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Turbulence Energy Dissipation Rates and Inner Scale Sizes From Rocket and Radar Data

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Estimates of turbulence energy dissipation rates and inner scale sizes have been obtained at altitudes of 80–90 km, using simultaneous rocket and radar data from the STATE experiments. Spectral widths from radar Doppler spectra and the rocket-derived temperatures were used to calculate the turbulence energy dissipation rate as a function of height; values generally ranged from 0.05 to 0.15 m^2 s^{-3}, with a long term average about 0.1 m^2 s^{-3}. The maximum observed energy dissipation rate was about 1.0 m^2 s^{-3}, but these occasional intense levels of turbulence lasted only a few minutes. The kinematic viscosity has been calculated from the rocket data, which was then used with the energy dissipation rates to estimate the turbulence microscale (η) as a function of height; values of about 1.5–2.0 m were obtained from 80 to 87 km, with η increasing rapidly for heights above about 87 km. The inner scale for neutral turbulence is approximately 13 times η, which therefore possibly ranges from 20 to 26 m, which is in approximate agreement with other estimates for the mesosphere. This result shows that the 3-m scattering wavelength for the Poker Flat Radar is well within the viscous subrange for neutral turbulence and raises questions as to why such large backscatterd signals are detected in the polar mesosphere. A companion paper (Kelley and Ulwick, this issue) discusses this within the context of the electron density fluctuation spectra measured during the STATE campaign.

1. INTRODUCTION

During June 1983 the STATE series of experiments were conducted at the Poker Flat Research Range, Alaska; these experiments are also described elswhere [*Fritts et al.*, this issue; *Kelley and Ulwick*, this issue]. The in situ rocket measurements were planned to complement mesospheric measurements from the nearby MST (mesospheric, stratospheric, tropospheric) radar. The objective of this paper is to use the spectral widths from the radar Doppler spectra to determine turbulence energy dissipation rates and inner scale sizes. *Kelley and Ulwick* [this issue] have also independently calculated these parameters from the rocket data.

Although other authors have previously either suggested or attempted to use radar spectral widths to calculate turbulence dissipation rates [e.g., *Gage et al.*, 1980; *Sato and Woodman*, 1982; *Hocking*, 1983*a*, *b*; *Royrvik and Smith*, 1984], with the exception of the estimates of *Hocking* and *Royrvik and Smith*, other radar-derived estimates of dissipation rates have been in the troposphere and stratosphere only. Further, since the calculations depend on the background neutral atmosphere, previous authors were forced to use standard model atmosphere parameters. By comparison, the present rocket measurements of neutral density and temperature profiles give a greater level of confidence in calculations using the radar data.

Although three rocket salvos were launched on different days, only one salvo (on June 15, 1983) included measurements of neutral atmosphere profiles using an accelerometer experiment and the falling sphere technique. As a result of instrument malfunction, only electron density data was obtained in the other two experiments. Our analysis concentrates on the June 15 data, although we will also present some results from the final experiment on June 17, even though no accelerometer data was available.

2. CALCULATION OF TURBULENT ENERGY DISSIPATION RATES AND INNER SCALE SIZES

The spectral widths can be obtained directly from the Doppler spectra at each height. The spectral width is a measure of the range of turbulent velocities within the scattering volume; however, there are a number of experimental corrections that may be applicable and which have been summarized by *Hocking* [1983*a*]. In the presence of a horizontal wind, the finite beam width is responsible for spectral broadening. Fortunately, the Poker Flat radar antenna has a relatively narrow beam width (1.1° for the oblique beams and 2.2° degrees for the vertical beam), and the beam broadening correction that has been made is very small for the typical horizontal velocities that were observed. A potentially large factor is shear broadening, which is most severe when the antenna is directed several degrees or more off vertical. Shear broadening is important for oblique antenna beams because different portions of the

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scattering volume at each range may be at different heights, where the horizontal wind component may be different. The third possible contributor to spectral broadening is mean wind variations (vertical and horizontal) during the time required to record one spectrum. We expect this to be insignificant because each spectrum was obtained in only 1 min; however, if rapid oscillations with periods less than about a minute were present, they would be undetectable in this data and would act to overestimate the spectral widths. To avoid possible errors due to shear broadening, we have chosen to use only data from the vertical radar beam.

Weinstock [1981] derived the following expression for the turbulent energy dissipation rate;

$$\varepsilon = 0.4\ \overline{v^2}\ \omega_B$$

where $\overline{v^2}$ is the mean square turbulent velocity, ω_B is the Brunt-Väisälä frequency (in radians per second). As discussed by *Hocking* [1983*a*], the constant in this expression is not precisely known, and Hocking derived a value of 0.45 . Since both *Hocking* [1983*b*] and *Royrvik and Smith* [1984] used Hocking's value of the constant, we chose to adopt it for meaningful data comparisons. The procedure followed in this paper is to determine $\overline{v^2}$ from radar spectral width and ω_B using the temperature profile derived from the rocket accelerometer experiment. *Hocking* [1983*b*] has outlined the method of radar data analysis in more detail. The spectral half widths for the calculation are determined at the 3 db level below the peak value and are a measure of the velocity fluctuations in the radio refractive index at scale sizes of half the radar wavelength.

The temperature profile obtained by the rocket is shown on the upper left panel of Figure 1; the minimum occurs at 84~88 km altitude. Small wavelike structures are evident in the data over the 80 to 90 km range, and we assume these small-scale features are due to short-term variations. Since several hours of radar data are used with a temperature profile obtained at only one time, the temperature data has been smoothed (7-km running average) to that shown in the upper right panel of Figure 1. The two lower panels of Figure 1 show the 80 to 90 km portion of the smoothed temperature profile and the corresponding Brunt-Väisälä frequency over over the height range where MST echoes were detected.

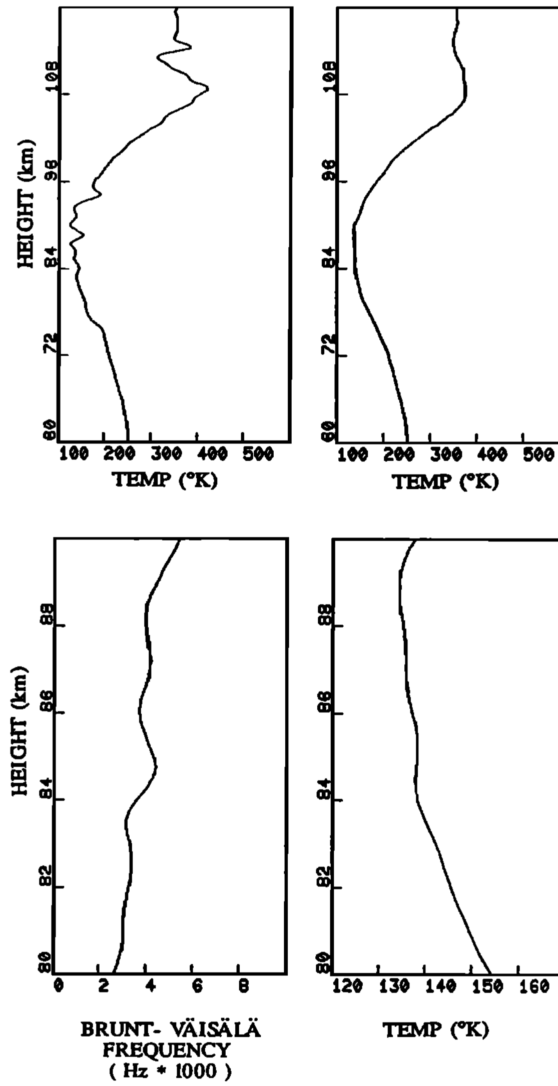

Fig. 1. Temperature data from the rocket experiment is shown in the upper left plot, with the corresponding smoothed data in the upper right. The lower two plots show the Brunt-Väisälä frequency (Hertz) and smoothed temperature data for the altitude range of the MST radar echoes.

The turbulence inner scale size has been estimated from our results. This is of interest for comparison with rocket results and also to determine whether the radar half-wavelength is located in the turbulence inertial subrange or in the viscous subrange. The turbulence microscale η, as originally defined by *Kolmogorov* [1941] and as discussed by *Tennekes and Lumley* [1972], *Crane* [1980], *Hocking* [1985], and many others, is defined by

$$\eta = \left[\nu^3 / \varepsilon \right]^{1/4} \tag{1}$$

where ε is the energy dissipation rate, and ν is the kinematic viscosity. The units of η in (1) are meters. By contrast, some authors have assumed units of meters per radian with an extra factor of 2π, and some confusion exists in the literature. *Hocking* [1985] has mentioned this problem of units and also suggests that the inner scale for velocity fluctuations in air is related to the microscale by $l_0 \approx 12.8\eta$. We have adopted this expression, but the exact value of the constant for the mesosphere is uncertain. The inner scale is also in units of meters. The microscale is well withion the viscous subrange since the spectral break occurs at a wavelength 2~4 times larger than l_0 [*Hill and Clifford* 1978]. These definitions must be kept in mind when discussing the radar results and comparing them to the rocket data of *Kelley and Ulwick* [this issue]. For these calculations the kinematic vioscosity may be obtained from tabulated values in the U.S. Standard Atmosphere (1976); however, we have calculated it with the rocket data, using the following expression from the U.S. Standard Atmosphere (1976):

$$\nu = \frac{\beta\, T^{3/2}}{\rho\,(T + S)}$$

where ρ is equal to density; T is temperature; S is Sutherland's constant (110.4°K); and β equals a constant with a value of 1.458×10^{-6} kg/(ms °K$^{1/2}$).

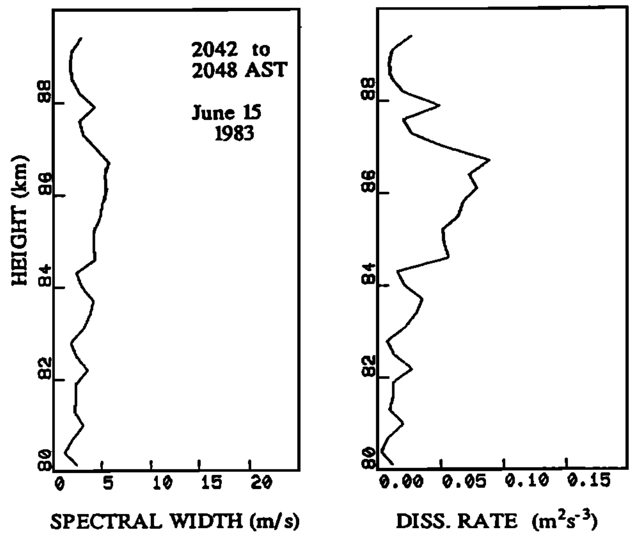

Fig. 2. Spectral widths and corresponding energy dissipation rates for the 6-min. period at the time of the rocket launch on June 15, 1983.

3. RESULTS

The launch time for the Nike-Hydac rocket that carried the accelerometer experiment was 2051 AST (Alaska Standard Time) on June 15, 1983. At this time, strong radar echoes covered about 2.5 km altitude, from 84.3 to 86.8 km. This region of strong signal returns was slowly moving downward and is shown in Figure 8 of Fritts et al. [this issue]. In this paper we have used radar data covering the 12-hour period starting at 1700 AST on June 16, 1983. Strong radar echoes were present for most of this period, covering about 2~3 km of height at any given time but occurring at different positions over the 83 to 88 km height interval at different times. When the radar returns are very weak, it is difficult to accurately determine the spectral widths; usually the widths tend to be underestimated for weak signals. Therefore it is only in this limited range of stronger detectable signals that our width measurements are reliable, and data for times of weak echoes have been discarded.

Figure 2 shows the spectral widths and dissipation rates near the rocket launch time. It is an average of data from five records. The time to gather and process data for one record was about 1 min. The vertical and oblique beams were alternated each record; thus there is a 1-min gap between each vertical beam record used in this paper. The strongest signals at this time occurred from 85 to 87 km altitude.

At other heights below about 80 km and above 90 km, it was not possible to obtain spectral width measurements because of very weak signals. Even over the 80 to 90 km range, the turbulence was frequently very weak at certain heights; however, if several records were averaged, then there was usually at least one width measurement available at most heights (80~90 km). In averaging records the widths were obtained separately from each record, then the widths were averaged from the records with detectable signals. An alternative approach would have been to average the individual Doppler spectra first, before obtaining the spectral widths. This latter approach has the advantage of increasing the detectability of signals, but it is a likely source of error, because when spectra are averaged for extended periods, short-term variations in the mean wind (either vertical or horizontal) will broaden the spectra. In a companion paper [*Fritts et al.*, this issue] it was noted that the heights of most intense turbulence coincided with regions in which the wave field was unstable, and the most intense turbulent regions slowly moved downward in response to the wave activity. These results are therefore weighted toward those periods of

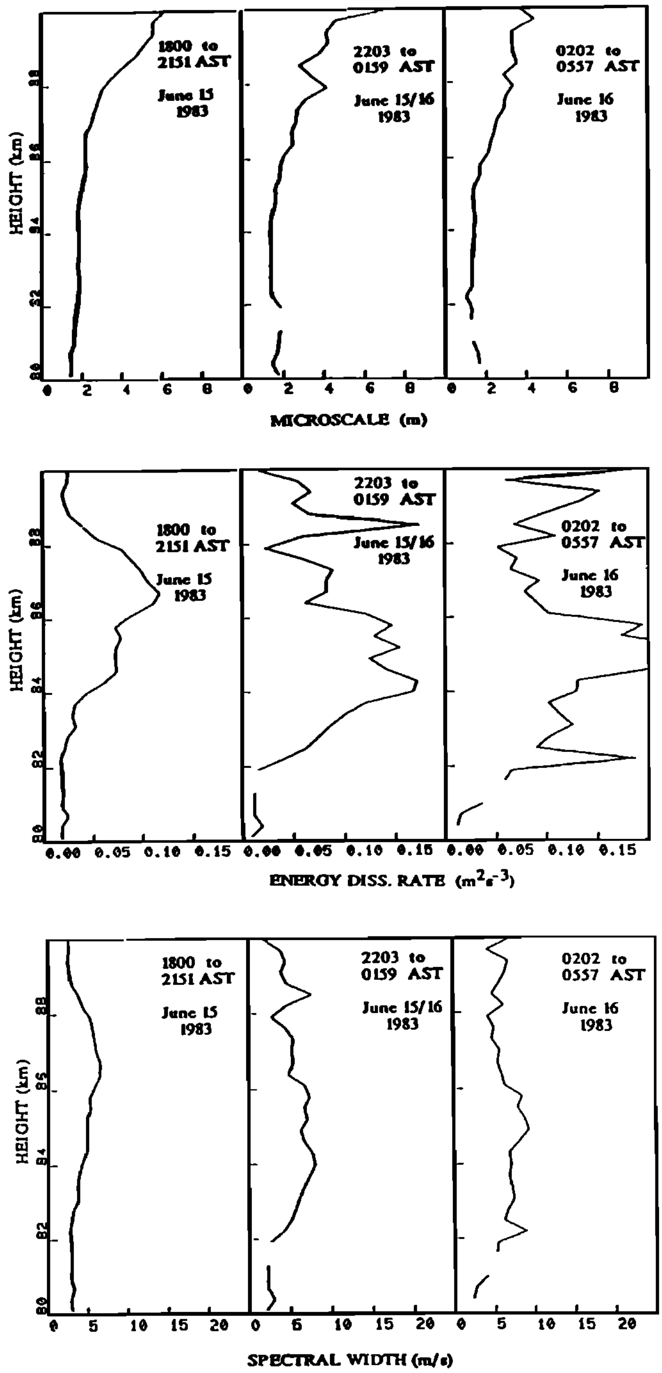

Fig. 3. Spectral widths, energy dissipation rates, and turbulence microscale sizes for three successive 4-hour periods on June 15/16, 1983.

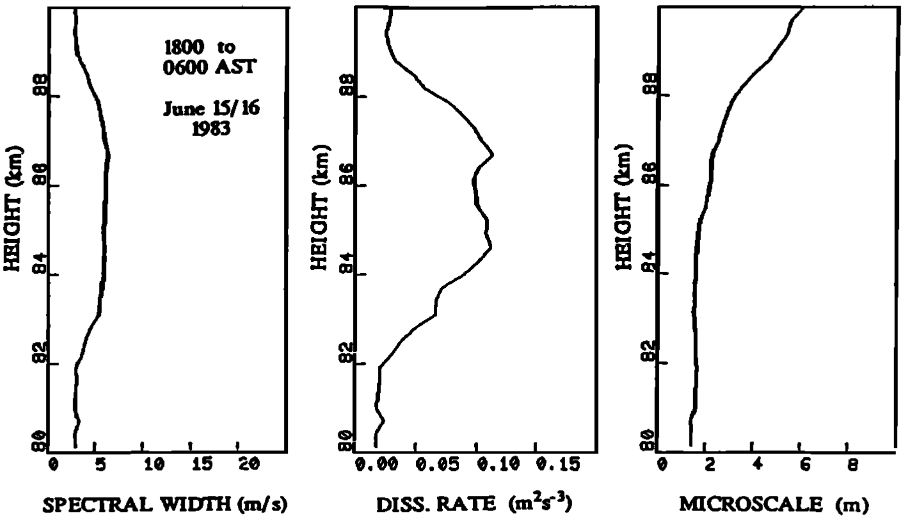

Fig. 4 Twelve-hour averages of spectral widths, energy dissipation rates, and microscale sizes for the rocket launch day of June 15/16, 1983.

more intense turbulence. There were long periods with no detectable signals.

Figure 3 shows three 4-hour averaged width profiles, and Figure 4 shows the 12-hour average. The corresponding energy dissipation rates and microscale sizes are shown on both Figures 3 and 4. Over the 12-hour period there were strong signals, at least part of the time, from 83 to 88 km, and the average spectral widths, when measurable, were quite constant with height. For heights above and below this range, the returned signals were consistently weak or nonexistent.

The energy dissipation rate for the period near launch time is shown in Figure 2; values about 0.08 m^2 s^{-3} were calculated for the heights where signals were strongest. Three 4-hour averages for the same day (Figure 3) have similar values. The first of these 4-hour averages is a smoother plot than the second and the third 4-hour average because of a higher sampling rate during that time; the first 4-hour average has 147 records, whereas the other two plots are averages of 87 records each. The large peaks at heights below 83 and above 88 km are probably false because the weak signals there give unreliable estimates. Over the longer term, the average dissipation rate is about 0.07–0.12 m^2 s^{-3}, although values in excess of 0.2 m^2 s^{-3} are sustained for a period from 0200–0600 AST.

The turbulence microscale calculations are sensitive to the values of the kinematic viscosity, and therefore we chose to compute this directly from the temperature data. The Figures 4 and 5 show the microscale η as a function of height with values about 1.5–2.0 m, increasing rapidly above 85 km. This agrees fairly well with *Hocking* [1985], who suggests that the inner scale, l_0, should range from 10 to 40 m, over the 80 to 90 km range, which corresponds to η in the range 0.8–3.0 m. However possibly larger values for ε in our high-latitude case should result in smaller values for l_0 compared to lower latitudes. This result is of some concern. Since the radar half-wavelength is 3 m, the fact that the turbulence inner scale is significantly greater than 3 m suggests that no radar echoes would be expected. *Kelley and Ulwick* [this issue] discuss this problem further, since they

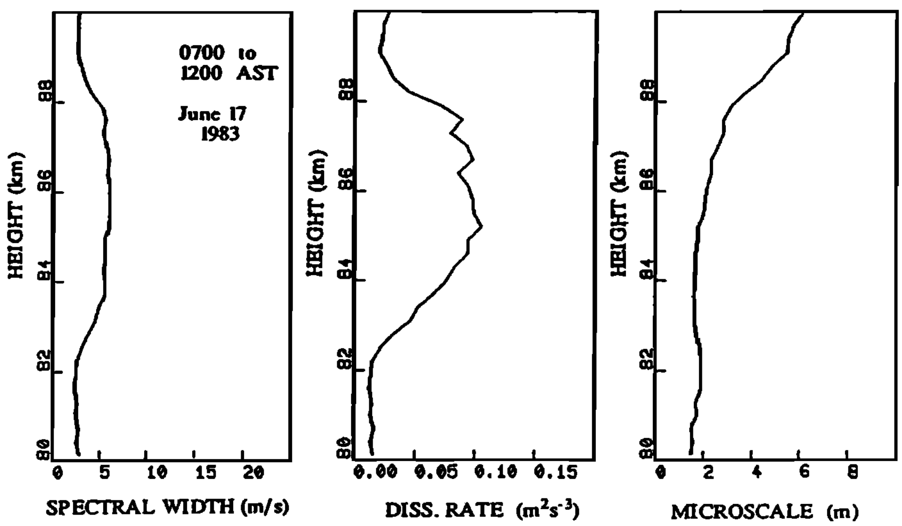

Fig. 5. Twelve-hour averaged data for June 17, 1983.

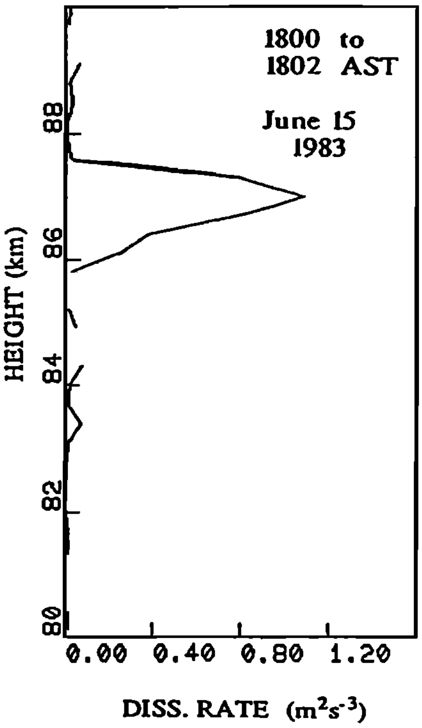

Fig. 6. An example of typical maximum values for the energy dissipation rate. The scale values in this figure differ from the other figures. Such large values near 1.0 m^2 s^{-3} persisted for short periods, no longer than a few minutes, and were restricted to the 1- to 2-km altitude range.

find that the inner scale for the electron gas is much smaller than for the neutrals.

For the next rocket salvo (on June 17, 1983) the height extent of strong echoes at launch time was greater than the previous data (about 83.5~89 km); however, values of energy dissipation rate and microscale size were quite similar to the previous data. An example is shown in Figure 5. There were no temperature data available for this day, therefore temperature data from June 15 was used.

A search was made to determine the absolute maximum energy dissipation rates because, during the experiments, occasional spectra were observed that were significantly broader than the average. Figure 6 shows dissipation rates as high as 1.0 m^2s^{-3}; however, these periods of intense turbulence were of short duration (a few minutes) and had a negligible effect on longer-term averaged data. It was not possible to identify periods longer than a few minutes where the dissipation rates persisted at such large values.

4. Comparison With Other Results

Our energy dissipation rates are comparable but somewhat larger than results from other experimenters. However, even the other radar results from *Hocking* [1983*b*] and *Royrvik and Smith* [1984] are liable to have minor differences, due to small differences in the analysis procedures or possibly the much longer radar wavelength (150 m) used by Hocking.

Hocking [1983*b*] reported values of 0.01~0.2 m^2s^{-3} for turbulence energy dissipation rates at 80~90 km altitudes. His data were obtained at Adelaide, Australia, a mid-latitide site. It is notable that *Hocking* [1983*b*] points out that his data are probably upper limits because long (~5 min) data samples were used. This long duration is comparable with possible gravity wave periods, but it is dictated by the long correlation times in the observations with the 150-m wavelength radar used by Hocking.

The results of *Royrvik and Smith* [1984] are particularly interesting because their experiments were similar to those reported in this paper. They used the Jicamarca 50-Mhz radar to obtain mesospheric data during times of rocket experiments. It is important to point out that unlike the high-latitude case [*Kelley and Ulwick*, this issue], for that lower latitude it seems the 3-m Bragg wavelength of the radar is in the dissipative subrange of the electron spectrum. This is evident in their spectra of rocket-derived electron density variations. Although not specifically stated by Royrvik and Smith, we infer from their results that the turbulence inner scale l_0 is at least 20 m, because this is the length scale for the break in their spectral slope, and the inner scale is 2~4 times this value [*Hill and Clifford*, 1978; *Hocking*, 1985]. They also computed the microscale $\eta = [\nu^3/\varepsilon]^{1/4}$, using ε from radar spectral width data. Values about 3 m were obtained; however, Royrvik and Smith assumed that the inner scale is the same as the Kolmogorov microscale in their discussion. By comparison, the Alaskan results indicate that the microscale $[\nu^3/\varepsilon]^{1/4}$ is less than 3 m up to about 90 km. Another, perhaps significant, difference is that in the Jicamarca data, one well-defined turbulent layer was observed from 79 to 82 km altitude. By contrast, the Alaskan data indicated turbulence that extended over a wider height range. *Royrvik and Smith* [1984] calculated 0.05 m^2 s^{-3} for the energy dissipation rate within the turbulent layer that was observed. This value may not be directly comparable with our results. They made an additional correction factor of $\sqrt{2}$ to their vertical velocities under the assumption that rms velocities are unlikely to be equal in the horizontal and vertical directions. We infer that this factor would act to increase their calculated dissipation rates by a factor of 2.

Wright and Hunsucker [1983] used ionosonde data from Fairbanks, Alaska, to determine values of ε from 0.005 to 0.03 m^2 s^{-3}. Their data were obtained at higher altitudes (103 km) than data presented in this paper. *Thrane et al.*, [1985] used rocket data from Andoya, Norway, from the altitude range 63~87 km. Values of ε from 0.005 to 0.03 m^2 s^{-3} were obtained, which are similar to the lower range of values in the Alaskan data.

Of particular interest here are the STATE data presented by *Kelley and Ulwick* [this issue]. The electron density data for the first and third STATE experiments (June 13 and 17, 1983) have been extensively discussed by Kelley and Ulwick, who found that the inner scale and microscale values for the electron gas were much lower than calculated here for the neutrals. Although this difference is not completely understood, they point out that the electrons may be acting as a passive scalar with a large Schmidt Number due to the existence of heavy positive ions. If true, that would explain why intense backscatter occurs at 50 Mhz, even though the inner scale, as calculated in this paper, is much greater than the scattering half-wavelength. There is a rapid increase in the microscale (and inner scale) above about 90 km, and this is a likely reason for the almost total lack of radar returns from above this altitude.

In summary, our average value of 0.1 m^2 s^{-3} for the energy dissipation rate is probably about a factor of 2~4 higher than the equatorial value reported by *Royrvik and Smith* [1984] and within the range (0.01~0.2 m^2s^{-3}) of mid-latitude data reported by *Hocking* [1983*b*] and *Roper* [1977], although Hocking's values are possibly upper limits. The Alaskan data values are greater than the high-latitude data presented by *Thrane et al.* [1985], whose values occur in the lower range of values presented in this paper. The short-term intense levels of turbulence produce energy dissipation rates that are considerably higher than have been reported elsewhere.

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