Reply

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The purpose of my paper[1] was to work out the consequences of a new shear model atmosphere so that its predictions could be compared with observations and its representation of reality thus assessed. I therefore welcome Dr. Browning's comments and hope others will respond with additional observations.

In my paper I did not suggest that shear layers occur *only* near isentropic layers nor that the periodic structures seen by radars occur only at such layers. I do contend that shear across nearly isentropic (and even superadiabatic) layers is not an uncommon occurrence in the atmosphere, and I suggest that this condition may lead to especially active "wave" generation and perhaps to some of the exceptionally "narrow-band" patterns seen by radars.

An example of such active wave generation associated with strong wind shear across an adiabatic layer is shown in Figs. 1 and 2 taken from Gossard and Sweezy (1974). Fig. 1 shows radiosonde sounding data taken during, and at the end, of the wave event shown in Fig. 2 recorded by a vertically pointing FM-CW radar (Richter, 1969). The balloon released at 1348 PST was tracked optically and was lost behind a rain shaft (see white areas in Fig. 2) before reaching the strong shear layer revealed by the 1600 rawinsonde to exist at a height of 2.5 km—shear layer which clearly occurred at a level of minimum stability. Dramatic altocumulus mammatus middle clouds were observed during the wave event. Unfortunately, the FM-CW radar was unable to see high enough to observe the patterns within the shear layer itself, which was presumably the region of wave generation.

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[1] I take this opportunity to point out three misprints appearing in my paper. A plus sign should be inserted before ω/k in Eqs. (9) and (15). In the line below Eq. (10a) the argument of ctn$h$ should be $\gamma_1 H$, and in Eq. (12) the last term on the left should be c instead of c^2. These errors are either typographical or misprints and are not in the final expressions nor in the results shown.

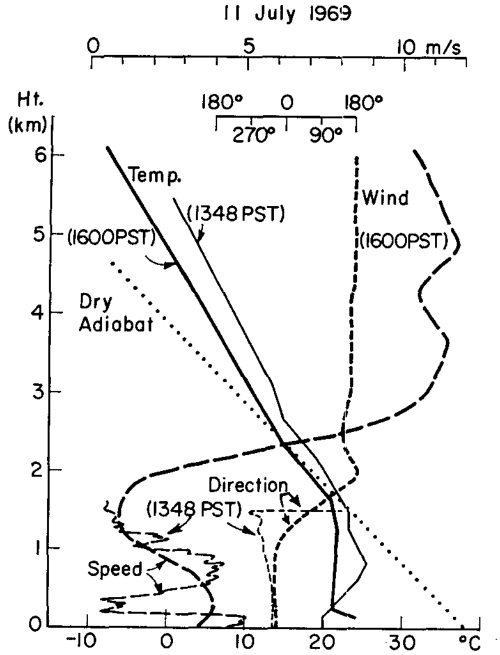

FIG. 1. Balloon sounding data on 11 July 1969. The sounding balloon launched at 1348 was lost behind a rain shower and no wind data were available above about 1.6 km. The 1600 sounding was the U. S. National Weather Service sounding from Montgomery Field, San Diego.

Other examples of shear across layers of minimum stability have been provided to me by Dr. Timothy Keliher, and are shown in Fig. 3. The soundings analyzed by Dr. Keliher were cases of exceptional wave activity as recorded on an array of microbarographs at the surface. The speed and direction of the waves, measured as they propagated across the array, are shown on each frame of the figure. In all cases the agreement is good between the speed and direction of the waves and the speed and direction of the wind in the shear layer at the height of minimum stability. (The adiabatic lapse rate is indicated by the straight line segment beside the temperature curves.) Other cases have shown the shear layer to occur at maxima in stability, but those shown here demonstrate that shear occurs not uncommonly across layers of minimal stability.

I do not consider the isentropic character of the shear layer to be the factor of primary importance in my model. The practical reason for assuming the shear layer to be precisely isentropic is the applicability then of solutions in terms of elementary functions which makes multi-layer models containing inversions tractable. The primary physical effect of this assumption is to produce a band of unstable wavenumbers at all scales of disturbances (since, obviously, the Richardson number cannot everywhere exceed $\frac{1}{4}$ in such a model). The width of the band quickly becomes infinitesimal as the Väisälä-Brunt frequency of the bounding medium becomes large or the shear becomes small.

I consider the inversions which bound the shear layer in my model No. 2 to be the characteristic of most interest. They are responsible for the narrow band of unstable wavenumbers which characterize the model. Such narrow band disturbances are evident in

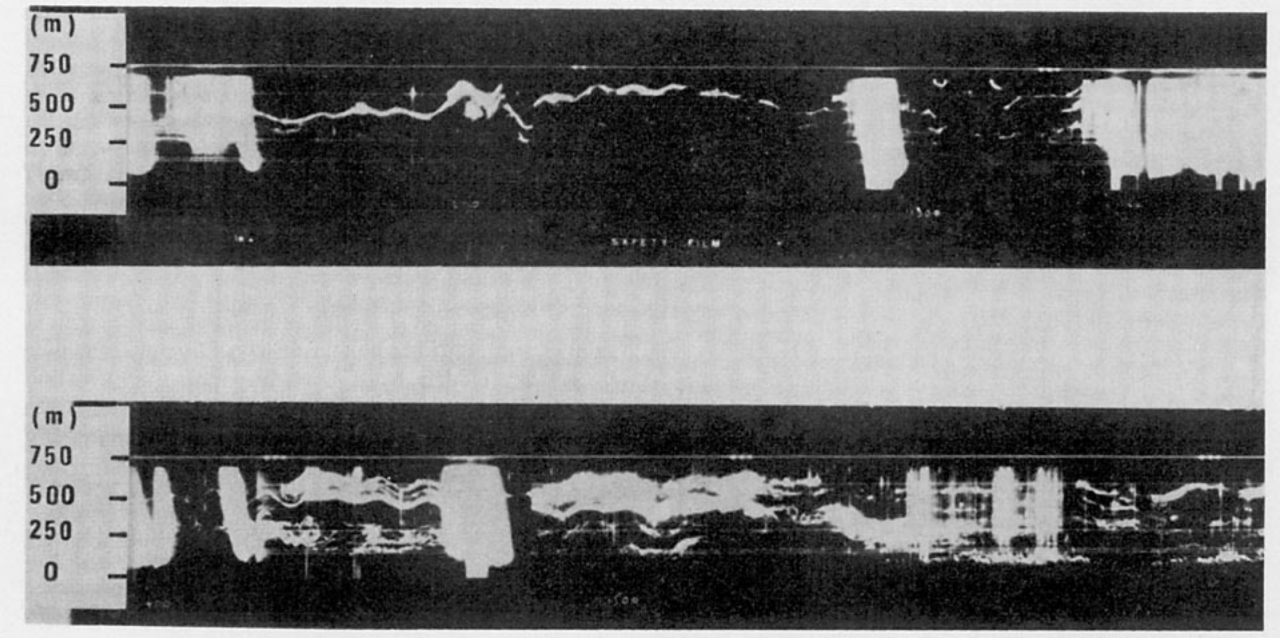

FIG. 2. High-resolution radar sounding showing waves aloft on 11 July 1969. Sounder is vertically pointing FM-CW radar (Richter, 1969). White areas are showers. Height range was shifted for a short time at about 1205. Times marked on record are daylight saving time, so one hour should be subtracted to obtain Pacific Standard Time (PST). Horizontal lines are range markers.

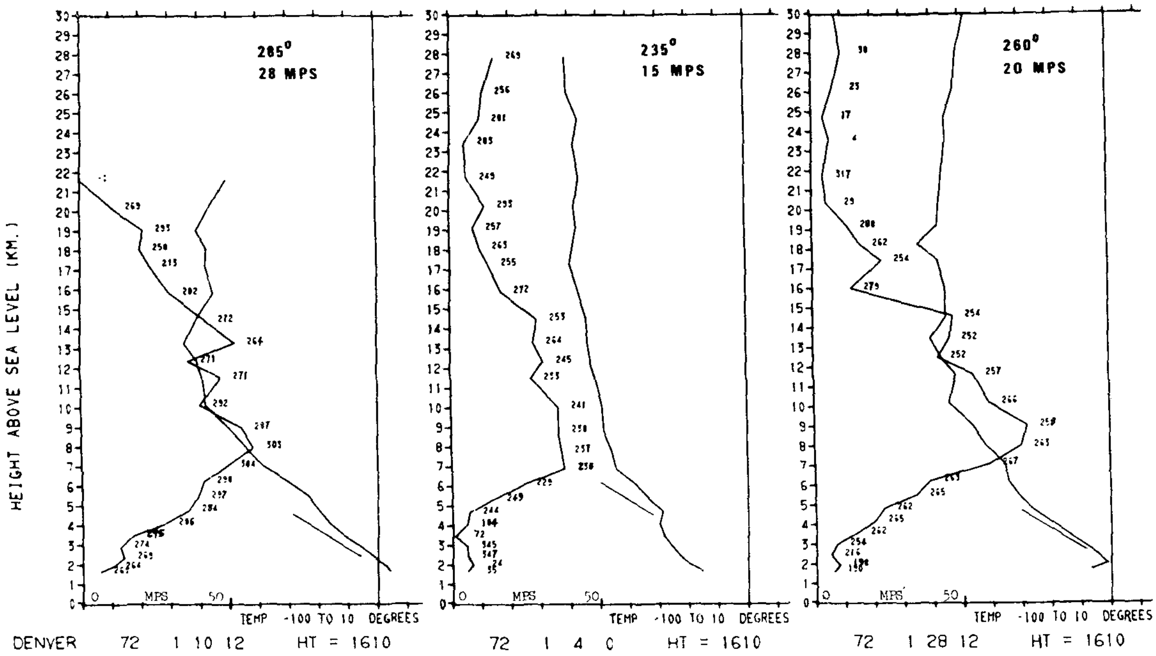

FIG. 3. Wind and temperature sounding data during significant wave events recorded on pressure arrays at Boulder, Colo. The short line segment beside the temperature curve indicates the adiabatic lapse rate. Wind directions are indicated by the figures alongside the wind speed curve. (Courtesy of T. Keliher.)

the observations of both Browning (1971) and Katz (1972). This effect is not likely to be erased by some small static stability within the shear layer, just as the cat's eye does not depend critically on the shear occurring in precisely homogeneous (isentropic) layers, although Kelvin (1880) deduced it for such layers.

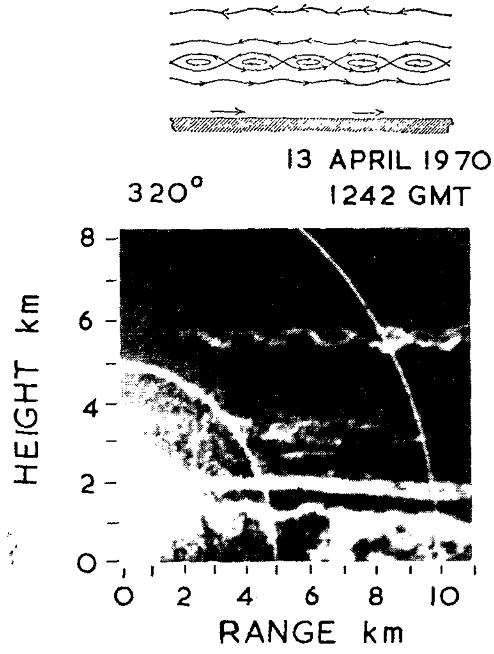

FIG. 4. Kelvin's original sketch of the cat's eye pattern displayed with the radar record from Browning's (1971) Fig. 1, for comparison.

If created by mixing in the shear layer, such bounding inversions would tend to be thin and thus not easily detected by conventional radiosondes such as those used by Browning. They may well provide the answer to Dr. Browning's question of how a well-mixed isentropic layer can give a radar return. The necessary gradients would certainly be present at the edges of the layer and would provide an explanation for the clear delineation of the cat's eye boundaries seen in Fig. 4 and similar double-echo structures commonly seen by radars. Kelvin's original sketch of the cat's eye is shown in Fig. 4 along with the radar record from Browning's Fig. 1 for comparison.

In case other workers attempt to deduce ratios of wavelength to layer thickness from radar records as Dr. Browning and I have done, it is, perhaps, well to point out that the wavelength of the intersecting sinusoids at the critical level is twice the wavelength of the disturbances generated as shown in the derivation of the cat's eye given in the Appendix of my paper, so the appropriate length is the width of the eye itself. Dr. Browning informs me that this is the length scale that he also used, so this should not lead to any discrepancy in our results. However, for the width of the layer he chose the distance between the centers of the radar echos (i.e., the eyelids in Fig. 4) whereas I chose the outer edges of the echos. In Fig. 4 this leads to a layer thickness of 400 m by his method and 700 m by mine. Thus the choice of different methods in compiling data of this kind can lead to a considerable discrepancy in the results.

REFERENCES

Browing, K. A., 1971: Structure of the atmosphere in the vicinity of large-amplitude Kelvin-Helmholtz billows. *Quart. J. Roy. Meteor. Soc.*, **97**, 283–299.

Gossard, E. E., and W. B. Sweezy, 1974: Dispersion and spectra of gravity waves in the atmosphere. *J. Atmos. Sci.*, **31**, 1540–1548.

Katz, I., 1972: The detection and study of gravity waves with microwave radar. *Proc. AGARD Conf. on Effects of Atmospheric Acoustic Gravity Waves on Electromagnetic Wave Propagation*, No. 115, 21–1 to 21–9.

Kelvin, Lord, 1880: On a disturbing infinity in Lord Rayleigh's solution for waves in a plane vortex stratum. *Nature*, **33**, 45–46.

Richter, J. H., 1969: High-resolution tropospheric radar sounder. *Radio Sci.*, **4**, 1261–1268.