Midtroposphere Wind Speed Spectra from Long-Term Wind Profiler Measurements

A. S. FRISCH, B. B. STANKOV, B. E. MARTNER, AND J. C. KAIMAL

NOAA/ERL/Wave Propagation Laboratory, Boulder, Colorado

(Manuscript received 28 December 1990, in final form 5 June 1991)

ABSTRACT

This study of a 5-yr continuous record of midtropospheric horizontal wind components from a radar wind profiler operating at Fleming, Colorado, shows a broad spectral peak centered around a period of 1 week and a minimum at about 4 months, in addition to the expected 1-yr peak. However, when the records are separated according to seasons, the pattern becomes more complicated, with several distinct peaks and clear differences between the summer and winter behavior emerging. In this paper the different spectral patterns observed are presented and the synoptic-scale features in the weather that could produce them are speculated on.

1. Introduction

Between 1984 and 1989, the NOAA Wave Propagation Laboratory operated a network of six radar wind profilers of different designs in Colorado to test their long-term performance characteristics (Strauch et al. 1984). Of these, the 50-MHz profiler at Fleming, near the northeast corner of the state, performed best, with the least number of interruptions and outages. Time series of the north–south and east–west components of the hourly wind data from the lowest four (3.9–6.6 km MSL) range gates appeared the most promising for a study of the spectral behavior in the middle troposphere because there were very few missing data at these levels. Such prolonged high temporal resolution records are rare for this altitude range. The study has enabled us to identify significant scales of motion and to relate them to synoptic weather patterns observed in Colorado. The spectra provide useful evidence of longer-term phenomena that may be important in climate modeling research. This study should be viewed as an extension of earlier work by Balsey and Carter (1982) on the spectral behavior of wind in the upper troposphere and mesosphere from another version of the same kind of wind profiler.

Continuous measurements from wind-profiling radars provide an opportunity to view wind velocity spectra with temporal detail not available from conventional rawinsonde data. Spectral studies have been conducted on profiler measurements for periods of about 1 month or less by several scientists, including Balsey and Carter (1982), Larsen et al. (1982), Ecklund et al. (1986), Scheffler and Liu (1985), Fritts et al. (1990), and VanZandt et al. (1991). Before this study, only Thomson and Henderson (1990), who analyzed data from four consecutive autumn seasons, examined multiyear spectral measurements, which are now becoming available at a few profiler sites.

Before wind profiler measurements, a number of researchers computed velocity spectra using wind measurements from instrumented towers or rawinsondes. One of the earliest studies was that of Van der Hoven (1957), who computed the spectrum for periods ranging from 4 s to 60 days from wind measurements on an instrumented tower at Brookhaven, New York. He observed a spectral power peak at a period of 4 days, which he ascribed to the passage of large-scale pressure systems. A similar peak was also evident in the east–west component at the 700-mb level in a study of 16 months of rawinsonde data by Chiu (1960). He also found this peak at higher levels in both the latitudinal (east–west, or U) and meridional (north–south, or V) components of the wind. The energy of both components reached a maximum at the 200-mb level. A large contribution to the kinetic energy of the latitudinal component was made by motions with periods greater than 30 days. Vinnichenko (1970) composited data from several sources to construct the velocity spectrum for a wide frequency range at Washington, D.C. He found a strong spectral energy maximum at a period of 1 year in the U component and a somewhat weaker one in the V component.

2. The profiler and multiyear dataset

Operating characteristics of the WPL 50-MHz wind profiler are summarized in Table 1. Data from the 9-μs pulse processing mode, which provided wind measurements at 870-m increments from 3.9 to 17.0 km MSL, were used. Details of the on-site data processing

---

Corresponding author address: Dr. A. Shelby Frisch, NOAA/ERL Wave Propagation Laboratory, 325 Broadway, Boulder, CO 80303-3328.

TABLE 1. Parameters of the 50-MHz profiler.

Radar		
Frequency	49.8 MHz	
Authorized bandwidth	0.4 MHz	
Peak power	30 kW	
Average power	400 W	
Pulse width	3.9 μs	
Pulse-repetition period	238.67, 672 μs	
Antenna aperture	50 m × 50 m	
Antenna pointing	15° off-zenith to north and east (two antennas)	
Antenna type	fixed phase array of colinear-coaxial dipoles	
Two-way beamwidth	5°	
Data processing	3-μs pulse	9-μs pulse
Time-domain averaging	419 pulses	124 pulses
Spectral averages	8	16
Maximum radial	± 15.05 m s^{-1}	± 18.06 m s^{-1}
Spectral resolution (64 points)	0.47 m s^{-1}	0.56 m s^{-1}
Height sampling	3-μs pulse	9-μs pulse
First height	1.7 km AGL	2.6 km AGL
Height spacing	290 m	870 m
Number of heights	24	18

have been given by Strauch et al. (1984). Each hour, samples obtained at 5-min intervals were subjected to a consensus test from which the hourly average wind speed components emerged. These hourly averages are the basic units for the postprocessing analyses. Measurements of the vertical component of velocity were not obtained with this profiler.

The hourly data collected at Fleming for almost 5 years (14 April 1984 to 17 January 1989) are examined by spectral analysis in the next section. A climatological context for these analyses is provided by inspection of the long-term mean-wind profiles shown in Fig. 1. The figure includes all data from the entire collection period and all measurement heights. Components of the mean wind and their standard deviations are displayed. The data are typical of midlatitude mean-wind profiles in that the maximum speed is located near the tropopause because of the presence of the jet stream, and the latitudinal (U) component is dominant because of the prevailing westerlies. The averaged meridional (V) component is nearly zero at all heights because V typically alternates between positive and negative values as pressure waves pass over. The highly variable nature of the wind in the troposphere is revealed by the large standard deviations, which are approximately equal to the mean total wind speed.

Frisch et al. (1986) show how the amount of missing profiler data, caused by insufficiently strong backscattered signal, increased with height. The percent of data missing was very low throughout the troposphere, but became significant above about 12–14 km MSL. Therefore, the data from the upper levels should be regarded as less certain than the data from the lower levels. In this study, data from only the lowest four range gates (3.9–6.6 km MSL) were selected for spectral analysis because the amount of missing data was minimal at these heights. Also, the spectra for each of these four heights showed virtually identical features, including the locations of peaks and valleys, which exhibited little variation with height.

This altitude range represents midtropospheric conditions above the influence of the planetary boundary layer. Even at these heights there were some periods of missing data. The longest gap of 2 weeks was caused by equipment failure, but most gaps were only 1 h long. Linear interpolation was conducted across the data gaps before performing the spectral analysis. For the spectrum analysis a fast Fourier transform was used that handled all 43 200 data points in the time series in a single pass (without block averaging or decimation). The spectral estimates were averaged over nonoverlapping blocks that increased in width with frequency to provide equally spaced data points on a logarithmic scale. No detrending or moving-average filtering was used on the time series.

3. The observed spectra

The 5-yr record of wind fluctuations in the midtroposphere over northeastern Colorado offers an oppor-

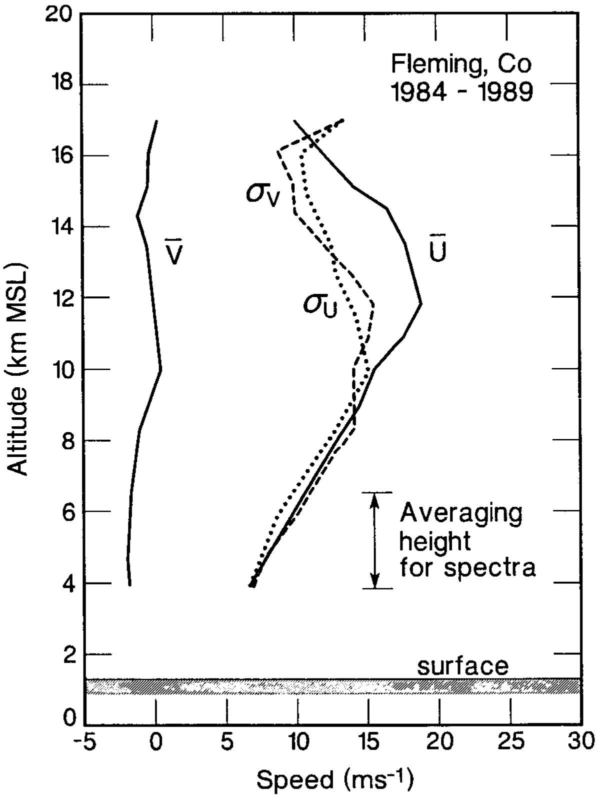

FIG. 1. Profiles of mean east–west U and north–south V wind components and standard deviations for wind profiler measurements at Fleming, Colorado, during the period 14 April 1984 to 17 January 1989.

tunity to explore the behavior of U and V in terms of their spectral content. Peaks and valleys in the spectral plots indicate how energy is distributed over the range of scales present in atmospheric motions. Confidence in the significance of the peaks and valleys observed here is based on the faithful replication of them at all of the four levels included in the spectral averaging.

Figure 2 shows the spectra for the entire 5-yr record, which includes the data from all seasons. It is obvious that U and V share several features: 1) the expected sharp peak at a period of 1 year, 2) a broad peak at about 1 week corresponding to synoptic-scale weather fluctuations, 3) a spectral gap centered at about 4 months, less pronounced in V than in U, and 4) an f^{-1} slope above 1 day, less than that predicted for two-dimensional (horizontal) turbulence. The absence of a prominent diurnal peak is not surprising, given the height range of these observations, well above the planetary boundary layer. Combining the data from all seasons (as in Fig. 2) further reduces the chance that a summertime convective diurnal peak would appear. The profiler's midtroposphere synoptic-scale peak at 1 week is longer than the 4-day peak measured at 125 m AGL in New York by Van der Hoven (1957) and at 30 m AGL in Denmark by Courtney and Troen (1990), using instrumented towers.

When the record is partitioned into summer (June, July, and August) and winter (December, January, and February) months and averaged over the 5 years, as shown in Fig. 3, differences in the behavior of U and V become apparent. The U component has a peak at 1 week in both summer and winter. The V component also peaks at about 1 week in summer (but not in winter) when it exhibits multiple peaks with, in fact, a relative minimum at 1 week. The 1-day peak absent in the all-seasons data of Fig. 2 does appear prominently in the summer spectra of Fig. 3. This summertime diurnal peak is almost certainly the result of diurnal modulations of convective circulations, which can reach these measurement heights in summer but are suppressed in winter. Figure 3 also shows that the energy at the high frequencies is greater in summer than in winter. The high-frequency part of the winter spectrum closely resembles that of the 5-yr, all-seasons spectra of Fig. 2.

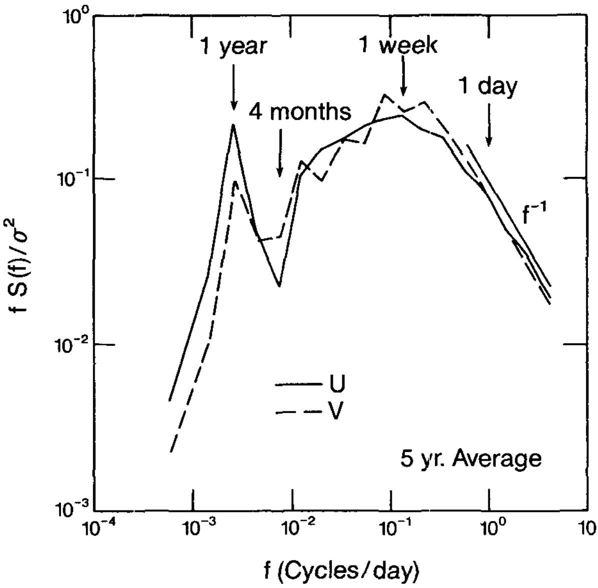

FIG. 2. Five-year spectra of horizontal wind components for all seasons combined, averaged for the altitudes 3.9–6.6 km MSL.

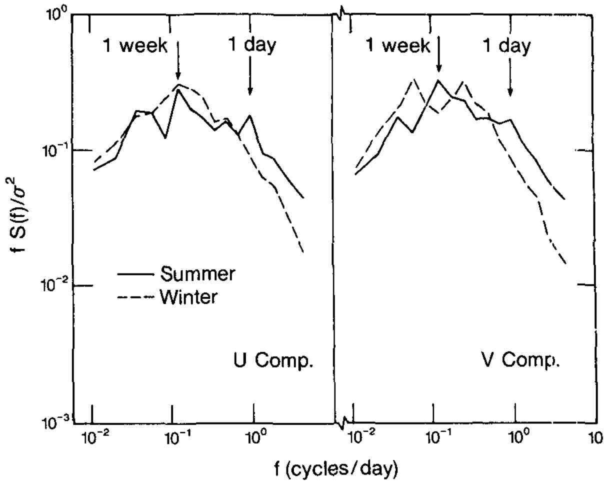

FIG. 3. Summer and winter horizontal wind spectra for U and V components averaged for 3.9–6.6 km MSL.

Additional information emerges when the U and V spectra are compared with each other in summer and winter, as in Fig. 4. The U and V spectra are very similar in summer: both show maxima at 1, 7, and 24 days. The winter patterns, however, are significantly differ-

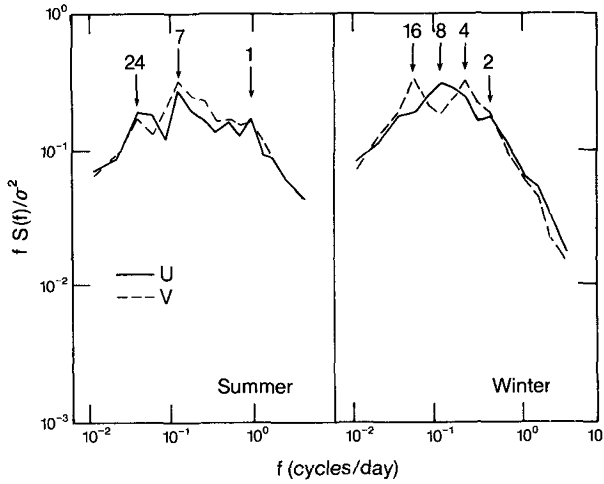

FIG. 4. (a) Summer and (b) winter wind component spectra averaged for 3.9–6.6 km MSL.

ent: U peaks at 2 and 8 days, whereas V peaks exactly an octave lower at 4 and 16 days. This doubling seems too systematic to be the result of chance, and warrants closer examination. An explanation of this behavior is offered in section 4.

The spectra of Figs. 2–4 are normalized by the velocity variances. Year-to-year variations of the variances themselves are presented in Fig. 5, where the data are divided into summer and winter month categories for each of the 5 years. During the measurement period, the winter variances were much greater than the summer variances (a factor of 2–7 greater) for both components. Variances of the U and V components were nearly equal in summer, but the V component variance greatly exceeded the U variance in winter. In addition, the V component's interannual variability changed by a factor of 2 over the 5 years, whereas the U component changed by about one-third. Thomson and Henderson (1990) also noted large interannual variability of the V component in their autumn season profiler measurements in Pennsylvania.

4. Discussion

A number of new features of tropospheric wind spectra were pointed out in the previous section. These features may have eluded detection in earlier studies that relied on rawinsonde data because of poorer measurement accuracies and temporal resolutions. When used in the two-beam (no vertical-velocity measurement) mode, as in the Fleming data, the wind profiler has an accuracy of about 1.7 m s^{-1} (Strauch et al. 1987). Hoehne (1980) has shown that relative errors for National Weather Service rawinsondes are about 3 m s^{-1}. The averaging of 5-min-interval measurements to yield hourly averaged samples of the wind diminishes the possibility of high-frequency aliasing to lower frequencies in the profiler data. This is not true for the rawinsonde data, which involve no temporal averaging. Another noteworthy difference is that a profiler provides nearly vertical profiles of wind, but a rawinsonde actually gives profiles along the balloon trajectory, which is usually very slanted.

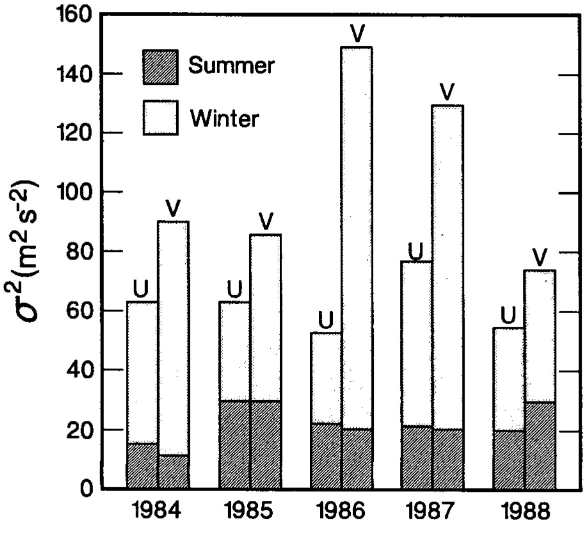

FIG. 5. Summer and winter wind component variances for the five individual years of measurements.

Knowledge of the behavior of the variances and spectra for the periods ranging from a day to several months has a number of applications. For example, the year-to-year variation of seasonal variances has implications for climate modeling. Kolesnikova and Monin (1971) discuss how the complexity of a climate model decreases when the interannual variability of a given meteorological element is small in comparison with its variability within a year. Construction of the climatology of such an element simplifies considerably because the small interannual variability can be ignored in solving some aspects of climatology. As shown in the previous section, however, the Colorado tropospheric wind data are of a different character. Differences between the variances of U and V are small in summer and large in winter. More significantly, the variance data show that the interannual variability is not small compared with the annual variability. Thus, according to Kolesnikova and Monin (1971), the wind climatology would not simplify.

Kolesnikova and Monin (1971) also emphasize the importance to long-term weather forecasting of global oscillations with periods of weeks to months. In the Colorado data, most of the spectral energy, in addition to the annual peak, is contained within a band from a few days to 2 weeks. Between these maxima lies a distinct minimum at a period of about 4 months. Thus, the observed spectra are not encouraging for forecasts much in excess of about 2 weeks.

As summarized by Nihoul (1984), the behavior of atmospheric phenomena within a particular range of scales is best revealed by selecting an appropriate averaging time and smoothing out smaller time-scale fluctuations. In the case of climatological circulations, these high-frequency fluctuations are Rossby and other kinds of turbulence. The averaging time must be chosen sufficiently large for the fluctuations to roughly cancel over a time of that order, yet sufficiently small to allow the signal from the phenomenon of interest to pass through the filter. That is, the averaging time should correspond to a valley in the energy spectrum. Nihoul (1984) speculated that an averaging time of approximately 1 month was long enough for climate applications. However, the spectral gap in the Colorado measurements (Fig. 2) indicates that an averaging time of about 4 months would be more appropriate. Without similar records elsewhere, it is impossible to know whether the 4-month Colorado spectral gap is representative of other geographic regions.

An interesting feature of the wintertime spectra shown in Fig. 4b is that the U and V components peak at different frequencies. These can be paired together such that the periods of the *V* peaks are twice the period of the *U* peaks (16 days for *V* paired with 8 days for *U*, and 4 days for *V* with 2 days for *U*). A possible explanation for this behavior is examined below.

Figure 6 shows a simplified sketch of the wind speeds in an atmospheric wave pattern in the troposphere. High-amplitude waves resembling this one are associated with the jet stream and with traveling synoptic weather systems. In winter, they are commonly located over Colorado latitudes. In summer, they retreat northward over Canada and leave Colorado under weaker flow patterns.

Consider the sequence of *U* and *V* speeds in a wave that would pass over a wind profiler located at position X_1 on the latitude line along the center of the wave's east–west axis (*AA*). As the wave moves eastward, the *U* component of the wind over the profiler would always be positive and would have two maxima (at points X_2 and X_4). However, in the same period, the *V* component would reach only one maximum (at X_2) and one minimum value (negative at X_4).

Time series of *U* and *V* at the profiler location for this situation are plotted in Fig. 7. It can be seen that, as the wave passes, the *U* component goes through two cycles, while the *V* component experiences only one. Thus, the period for *V* is twice that for *U*. For synoptic short-wave weather systems, a typical period between trough passages is about 4 days. Long-wave (Rossby wave) patterns are more stagnant and typically have periods that are much longer. Thus, we speculate that the observed spectral peaks of Fig. 4b at 4 days for *V* and 2 days for *U* are the result of traveling synoptic weather-system short waves, and the peaks at 16 days for *V* and 8 days for *U* are caused by long waves.

If the wind profiler were located at a different latitude with respect to the wave axis (e.g., at *BB* or *CC*) the *U* component would still experience two maxima, and *V* still has only one, but the *U* maxima would be spaced differently in time than for the *AA* location. The *U* maxima would be farther apart for the *BB* location and closer together for *CC*. It is expected, however, that over several years the average situation in the midlatitudes will resemble the Fig. 6 *AA* location results, which are shown in Fig. 7. The multiple-of-two period spectral peaks for *U* and *V* is not expected in summer for Colorado because the jet stream and associated wave pattern are usually located too far north. This expectation agrees with the observed summer spectra shown in Fig. 4a.

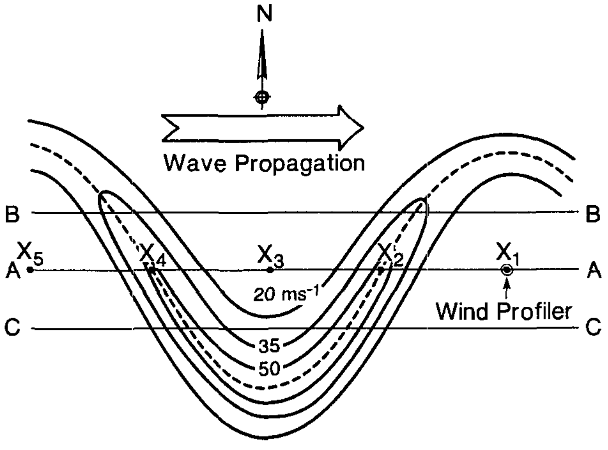

FIG. 6. Schematic diagram of wind speed in an eastward migrating tropospheric wave, typical of conditions at midlatitudes in winter.

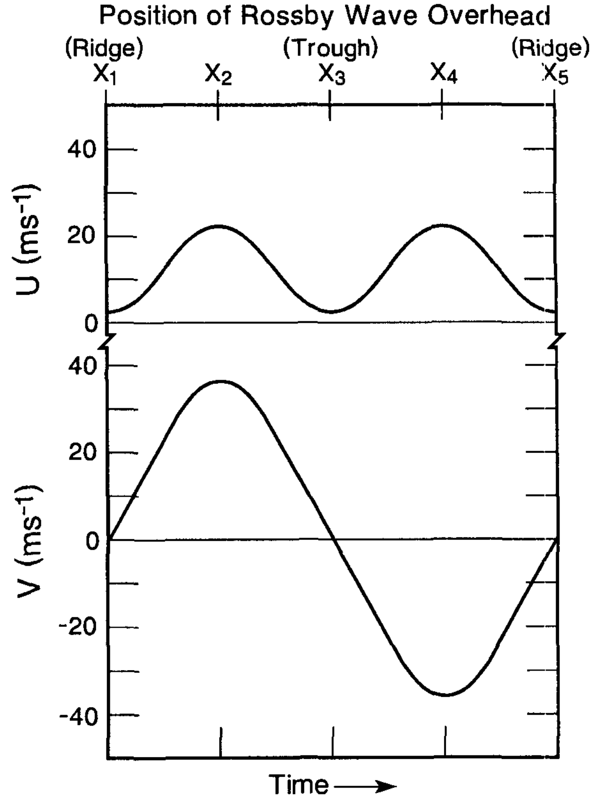

FIG. 7. Schematic plot of relative time series of *U* and *V* wind components that would be measured by the wind profiler, shown in Fig. 6, as the wave passes over it.

5. Conclusions

Five years of continuous measurements of horizontal winds in northeastern Colorado using a wind-profiling radar have provided detailed information on wind characteristics that was not available from previous means. Wind speed component spectra and variances computed from the profiler measurements of the middle troposphere have been analyzed. The variance data show that the interannual variation of wintertime winds is as large as the annual variations for winter. The 5-yr spectra for all seasons combined show most of the energy contained in atmospheric motions with periods between about 4 days and 2 weeks in addition to an annual peak. There is a marked spectral energy minimum at a period of about 4 months.

When the data are partitioned into winter and summer months, interesting differences in the spectral behavior are revealed. In summer, a convective circulation peak is apparent in the *U* and *V* component spectra at a period of 1 day, in addition to peaks at 7 and 24 days. The winter pattern shows spectral energy peaks for the *U* component at 2 and 8 days, while the *V* component has peaks at 4 and 16 days. The factor-of-2 difference in these periodicities is consistent with the different periodic nature of *U* and *V* wind components expected from migrating tropospheric waves over midlatitude locations.

REFERENCES

Balsey, B. B., and D. A. Carter, 1982: The spectrum of atmospheric velocity fluctuations at 8 and 86 kilometers. *Geophys. Res. Lett.*, **9,** 465–468.

Chiu, W.-C., 1960: The wind and temperature spectra of the upper troposphere and lower stratosphere over North America. *J. Meteor.*, **17,** 64–77.

Courtney, M., and I. Troen, 1990: Wind speed spectrum from one year of continuous 8 Hz measurements. Preprints, *9th Symp. on Turbulence and Diffusion,* Roskilde, Denmark, Amer. Meteor. Soc., 301–304.

Ecklund, W. L., K. S. Gage, G. D. Nastrum and B. B. Balsey, 1986: A preliminary climatology of the spectrum of vertical velocity observed by clear-air Doppler radar. *J. Climate Appl. Meteor.*, **25,** 885–892.

Frisch, A. S., B. L. Weber, R. G. Strauch, D. A. Merritt and K. P. Moran, 1986: The altitude coverage of the Colorado wind profilers at 50, 405 and 915 MHz. *J. Atmos. Oceanic Technol.*, **3,** 680–692.

Fritts, D. C., T. Tsuda, T. E. VanZandt, S. A. Smith, T. Sato, S. Fukao and S. Kato, 1990: Studies of velocity fluctuations in the lower atmosphere using the MU radar. Part II: Momentum fluxes and energy densities. *J. Atmos. Sci.*, **47,** 51–66.

Hoehne, W. E., 1980: Precision of National Weather Service upper air measurements. NOAA Tech. Memo T&ED-16, 12 pp.

Kolesnikova, V. N., and A. S. Monin, 1971: The spectra of micrometeorological, synoptic and climatic oscillations of meteorological fields. Meteorological Translation, No. 17, Canada Dept. of Environment, Atmospheric Environment Service, Downsview, Ontario, 33 pp.

Larsen, M. F., M. C. Kelley and K. S. Gage, 1982: Turbulence spectra in the upper troposphere and lower stratosphere at periods between 2 hours and 40 days. *J. Atmos. Sci.*, **39,** 1035–1041.

Nihoul, J. C. J., 1984: Interactive ocean–atmosphere models for forecasting. *Current Issues in Climate Research,* D. Reidel, 163–356.

Scheffler, A. O., and C. H. Liu, 1985: On observation of gravity wave spectra in the atmosphere by using MST radars. *Radio Sci.*, **20,** 1309–1322.

Strauch, R. G., D. A. Merritt, K. P. Moran, K. B. Earnshaw and D. Van de Kamp, 1984: The Colorado wind-profiling network. *J. Atmos. Oceanic Technol.*, **1,** 37–49.

Strauch, R. G., R. L. Weber, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran and D. C. Welsh, 1987: The precision and accuracy of profiler wind measurements. *J. Atmos. Oceanic Technol.*, **4,** 563–571.

Thomson, D. W., and H. W. Henderson, 1990: Attractor dimensions and statistical properties of surface and profiler-measured tropospheric winds. Preprints, *9th Symp. on Turbulence and Diffusion,* Roskilde, Denmark, Amer. Meteor. Soc., 220–223.

Van der Hoven, I., 1957: Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. *J. Meteor.*, **14,** 160–164.

VanZandt, T. E., G. D. Nastrom and J. L. Green, 1991: Frequency spectra of vertical velocity from the Flatland VHF radar data. *J. Geophys. Res.*, **96,** 2845–2855.

Vinnichenko, N. K., 1970: The kinetic energy spectrum in the free atmosphere—1 second to 5 years. *Tellus,* **22,** 158–166.