Microstructure of Radar Echo Layers in the Clear Atmosphere

JAMES I. METCALF

Air Force Cambridge Research Laboratories, Bedford, Mass. 01730

(Manuscript received 9 July 1973, in revised form 9 September 1974)

ABSTRACT

Previous observations of clear air echo layers by high-resolution radar are reviewed briefly and compared with theoretical models. Quantitative radar reflectivity records reveal a variety of features common to these echo layers. In particular, some of the records show that the backscatter from layers only a few meters thick is strongly anisotropic with maximum reflectivity at 0° incidence angle, although these 0° echoes are not specular in the strict sense. The anisotropy is consistent with the presence of large shears across the thin layers. The data leave open the question of whether or not microscale (<1 m) instability always or necessarily precedes the occurrence of large-amplitude (10–100 m) breaking waves.

1. Introduction

In several recent papers (Atlas et al., 1969b, 1970; Gossard et al., 1970; Metcalf et al., 1970; Atlas and Metcalf, 1970; Gossard et al., 1971; Metcalf and Atlas, 1973; Metcalf, 1974) quantitative or semi-quantitative radar data have been presented and various characteristics of breaking gravity waves (Kelvin-Helmholtz waves) have been discussed. The purpose of this paper is to document more fully some of the earlier conclusions and to present more details of the microstructure of radar echoes associated with these waves. In particular, some of the data reveal a distinctly anisotropic structure of the small-scale refractivity fluctuations detected by the radar. The radar data presented here are observations made primarily during June 1970 at San Diego, using the high-resolution 10-cm FM-CW radar (Richter, 1969) at the Naval Electronics Laboratory Center (NELC). Supporting meteorological data were derived from radiosondes, pilot balloons, and the instrumented Buffalo aircraft (Lenschow, 1972) operated by the National Center for Atmospheric Research.

Radar signal data were recorded on analog tape for subsequent digitizing and computer processing. The details of the radar calibration are described by Stratmann et al. (1971) and the data processing technique for deriving radar reflectivity is described by Stratmann and Metcalf (1971). Briefly, the computer program corrects for height-dependence of the received signals and for incomplete intersection of the transmitter and receiver beam patterns, and includes a calibration of the tape recorder. The resulting displays of reflectivity in height-time coordinates yield more information on the small-scale structure of waves and thin echo layers than is obtainable from the qualitative data recorded on continuously moving film from the intensity-modulated oscilloscope display.

All of the data shown here were recorded under strong thermal inversion conditions, with the inversion base at 150–300 m and an average potential temperature gradient $\partial \theta / \partial z \geq 0.1$ K m$^{-1}$ through the layer in which the echoes occurred. The gradient of radio refractive index $[N = (n - 1) \times 10^5$, measured in $N$ units], which is strongly dependent on humidity, was more variable from day to day, due to variations in the humidity structure, but was as large as 1 N m$^{-1}$ in one case on 19 June. The radar reflectivity maxima were of order $10^{-11}$ cm$^{-1}$ on this day [see Atlas et al. (1970) for a discussion of clear air radar reflectivity]. Winds in the surface layer were generally from the west or northwest, but the wind structure in the inversion was often more complex, due primarily to land and sea breeze effects. An example of the low-level atmospheric structure is shown in Fig. 1. On 25 June 1970 the inversion base was particularly low, and $\partial \theta / \partial z \approx 0.05$ K m$^{-1}$ between 175 and 500 m, although the refractive index lapse in the inversion was less than usual. The wind was generally from the northwest at all heights, but with sharp variations in speed. Several of the cases presented below occurred on this day.

Some of the earliest observations with the FM-CW radar revealed clear-air structures suggestive of breaking Kelvin-Helmholtz waves, with amplitudes from 5 to 60 m, within the strong thermal inversion. Other observations showed thin echo layers which appeared smooth at the scale of the radar resolution, and led to the hypothesis (Atlas et al., 1969b) that the turbulence

1 Much of the research was performed while the author was at The University of Chicago.
and refractivity spectra might be confined to vertical scales \(< 1-2 \text{ m}\). One of the subjects of continuing study has been the structure of these smooth thin layers, and particularly their relationship to larger-scale wave phenomena. Several particular problems can be identified: (i) the origin of the thin layers and their precedence of large-scale breaking waves; (ii) the modification of thin layers by large waves, particularly the possibility of microscale instability and the development of a distinct microscale turbulence spectrum; and (iii) the relationship of the layer reflectivity to turbulence generated by large-amplitude waves. This paper is directed primarily toward the first two of these problems.

2. Discussion of particular observations

One of the early radar records is shown in Fig. 2, reproduced from Metcalf et al. (1970). Small waves, barely larger than the radar resolution, appear on thin echo layers between the crests of the large waves. The original interpretation of this feature (Metcalf et al., 1970) was that the thin layers are remnants of a previous turbulent breakdown at sub-meter scales. According to this interpretation the large-amplitude waves develop as the depth of the unstable layer increases, and the resulting tilting and stretching of the pre-existing thin layers produces an outbreak of microscale waves in these layers, similar to those hypothesized by Scorer (1969).

An alternate explanation for the origin of the thin echo layers is offered by Kelly and Masloue (1970) and Masloue (1972, 1973). They present a solution for flow structure at a critical layer for a neutrally stable wave, deriving a “cat’s eye” streamline pattern with diffusive layers at the boundaries of the “cat’s eye” cells. While the non-steady flow inherent in the instability limits the applicability of the Kelly and Masloue results, Masloue (1973) notes that the solutions represent an asymptotic condition for an amplifying instability. He also predicts the occurrence of small-scale instabilities within the diffusive layers due to the small local Richardson number and strong local shear. The possible result of such an occurrence is depicted schematically.
Fig. 3. Schematic view of amplifying wave, showing instability of thin boundary layers where temperature and refractivity gradients are concentrated. Microscale turbulence generated in these layers can produce the braided structure commonly associated with breaking waves observed in the atmosphere by radar.

in Fig. 3, which may be compared to the radar observations of Fig. 2. If the amplitude of the microscale waves is less than the radar resolution, then the instability might appear only as a local brightening of the echo layer.

Metcalf and Atlas (1973) showed that the local Richardson number in these thin layers may be reduced by a factor of 15 or 20 from its value over the depth of the large waves (where it is already $\leq 0.25$). As the time scale for the microscale instability is much less than for the large waves, the thin echo layers observed by the radar can develop as the large waves amplify, while giving the appearance of a pre-existing thin layer deformed by the large waves.

The key question arising out of these considerations is whether a thin (sub-meter scale) instability layer can or must precede the onset of instability at 10 to 100 m scales. Ottersten (1970) analyzed radar data from Wallops Island, Virginia, and concluded that shear instability occurred first in thin “friction layers” and subsequently in deeper layers, producing the characteristic braided structure observed by radar. Generally, the height-time radar records such as that of Fig. 2 do not provide adequate time histories of a particular structure to resolve the sequence of thin layers to large-scale instability. However, in some cases, a few of which are discussed below, there is evidence that thin layers do precede the large waves.

Several cases of large-amplitude breaking waves were studied in an attempt to resolve this problem. Fig. 4 is taken from a day on which multiple layers and several groups of large waves were observed. Evidence of the “secondary instability” of the thin layers is found in the reflectivity maxima located at the point of maximum layer slope. These suggest that turbulent breakdown has occurred there, leading to intense reflectivity fluctuation at the 5 cm scale sensed by the radar, although the contour shapes reveal no structural details of the instability. The later (and presumably more developed) waves at 1204:30-1206:00 show the maxima extending further around the “cat’s eye” vortex, suggesting that the microscale structure has been advected, as might be inferred from Fig. 3.

Figs. 5 and 6 depict echo structure in layers perturbed by long-period gravity waves. The effect of the long waves on the layer microstructure is uncertain, but these figures reveal several noteworthy features. The reflectivity maxima in Fig. 5 at 1258:30 and 1258:55 are suggestive of the local microscale breakdown described above. While the structure between 1258:40 and 1259:30 again suggests advection of the microscale structure around the “cat’s eyes,” the strong reflectivity maxima at 1258:45, 1259:05 and 1259:15, where the layer is normal to the radar beam, suggests a strongly anisotropic layer structure and the possibility of specular reflection. This latter characteristic is discussed in more detail below. Finally, at 1259:10 the figure shows a relatively rare convoluted layer structure, similar to that shown by Atlas et al. (1970), which implies that the thin layer preceded the large waves and that while the wave has begun to roll up, it has not produced sufficient turbulence to diffuse the echo in the vortex region.

Some of the features described above appear again in Fig. 6. Reflectivity maxima occur in the sloping layer at 1129:50, 1130:20, 1130:50, 1131:20 and 1131:50, and in the wave troughs where the layer is normal to the radar beam at 1129:30, 1130:00, 1130:30, 1131:10, 1131:40, 1132:10 and 1132:30. An unusual feature shown in this record is the asymmetry of the small waves, which have rounded troughs and sharply peaked crests. This can best be explained as being due to a pre-existing thin echo layer which is offset downward slightly from the mean height of the “cat’s eye” cells associated with the breaking waves. If the refractivity gradient (i.e., the humidity gradient) is concentrated entirely across the thin layer and is negligibly small above, then the thin layer will show nearly sinusoidal perturbations below the breaking waves, but with the peaks of the fluctuations drawn up into the wave vortices to form the observed structure. This interpretation is supported by the double layer structure observed at 1124-1126, suggesting that turbulent mixing has concentrated the gradient in two layers, of which the upper is the weaker. The lower layer, possibly enhanced by upward flux of water vapor from the surface, persists to reveal the wave structure at 1129-1132.

The possibility of specular reflection, mentioned above, is suggested even more strongly by Fig. 7, where reflectivity maxima occur at the crest and trough of many of the waves. The implications of this segment for the microstructure of thin echo layers are discussed in the following section.

3. Anisotropy of radar echo layers

The mechanism of specular reflection was considered when the first observations with the FM-CW radar at NELC were examined, but to my knowledge the discussions never appeared in the literature. Specular reflection was rejected as a source of the observed echoes because 1) the requirement of layer uniformity across
Fig. 4. Quantitative radar reflectivity record of 23 June 1970 from 1159-1208 PDT. Contours are of $10 \log_{10} \eta = -134$ with $\eta$ in cm$^{-4}$. One of a succession of groups of breaking waves observed at this time, this group shows a nearly symmetrical layer structure, with echo layers $\eta$ encircling the vortices at 1204:40 and 1205:30. Peak reflectivities up to $10^{-12}$ cm$^{-4}$ in the sloping layer between the wave crests are indicative of small-scale turbulent breakdown occurring there.

Fig. 5. Quantitative radar reflectivity record of 25 June 1970 from 1257-1302 PDT. Contours are of $10 \log_{10} \eta = -136$, with $\eta$ in cm$^{-4}$. Structure of breaking waves within the layer is generally not well defined. Between 1258:30 and 1259:30 the layer shows distinct wave structure, with reflectivity peaks not only at crest and trough but also in the intervening tilted layers. The layer at 1259:10 appears to be convoluted by the wave without being substantially weakened either by stretching or by turbulent mixing.
Fig. 6. Quantitative radar reflectivity record of 25 June 1970 from 1124–1134 PDT. Contours are of $10 \log r \geq -138$, with $r$ in cm$^{-1}$. Breaking waves of 30 s period are superimposed on gravity waves of approximately 5 min period. Double echo layer structure, suggesting a prior mixing of the intervening refractivity gradient, is evident at 1124–1127. Reflectivity is modulated by the breaking waves, with reflectivity maxima occurring both in the sloping layers and in the horizontal portions at the troughs of the short waves.

Fig. 7. Quantitative radar reflectivity record of 25 June 1970 from 0758–0802 PDT. Contours are of $10 \log r \geq -136$, with $r$ in cm$^{-1}$. Peak reflectivities of $1.3 \times 10^{-18}$ cm$^{-1}$ often occur near the wave crests where the layer is oriented normal to the radar beam, suggesting specular or quasi-specular reflection.
the beam seemed extreme, especially since weak turbulence was thought to be present often, and 2) the observed reflectivities were generally too high (by several orders of magnitude) to be attributable to specular reflection from the measured refractivity structures. Hence these records have been interpreted by means of the equations derived by Boglino (1958) and from Tatartski (1961) relating reflectivity to the refractive index fluctuation spectrum. These equations assume isotropic turbulence and an inertial subrange with a specified outer scale $L_o$ describing the largest isotropic eddies. While the validity of these assumptions is somewhat uncertain in the presence of strong thermal stability and wind shear at scales of the order of the smallest layer thickness, the equations do provide reflectivity estimates from the measured refractivity structure having better than order-of-magnitude agreement with measured reflectivities (Metcalf and Atlas, 1973).

Given the very small estimates of outer scale ($\sim 1$ m) derived from some of the aircraft and radar data, and particularly the implied anisotropic character of the refractivity fluctuation spectrum, the microstructure of the echo layers needs to be examined carefully and in great detail. One alternative hypothesis for the echo mechanism was suggested by Metcalf and Atlas. They proposed that the echo from the tilted portion of the thin layer might be due to multiple incoherent specular glints from microscale waves developing on the layer, as shown in Fig. 8 (Fig. 8 in Metcalf and Atlas, 1973). This model assumes a wavelength much less than the beam diameter, so that several waves are within the beam simultaneously. The reflectivity estimated from this model is 20–30 dB below the observed values, although one can hypothesize increased backscatter gain due to focusing by layer curvature. The radar records of Figs. 5, 6 and 7, however, show that while this specular model is not accurate in detail, some related model of quasi-specular reflection may be considered as an explanation of the anisotropic echo layer structure.

This anisotropic characteristic is generally associated with very thin layers which are often only a few meters thick, or two or three times the radar resolution increment. There is no definite correlation with magnitudes of reflectivity or reflectivity gradient, as these are likely to vary strongly with day-to-day changes in mean refractivity structure. The best example of the quasi-specular phenomenon is the case of 25 June 1970 shown in Fig. 7. A pibal wind sounding at 0818 PDT determined a wind component of 3.4 m s$^{-1}$ parallel to the shear (assumed normal to the wave fronts) at the altitude of the waves, so that the mean period of 16 s observed by the radar implies a spatial wavelength of 54 m. This gives a value of the wavelength to wave-height ratio $\lambda/2h = 54/20 = 2.7$, which is about equal to values of this parameter reported by Hicks and Angell (1968) from RHI radar observations of breaking waves.

The vertically-pointing radar beam thus intersects the thin echo layer at angles of incidence between 0° (at crest and trough) and 30° (at the point of maximum layer slope between the crests). For analysis of the layer structure, the maximum reflectivity as a function of time was extracted from the quantitative record and plotted in the upper part of Fig. 9, with the heights at which the maxima occur plotted in the lower part. The height plot reveals the same wave form as Fig. 7, and the reflectivity plot shows the character of the fluctuations along the thin layers. For several waves exhibiting reflectivity maxima at crest and trough (where $\phi = 0^\circ$) the peak values are 2–9 dB greater than at the point of maximum layer slope.

The radar data of Fig. 9 can be used to construct a diagram of relative reflectivity vs incidence angle, shown in Fig. 10. Here the radar data are shown schematically by the shaded area between 0° and 30°. The reflectivity function expected for true specular reflection is included for comparison. The specular curve for this case is wider than the radar beamwidth because the beam encompasses about $\frac{1}{3}$ of the 54 m wavelength at 230 m range and, due to layer curvature, would detect a specular reflection over a larger portion of the wave period. (For waves of greater length or smaller amplitude the portion of the layer within the beam would have a more nearly uniform slope and the apparent angular width of the specular peak would be smaller.) Comparison of the data to the specular curve shows that the echo is not due to specular reflection, nor to a specular component superimposed on an isotropic echo, although in two cases (0801:46 and 0802:22) the peaks

![Fig. 8. Schematic substructure of refractivity gradient layer, showing possible specular reflections from properly oriented portions of microscale waves (from Metcalf and Atlas, 1973).](image-url)
Fig. 9. Maximum reflectivity of echo layer as a function of time, and height at which maximum occurs, extracted from radar reflectivity record (Fig. 7). Heights of maximum reflectivity reveal wave pattern identical to that shown by the original record. Reflectivity variations along the layer show distinct maxima at the crest and trough of the waves, implying strongly anisotropic reflectivity structure.

are almost sharp enough to coincide with the specular curve. For further comparison, a reflectivity function corresponding to a simple angular dependence between a maximum at $\phi = 0^\circ$ and a minimum at $\phi = 90^\circ$, namely $\eta/\eta_{\text{max}} = \cos^2 \phi$, is also shown in Fig. 10. The observed reflectivity values reveal a greater degree of anisotropy than is implied by this curve or by analogous functions having a non-zero minimum value at $\phi = 90^\circ$.

It should also be noted that the occurrence of the reflectivity maxima with nearly equal frequency at the top and bottom of the waves implies that focusing of the reflected signal by layer curvature is not significant.

The most likely explanation of this phenomenon is that the turbulent eddies, even at very small scales, are influenced by the strong mean temperature gradient or wind shear. The mean shear (strain rate) computed from aircraft soundings through the inversion (Metcalf and Atlas, 1973) is about 0.1–0.2 s$^{-1}$ in layers a few meters thick, and may be somewhat larger where the wind structure is modified by waves. Analysis of the energy budget from the same soundings yields values of energy dissipation of order 5–15 cm$^2$ s$^{-3}$, from which the turbulent strain rate, defined as $\epsilon \nu^{-1}$ (where $\epsilon$ is the dissipation rate and $\nu$ the kinematic viscosity), is about 6–10 s$^{-1}$. Stewart (1969) found anisotropy of velocity fluctuations down to centimeter scales in the atmospheric boundary layer with mean strain rate about $10^{-1}$ s$^{-1}$ and turbulent strain rate about 10 s$^{-1}$. The anisotropy deduced in the present case therefore seems reasonable.

It is important to note that in the absence of isotropy there is no well-defined relationship between one-dimensional measured refractivity spectra and radar reflectivity (Ottersten, 1969). Theoretically, one can extrapolate a refractivity spectrum to the wavenumber of fluctuations measured by the radar, given by $4\pi/\lambda$, where $\lambda$ is the radar wavelength, and use that spectral density to estimate the reflectivity. Spectra computed from refractivity measurements on long horizontal flights (~4–5 km) generally yield reflectivity estimates which are several orders of magnitude below the values deduced from the radar measurements. Short flight segments within the echo layer region sometimes yield

Fig. 10. Relative reflectivity of layer as a function of incidence angle, derived from parameters of the case of 25 June 1970 shown in Figs. 7 and 9. The effect of specular reflection is shown by the broken line and a hypothetical reflectivity function by the dotted line. Anisotropy is not sufficient to be attributable to specular reflection.
higher estimates, but these are still below the observed values. A typical spectrum, computed from a 15 s segment of 8 s⁻¹ data on 19 June 1970, gave an extrapolated value $S_N(4\pi/10) = 10^{-3}$ N² cm and a reflectivity estimate of $10^{-18}$ cm⁻¹ based on isotropic scatter theory. The observed peak reflectivities on the same day were about $10^{-11}$ cm⁻¹, including some maxima of the quasi-specular type. The explanation of this discrepancy has generally been based on the difficulty of directing an aircraft into the echo layer and on the effect of averaging small regions of intense fluctuations with more quiescent regions. However, if the centimeter-scale refractivity structure is strongly anisotropic, one can hypothesize that the reflectivity estimated from spectra corresponds to that which a radar would measure if the beam were oriented along the echo layer ($\phi_r = 90^\circ$), and that such a decreased reflectivity relative to values measured by the radar at vertical incidence is a measure of the anisotropy of the microstructure. The practical considerations just noted are still applicable, so that any extrapolation of the reflectivity curve in Fig. 10 beyond the angles actually observed by the radar must be considered tentative.

Some additional remarks will help to place these results within the larger context of research on microwave scatter from the clear atmosphere. One of the problems arising from the reflectivity measurements at San Diego has been the explanation of the high reflectivities relative to the magnitudes measured at Wallops Island or at Delford, England, with high-power pulse radars. Atlas et al. (1970) explained the difference largely in terms of averaging down of peak reflectivities by the large pulse volumes, although they hinted at the possible effect of layer anisotropy. The present data imply that a decrease of 10–20 dB can be expected when the thin layers are viewed at incidence angles $\geq 60^\circ$ (radar elevation angle $\leq 30^\circ$), as is generally the case with the high-power scanning radars. More recent observations with a scanning FM-CW radar (Richter et al., 1972) show no significant angular dependence of reflectivity up to $30^\circ$ from the vertical, although no quantitative measurements were presented. Some vertical resolution is lost with this radar in the scanning mode, as the beamwidth is about 10–15 m at the ranges of interest (compared to 1–2 m beamwise resolution), so that measurements at large incidence angles approaching $90^\circ$ would have to be corrected for beam filling.

Independent evidence for the anisotropy of the atmospheric microstructure comes from forward-scatter of microwaves. Experimental results such as those of Atlas et al. (1969a) and Gage et al. (1973) reveal a distinct signal component with zero Doppler shift due to specular reflection from thin layers along a great circle path. Because the scatter angles involved in forward-scatter experiments are small, the signals respond to atmospheric structure on the order of meters or tens of meters (compared with centimeters in the case of backscatter). Layers that appear moderately anisotropic at centimetric scales (as discussed above) may be expected to appear more anisotropic at larger scales, approaching the limiting case of specular reflection for forward-scatter observations.

4. Conclusion

The available data reveal that radar echoes in thermally stable layers are due to locally intense and possibly isotropic turbulence resulting from dynamical instability at sub-meter scales and to anisotropic refractivity structure with maximum spectral density perpendicular to the echo layer orientation. While the latter may be only a more advanced state of the former, the distinction seems justified on the basis of the particular reflectivity distribution associated with each. Both mechanisms appear to be related to the effects of amplifying waves on the thin layers, the former occurring where the tilting and deformation of the thin layers has led to local dynamical instability, and the latter occurring in extremely stable layers where the wind shear, although not large enough to induce dynamical instability, has attained a magnitude at the scale of the echo layer thickness that is significant relative to the local turbulent strain rate. Under the latter conditions the turbulent eddies would be stretched by the shear to form quasi-horizontal refractivity structures within the thin layer. This structure should always be detected, whenever it is present, as a reflectivity maximum at the crest and trough of a wave. Instability at sub-meter scales within the thin layers may not always be detected, since the backscatter reflectivity from the resulting turbulence may be no greater than that from a pre-existing refractivity gradient layer. Thus, while the present research shows that the refractivity structure is sometimes strongly anisotropic, it remains a subject for future research to determine the extent of this characteristic in time and space and the conditions governing its occurrence.

Acknowledgments. The author is indebted to Dr. Juergen H. Richter and Dr. Douglas R. Jensen of NELC for the unique radar data used in this analysis. Dr. Ernst Stratmann, formerly of the Laboratory for Atmospheric Probing, The University of Chicago, developed the computational techniques. The National Center for Atmospheric Research, which is sponsored by the National Science Foundation, provided the use of its CDC 6600 computer for the reflectivity computations. Dr. David Atlas of NCAR and Dr. Kenneth R. Hardy of Environmental Research and Technology, Inc. (formerly at AFCLR) reviewed the manuscript and offered helpful suggestions.

The portion of the research conducted at The University of Chicago was supported by grants from the United Airlines Foundation, the Environmental
REFERENCES


Lenschow, D. H., 1972: The measurement of air velocity and temperature from an aircraft as applied to the NCAR Buffalo measuring system. Tech. Note 74, National Center for Atmospheric Research.


