds increased from 280°/17 m s$^{-1}$ at 1 km to 280°/75 m s$^{-1}$ at 8 km.

An example of the kind of R.H.I. radar data obtained is shown in Fig. 6. As a result of the implementation of an M.T.I. system the display is better at close range than on 3 November owing to the absence of side lobe echoes from the ground. The only cloud at
Figure 4. Variation with height of the crest-trough amplitude $A_m$ for the lee waves on 3 November 1969, derived from radar data along $070^\circ$ and $260^\circ$. Typical spread of amplitudes is indicated by the horizontal lines.

Figure 5. Vertical profiles of Scorer's $L^2$-parameter on 3 November 1969 computed from soundings made at Pershore and Aberporth. The vertical cross-hatched band indicates the range of values of the parameter $k^2 = (2\pi/\lambda)^2$ corresponding to the observed wavelength.

low levels was scattered cumulus humilis and the rather extensive echo in the planetary boundary layer was due to refractive index inhomogeneities associated with convective circulations beneath a weak inversion at 2 km. The top of the convective layer and a clear-air layer 1 km above it are seen to be distorted by a pronounced lee wave with $\lambda = 25$ km
Figure 6. Photograph of the R.H.I. display along azimuth 110° showing lee waves at 1437 GMT on 3 February 1970. Height markers are at 2 km intervals. There are two overlapping sets of range markers representing horizontal and slant range at 5 km intervals. Echoes due to ground clutter have been reduced compared with those in Fig. 1 by use of a moving target indicator (M.T.I.) system. See text for a discussion of the other echoes.
and $A_m = 800$ m. Echoes between 4 and 7 km are associated with a layer of cirrus whose sharply-defined base acts as an air-motion tracer as in the 3 November study. (The sloping echo-free zone extending from 5.8 km at 10 km range to 5.3 km at 50 km is an artifact due to the M.T.I. system which discriminates not only against stationary targets but also against targets whose line-of-sight velocity is a multiple of 43 m s$^{-1}$.) A further clear-air echo layer was detected at tropopause level near 11 km, but this was faint and no attempt has been made to reproduce it in Fig. 6.

The $x$-$t$ section in Fig. 7 reveals a complex and unsteady wave pattern with a spread of wavelengths between 15 and 30 km, the larger values dominating at close range and during the latter part of the observing period. There was a tendency for crests and troughs to travel gradually upwind throughout the day. An attempt has been made to synthesize Mode 2 radar data between 1343 and 1455 GMT and this confirmed the confused nature of the lee wave pattern at low-levels, there being a variety of orientations of wave crests, and wavelengths between 15 and 30 km.

![Figure 7](image)

Figure 7. Height of the top of the convective boundary layer on 3 February 1970 plotted in an $x$-$t$ plane, where $x$ is distance from the radar towards 280° and $t$ is time. Isopleths are at 200 m height intervals. Areas above 2 km are stippled and below 1.8 km hatched. Heavy lines indicate the positions of crests, broken lines the positions of troughs. Arrows indicate times of data.

Fig. 8 shows the variation with height of $A_m$ at various times throughout the Mode 1 observing periods. The maximum amplitude occurred in the middle and lower troposphere and diminished to half its maximum value at the tropopause (11 km). The maximum slope of the layer at 2.8 km was about 1 in 10 and, since radiosonde measurements showed the wind component at this level to be about 26 m s$^{-1}$, this implies a vertical velocity of 2.6 m s$^{-1}$.

The $l^2$-profiles derived from the soundings at Pershore and Aberporth are shown in Fig. 9. The observed range of $\lambda$ fell between the maximum and minimum values of $2\pi/l$.

(c) 22 April 1970: damped lee waves

Mode 1 radar observations were made along directions 250°, 270° and 070° during the period 0833 to 1351 GMT in a moist west-south-westerly airstream just ahead of a cold
Figure 8. Variation with height of the crest-trough amplitude $A_m$ of the lee waves on 3 February 1970 derived from radar data along 280° at five different times. Typical spread in amplitude around these times is indicated by the horizontal line on the 1312 GMT profile.

Figure 9. Vertical profiles of Scorer's $l^2$-parameter on 3 February 1970 computed from soundings made at Pershore and Aberporth. The vertical cross-hatched band indicates the range of values of the parameter $k^2 = (2\pi/l)^2$, corresponding to the observed wavelengths.
Figure 10. (a) Photograph of the R.H.I. display along azimuth 250° at 1200 GMT on 22 April 1970. The nearly vertical markers represent slant range at 5 km intervals. The M.T.I. system has been used to reduce ground clutter. Two principal echo-layers can be seen, revealing a damped lee wave system with a maximum amplitude at a range of 70 km. (b) Diagrammatic representation of the lee wave pattern within a section orientated along 250° - 070° through Deford at about 1200 GMT on 22 April 1970. Data along 250° have been derived from a composite of photographs obtained between 1138 and 1215 GMT; data along 070° have been derived from photographs obtained between 1130 and 1133 GMT. Corrections have been applied for Earth's curvature and refraction. Smoothed topography in the region of the section is illustrated. Wind speed and direction at 2 km and 4 km are indicated at the right-hand side of the Figure.
front. The front, orientated north-east/south-west, passed through Defford in the late afternoon. Radiosondes were released from Pershore at 1034 and 1304 GMT and from Aberporth at 1102 GMT. Winds increased from 250°/23 m s⁻¹ at about 1.5 km to a maximum of 260°/50 m s⁻¹ at 11 km. The stability structure was broadly similar to that of 3 November 1969, with a roughly isothermal layer between 2 and 3 km and an almost saturated adiabatic lapse rate above and below.

The most striking characteristic of the lee waves on 22 April was their rapid decrease in amplitude downwind (Fig. 10(a)). The largest amplitude (0.8 to 1 km) was observed at a radar range of 60 - 80 km, indicating the Black Mountains of south Wales to be the source of the wavetrain. This was confirmed by Mode 2 data, taken every 30° between 1105 and 1138 GMT, which showed the lee-wave pattern to be similar in orientation to that obtained in the 3 November study. However, unlike the 3 November case, only one major wave crest (at 50 km range) was observed to the lee of the mountains; at ranges closer to the radar the amplitude dropped rapidly to zero. This is illustrated more clearly in Fig. 10(b) which is a diagrammatic representation of the damped wave train.

The variation of wave amplitude $A_m$ as a function of height and time between 0930 and 1230 GMT is illustrated in Fig. 11. Lack of data simultaneously at all heights at any given flat range meant that measurements of the height dependence of $A_m$ had to be made at different ranges. To overcome the effect of the range dependence of $A_m$, the measured amplitudes were normalized with respect to the maximum amplitude at the corresponding range. Generally this maximum amplitude occurred close to the 2.5 km level. The normalized $A_m$ is seen to fall rapidly to half the maximum value at between 5 and 6 km. A maximum slope of 1 in 6 at 75 km range in the lower wave train in Fig. 10 indicates a vertical velocity of more than 4 m s⁻¹. An x-t section in the direction 260° for the layer echo at the top of the planetary boundary layer revealed that the lee wave pattern out to 80 km range maintained a virtually steady state from 0900 until at least 1330 GMT.

![Figure 11](image.png)

Figure 11. Variation with height of the normalized value of $A_m$ on 22 April 1970 derived from radar data along 250° to 270° for five observing periods.

Amplitudes have been normalized to the corresponding values at altitude 2.5 km since data were rarely available at the same range at all heights up to 10 km. Typical spread of amplitude is indicated by the horizontal line on the 1035-1144 GMT profile.
The $l^2$-profiles (Fig. 12) display a comparatively rapid decrease with height. This behaviour is similar to that of the profiles on the other steady-state day, 3 November 1969.

(d) 15 April 1970: transient lee waves aloft

Mode 1 radar observations were made from 0947 to 1504 GMT in the direction 270° within a moist west-south-westerly warm-sector airstream. A front, initially 180 km north of Defford at 0900 GMT retreated slowly northward throughout the observing period. Radiosondes were released from Pershore at 1130 and 1232 GMT and from Aberporth at 1106 GMT. Winds attained a low-level maximum of 250°/20 m s$^{-1}$ at 1.5 km decreasing to 265°/12 m s$^{-1}$ at about 4 km and then increasing again to a maximum of 300°/30 m s$^{-1}$ at 10.5 km. Above 4 km the temperature lapse was close to saturated adiabatic; below 4 km it was rather more stable, although nowhere did it approach isothermal.

![Figure 12](image)

Figure 12. Vertical profiles of Scorer's $l^2$-parameter on 22 April 1970 computed from soundings at Pershore and Aberporth. The vertical cross-hatched band indicates the range of values of the parameter $k^2 = (2\pi/l)^2$ corresponding to the observed wavelengths.

Examples of the kind of R.H.I. data obtained are shown in Figs. 13 (a) and (b). Many echo layers were present, those below 4.5 km being from the clear air, those above 6 km being from cirrus particles, and those between 4.5 and 6 km probably being from both causes. For much of the time the echo layers exhibited waves of only very small amplitude, with an ill-defined wavelength between about 8 and 10 km. However, during the period 1115 to 1140 GMT there was a dramatic growth and decay of lee waves at between 5 and 7 km height. Time-lapse film revealed that the process was apparently associated with the passage of a patch of cirrus with cumuliform tops extending from about 7 to 12 km (Fig. 13(a)). Following the passage of the cirrus, the wave motion decayed (Fig. 13(b)), only to be re-initiated at 1154 GMT in association with the passage of further cumuliform cirrus. The wavelength of these waves was observed to be about 16 km, with a value of $A_m$ of 700 m at between 5 and 7 km (Fig. 14). In contrast, the layer between heights of 2 and 5 km was characterized throughout by waves with a shorter, but relatively ill-defined, wavelength of typically 8-10 km, with a corresponding value of $A_m$ of only 200 m. No good tracers of air motion existed above 7 km, the vertical motion of the tops of the cirrus being indeterminate. The crests and troughs of both families of waves remained geographically
Figure 13.  (a) Photograph of the R.H.I. display along azimuth 270° at 1124 GMT on 15 April 1970. Height markers are at 4.3 and 8.3 km. Vertical markers represent horizontal range at 5.1 km intervals and the curved markers represent slant ranges at 5.0 km intervals. The M.T.I. system has been used to reduce clutter. Notice the cumuliform tops to the cirrus at about 25 km slant range and 11 km height and the waves of rather large amplitude between 5 and 7 km height. The wind within this height range, derived from the 1130 GMT Pessah ascent, was 276/17 m s⁻¹ at 5 km, 271/18 m s⁻¹ at 6 km and 280/24 m s⁻¹ at 7 km. See text for further details. (b) Photograph of the R.H.I. display along azimuth 270° at 1146 GMT on 15 April 1970 following the passage of the cumuliform cirrus. Range and height markers are as described in (a).
fixed even as the cirrus passed through the system, indicating that the entire wave system was driven by the surface topography. It is unlikely that the rapidity of the growth and decay of the high level wave system can be attributed to variations in wave structure in the parallel-ridge direction since the winds between 5 and 7 km were within 10° of the scanned section. It is possible, however, that local and short-lived reductions of static stability aloft, as indicated by the intermittent cumuliform nature of the cirrus tops, may have been responsible for the sudden growth of the latent high level wave system.

The $l_{max}$-profiles in Fig. 15 show subsidiary maxima at both 3-5 and 7-8 km indicating that these are both possible levels of maximum lee wave development (Scorer 1949). Two vertical cross-hatched bands are shown, corresponding to the observed spread of $k^2$ appropriate to the two ranges of observed wavelength. The left-hand band, corresponding to the longer wavelength family shows that, according to Scorer's (1949) premise, the atmosphere was resonant between 5-5 and 8 km. This was indeed the level at which the long wave family was observed. The right-hand band corresponds to $k^2$ values for the shorter-wavelength family which was observed at lower levels.

Characteristics of lee waves within the troposphere have been estimated for all four case studies using a simple one-level model due to Foldvik (1962) in which the vertical $l$-profile is approximated by an exponential decrease with height. Foldvik's model often predicts the occurrence of two wave families attaining maximum amplitudes at different heights. In the first three case studies the second family of waves was predicted to attain maximum amplitude at heights above 13 km, the wavelength being large (30 km to $\infty$). Only on 15 April were two realistic families of lee waves predicted to occur within the
troposphere. The first family had a predicted wavelength of 6 to 10 km with a maximum amplitude at a height of 1.3 to 2.5 km. The second family had a predicted wavelength of 14 to 22 km with a maximum amplitude at 4.5 to 8.3 km. The maximum amplitude of the second family was predicted to be about twice that of the first and this is in good accord with the observations.

4. Conclusions

This paper has described and illustrated a radar technique for measuring the three-dimensional structure of lee waves. Radar detects the lee waves by observing the distortion of otherwise horizontally stratified echoes from the clear air (and, to a lesser extent, echoes from some cirrus 'clouds'). The clear air layer echoes are associated with naturally occurring inhomogeneities of refractive index which result from the action of turbulence within layers of strong potential temperature and/or humidity gradient. Although the reflectivity of the clear air echoes may be intensified due to locally increased turbulence associated with the lee waves, it is emphasized that the layer echoes are a feature of the undisturbed flow and that they can exist in the absence of lee waves.

Clear air layer echoes are found to be relatively abundant in situations conducive to strong lee wave activity. The most intense echoes tend to occur within the layer of strong stability at the top of the planetary boundary layer where the lee wave amplitude is often greatest. The contribution of humidity to the radar-detected refractive index inhomogeneities exceeds that due to temperature in the lower troposphere but its contribution decreases rapidly with height. As a result, echoes suitable as tracers of the airflow are less abundant at higher levels. Nevertheless, as the case studies in this paper have shown, there are some occasions when layer echoes are present simultaneously at many levels, thereby permitting the structure of lee waves to be measured over a substantial depth of the troposphere within the 2 to 3 minutes taken to complete a single R.H.I. scan.

The four case studies in this paper portray widely different lee wave patterns associated with strong westerly airflow crossing the south Wales mountains. In one case the waves were found to be rapidly damped downstream of the mountains; in another they maintained an undiminished amplitude for more than 110 km. Although two of the wave patterns were in a steady state for periods of many hours, the other wave patterns changed drastically over periods less than an hour, suggesting that the conditions for lee waves of
relatively large amplitude can be rather critical. For some operations, such as those at ballistic ranges, measurements of lee wave length are required to ± 1 km and maximum vertical air velocity to ± 0.5 m s\(^{-1}\). Because major changes in lee wave characteristics can occur over short periods, a combination of radiosonde observations plus theory cannot be expected to predict them adequately; indeed, the required precision is unlikely to be attained other than by continuously monitoring the actual wave structures by techniques such as that described in the present paper.

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**References**


