NOTES AND CORRESPONDENCE

Wind Variability Measured by Doppler Lidar*

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31 December 1987 and 1 June 1988

ABSTRACT

Wind power spectral density measured in the lower and middle troposphere under zonal flow conditions is consistent with a $-5/3$ slope to frequencies as high as 10^{-2} Hz. By conversion of frequency to a spatial coordinate it is found that a satellite-borne lidar when averaging such winds over a 300 km grid scale would measure the synoptic-scale wind with a 98% representativeness index.

1. Introduction

Future lidar technology may enable the measurement of the global wind field from satellites, a concept we call WINDSAT (Wind-measuring Satellite) (Huffaker et al. 1984). How often and at what spacings will such wind measurements be required? To answer this question we need to know how variable the wind is in the free atmosphere and then determine what constitutes a representative wind value.

Previous investigations of wind variability have used theodolite tracking of sequential pilot balloons (Singer 1956), radar tracking of sequential Jimspheres (Johnson and Vaughan 1978), sequential tracking of METRAC (Meteorological Tracking) balloons (Gage and Jasperson 1979), and both aircraft and radar wind profiler data analyses (Gage and Nastrom 1985). These latter analyses gave horizontal velocity spectra to periods as short as 10 min. With the NOAA pulsed, Doppler lidar we can measure a velocity profile (in principle) in a time period as short as 20 s. In this note, we report wind variability measured with the lidar over periods from 24 h to as short as 30 s. Since the lidar has a demonstrated wind measurement accuracy of better than 0.5 m s^{-1} when compared with tower anemometers for a single VAD (velocity-azimuth display) scan (Hall et al. 1984), and repeatability from one VAD to the next of better than 0.05 m s^{-1}, we have a unique tool for this investigation.

Our methodology was to operate the lidar in the VAD scan mode at different elevation angles and compare wind profiles so measured at different time intervals. Data were acquired under near-zonal flow conditions in the free atmosphere at Boulder, Colorado; White Sands Missile Range, New Mexico; Oshkosh, Wisconsin; and Monterey, California during the fall, winter, and spring seasons.

2. Results

An example of wind profiles measured 15 min apart is shown in Fig. 1. These measurements were made at White Sands Missile Range using a 30° elevation VAD. For clarity, only three profiles are shown although the series of measurements continued for 6 h. On this day the aerosol loading at heights greater than 6.2 km MSL was too low to provide a reliable wind measurement; the greater scatter of the data at higher altitude is indicative of this problem. Our VAD computer program calculates the signal-to-noise (S/N) ratio for each range gate; above 6.2 km the S/N was below 3 dB. More than 40% of the measurements failed our complex covariance algorithm test. This was our indication that these data were too noisy to measure winds to the desired 0.1 m s^{-1} accuracy required for this study.

Reliable wind profiles were computed for fifteen different experiments, each lasting from 6 to 24 h, on days when the flow was of a zonal nature and there were no mesoscale disturbances of the winds. The profiles were then entered into large spreadsheets. The average wind speed, the variance of the wind, and the standard deviation of the wind at each range gate, all at heights significantly above the planetary boundary layer, were calculated. Then the average variance for each profile (relative to the various means at each range gate) was computed.

The effective bandwidth, $[(1/\tau) - (1/T)]$, of the variance is determined by the length of the experiment, T, and the time lag, τ, of individual profile measure-

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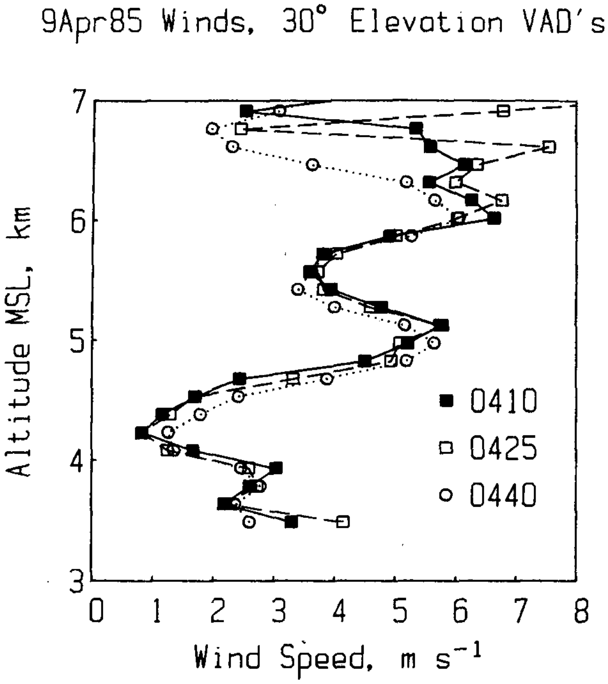

FIG. 1. Three sequential wind profiles measured at White Sands Missile Range: 0410, 0425, 0440 MST 9 April 1985. Measurements continued at 15 min intervals for an additional 6 h.

ments. For most of the experiments reported here, $T \gg \tau$. Figure 2 is a plot of the power spectral density in which the ordinate is the wind variance divided by the effective bandwidth of each observation, and the abscissa is the center frequency of the band, f, where:

$$f \equiv \tfrac{1}{2}[(1/\tau) + (1/T)].$$

The solid line (slope of -1.71) is the least squares, best fit; the error bars indicate the standard deviation of the wind power spectrum. The dashed line has a $-5/3$ (-1.67) slope. From the plot it appears that the $-5/3$ slope does describe rather well the wind fluctuations, even to frequencies as high as 10^{-2} Hz with no apparent spectral map near 10^{-3} Hz. This extends the similar conclusion of Gage and Nastrom (1985), who measured to frequencies of 10^{-3} Hz, about one order of magnitude in frequency. They obtained their spectra by the correct and traditional method of Fourier transforming a continuous time series of wind measurements. Note that each plotted point in Fig. 2 represents the average spectral density of the wind throughout the lower and middle troposphere (nominally from 2 to 7 km above the surface), from time series of 4 to 24 independent wind profile measurements and over individual height ranges of 100 to 260 m. For those daytime runs when the convective planetary boundary layer clearly extended more than 2 km above the surface, those PBL wind values were not used to calculate the wind variance. The laser fired several million times while gathering these data.

One explanation for the results of Fig. 2., which overlay rather well the spectrum of Gage and Nastrom (1979), probably lies in our approximation to modern digital techniques for sampling spectra, such as Bartlett's procedure for averaging periodograms (Oppenheim and Schafer 1975). In essence, our time-lagged sampling of averaged-together wind profiles produces a periodogram of from 80 to as many as 500 points. The spatial smoothing provided by the VAD scan used to measure each profile seems to provide an appropriate, stable sequence of spectrum windows for sampling.

Ellsaesser (1969) has shown that assuming the similarity theory of turbulence and the frozen turbulence hypothesis hold, a consequence is that the standard deviation of wind speed, σ_u, varies directly as the 1/3 power of the lag period, τ, between measurements. Figure 3 is such a plot for our data where τ is the time lag between wind measurements; each datum is the

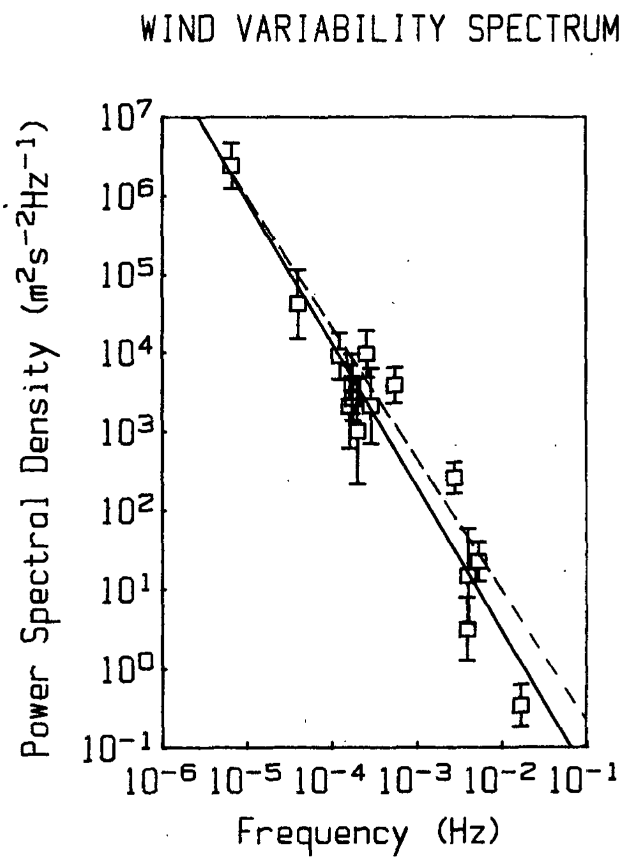

FIG. 2. Zonal wind power spectral density plotted versus frequency for all of the data analyzed during this investigation. The solid straight line is the regression or best fit for the data. The dashed line has a $-5/3$ slope. Error bars show the standard deviation for each data point; each point represents from 80 to 500 independent VAD wind measurements.

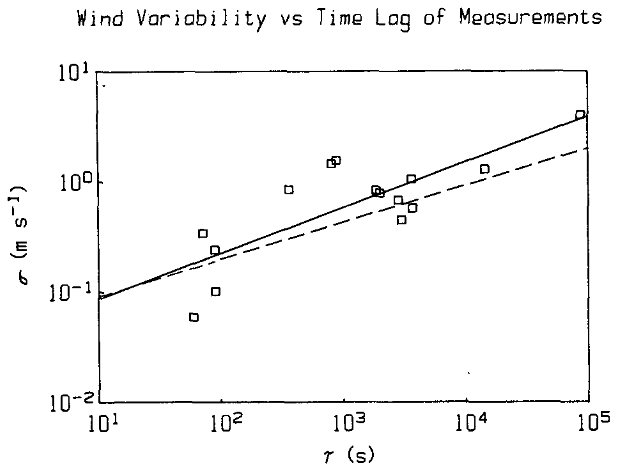

FIG. 3. Wind variability, the standard deviation of the zonal wind in the free atmosphere, plotted versus the time lag between the measurements. Sequences of from 4 lags to as many as 24 are plotted. The solid line is the least squares, best fit for the data. The dashed line has a slope of 1/3.

standard deviation of the (more or less) zonal wind speed averaged throughout the lower to middle troposphere where the lidar signal-to-noise provided reliable winds. The solid line (slope of 0.42) is the least squares best fit to the data. The dashed line has a slope of 1/3, and this line is consistent with the data (although a slope of 1/2 would fit the data just as well). Figure 3 is just another way of interpreting Fig. 2. As pointed out by one of the reviewers, if $T \gg \tau$ always, then a $-5/3$ slope in Fig. 2 requires a 1/3 slope in Fig. 3. Since a few of the data runs had $T = 8\tau$, these relatively shorter data sets may have led to the steeper slope than expected in Fig. 3. The σ_u values were nearly constant with height in the free atmosphere measurable by the lidar, in agreement with the results of Pinus (1968).

If a WINDSAT lidar, designed primarily to measure the synoptic wind field, measures the mean u and v components of the wind in a smaller box with dimensions x, y, z, how well does the measurement describe the mesoscale flow characteristics of the atmosphere for input to circulation models? A Representativeness Index (RI) may be defined as (Korrell 1980),

$$\mathrm{RI}(\%) = \left(1 - \frac{\text{wind variance at scales} \leqslant x \text{ km}}{\text{wind variance at scales} < 2000 \text{ km}}\right) \times 100\%.$$

This provides a relative measure of how well the mean winds measured on a grid scale of x km represent the mesoscale flow within the larger box with dimensions 2000 km × 2000 km. Here the maximum dimensions describe the upper limit of mesoscale-α as defined by Orlanski (1975), or essentially at the synoptic scale.

During the experiments reported here the average zonal winds were about 10 m s^{-1}. The variance over 2000 km for this mean speed was 4.0 m^2 s^{-2}; if we choose a grid scale of 300 km, as we used in our earlier WINDSAT analysis (Huffaker et al. 1984), we find that the variance at this scale is 0.07 m^2 s^{-2}, so the RI is 98% for these zonal wind conditions. A few of our measurements (but not plotted in Fig. 2) were made when there were jets overhead or during trough passages. For these conditions the wind variance at 10^{-3} Hz was ten times greater than for the unperturbed, zonal flow cases. For such conditions the RI is lower, about 83%. The apparent lack of a spectral gap implies that if a WINDSAT lidar measured the winds at higher spatial resolution than 300 km, it may be possible to obtain representative winds even at the mesoscale-β.

3. Conclusions

We have found that the $-5/3$ wind power spectral density slope in the free atmosphere, under approximately zonal flow conditions, extends to frequencies of 10^{-2} Hz. The wind spectral density values in Fig. 2 near 10^{-3} Hz do lie somewhat above the best fit line, but by less than one order of magnitude. This may represent a slight mesoscale spectral gap (Fiedler and Panofsky, 1970) at a frequency near 3×10^{-3} Hz (or about 1 per hour) under these conditions. The few observations that we had under disturbed conditions indicate that such a gap may then be more prominent. Such a gap is more apparent if a plot of the spectral density, $S(f)$, multiplied by frequency, f, is used.

The "well behaved" wind power spectrum of Fig. 2 indicates that representative synoptic scale zonal winds (RI = 98%) are measurable by a WINDSAT system that averages a number of independent measurements taken in a 300 km × 300 km box or "patch."

Acknowledgments. R. E. Cupp, R. M. Hardesty, J. K. Holler, J. M. Intrieri, R. A. Richter, and S. E. Troxel contributed many long stints at odd hours with the author while gathering the data. Computer programming was provided by T. S. Balzer, K. R. Healy, and B. F. Weber. Discussions with J. C. Kaimal were most helpful while working on this note. Partial support for the measurements came from the U.S. Air Force, Army, and Navy, and from NASA.

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