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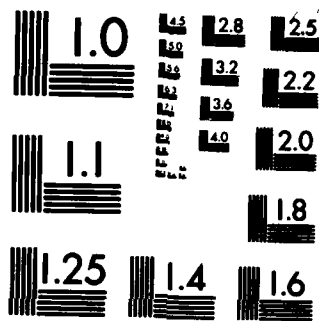
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FINAL REPORT

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- 2. PRINCIPAL INVESTIGATORS: Dr. Gerald J. Romick
Dr. Kolf Jayaweera
Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701
- 3. INCLUSIVE DATES: October 1, 1980 - September 30, 1982
- 4. GRANT #: AFOSR-80-0286
- 5. JUNIOR RESEARCH PERSONNEL:
Steven A. Smith

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ABSTRACT

Wind speed and C_n^2 measurements made with the Poker Flat, Alaska MST radar are used to study the development of clear air turbulence (CAT) near the tropopause. Arguments and observations that indicate C_n^2 is proportional to the intensity of turbulence are presented. The relationship between wind shear and turbulence is examined using time-lagged cross correlations of measured shears and C_n^2 time series. From analysis of data taken with spatial resolutions of 2200 m and 750 m, it is found that the correlation improves as the time and spatial resolutions of the measurements improve. The implications for forecasting CAT are discussed, based on the correlation results and a comparison of radar data with National Weather Service CAT forecasts.

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INTRODUCTION

Continuous monitoring of turbulence throughout the troposphere and lower stratosphere is possible with Mesosphere-Stratosphere-Troposphere (MST) radars. These radars employ high peak powers and large antenna areas to measure the backscattered power from weak spatial irregularities in the atmospheric radio refractive index. An estimate of wind velocity can be obtained by measuring the Doppler shift of the radar signal, which is produced by the motion of the irregularities with the background wind. James (1980) gives a brief history of the development and outlines the capabilities of these high power, clear air radars. The work presented here has used radar measured wind speeds and shears along with estimates of turbulence intensity derived from radar signal strengths to study the relationship of wind shears to clear air turbulence (CAT).

Several studies have shown that radar measurements can be used to infer the intensity of CAT. Radar measurements of C_n^2 , the radio refractivity turbulence structure constant, were used by Crane (1970) to identify regions of CAT. Crane reported that turbulent layers with values of C_n^2 greater than the detection threshold of the Millstone Hill L-band radar were nearly always located in close proximity to regions that a U-2 had found to be turbulent. Estimates of ϵ , the eddy dissipation rate which is a measure of turbulent kinetic energy density, were computed by Kropfli (1971) from Wallops Island radar measurements of C_n^2 and radiosonde measurements of wind shear. Kropfli then compared the radar ϵ with ϵ calculated from the velocity fluctuations recorded by a hot-wire anemometer flown through the radar beam and found the two rates to be of the same order of magnitude.

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MATTHEW J. KERPER

Chief, Technical Information Division

for the four flights that were analyzed. Green et al. (1978) compared C_n^2 derived estimates with pilot reports of CAT from a plane flying in the vicinity of the Sunset (Colorado) radar and found good correspondence between the two. Smith (1982) found a threshold for C_n^2 , near the tropopause, equivalent to moderate CAT by comparing C_n^2 estimates from the Poker Flat (Alaska) MST with several nearby pilot reports of turbulence. It was then shown that C_n^2 exceeded the threshold at sometime during each National Weather Service forecast of moderate or greater CAT issued over a six month study period. Thus, C_n^2 measurements are closely related to the intensity of CAT.

MST radars not only provide turbulence intensity estimates, but also obtain measurements of wind velocities which can be used to study the development of CAT. The height profiles of wind velocity can yield the continuous time history of wind shears, the mechanism responsible for producing turbulence. Green et al. (1979) and Gage et al. (1980) have presented time-height cross sections of turbulence intensity estimates and wind speed showing good correlation between turbulence intensity peaks and regions of strong wind shear and low Richardson number. However, Nastrom et al. (1981b) correlated wind speeds and shears with C_n^2 and found the best correlation between wind speed and C_n^2 , with weaker and much more variable correlations between shears and C_n^2 . The study of shear induced turbulence is continued in this paper through use of velocity and C_n^2 measurements made with the Poker Flat MST radar.

The data used in this study is described in section 2, and the relation between C_n^2 and turbulence intensity is presented. Section 3 presents the cross correlations obtained from the wind speed, shear and C_n^2 time series. Section 4 discusses the biasing of the relationship between shears

and turbulence by the time and spatial resolutions used in making the measurements.

Correlations between shear and C_n^2 were found to increase as the time and height resolution of the data improved. The implications of this finding are that the shears producing turbulence near the tropopause are smaller than a kilometer and have lifetimes on the order of minutes. The best correlation between wind shear and turbulence was found when a region of shear associated with a weak jet stream descended from the stratosphere to the less stable troposphere.

System and Experiment Description

The antenna of the Poker Flat 50 MHz MST radar (Balsley et al., 1980) consists of two coplanar, orthogonal, dipole antenna arrays covering a square 200 m on a side. Three-fourths of each orthogonal array is phased to produce a narrow beam directed obliquely, 15° off the zenith. The two beams are pointed eastward (64°E) and northward (334°E), 90° apart in azimuth. The fourth quarter is phased to look vertically and was not used in the studies presented here. The antenna system is divided into quarters of 100 m on a side and each quarter has 8 transmitters per beam. The power output by each transmitter was nominally 50 kW peak.

This study uses data obtained from two separate radar experiments. The primary data set used in this study covers the period from September 1980 through March 1981 when the radar was operating continuously with only one quarter of the final system. The two orthogonal arrays in that quarter were in oblique operation with approximately 400 kW per beam, with each beam having a two-way beam width of 2.2° .

Measurements of average radial wind speed and signal strength were made over volumes spaced 2.2 km apart. A 2.2 km height resolution profile was obtained approximately every three minutes. Contaminants, such as airplanes in the beam, power outages, etc., caused rejection of some profiles and left small, irregularly spaced gaps in the time series. To minimize the effect of those gaps, a 16 minute running average was applied to the data. This procedure yielded a series of profiles of wind velocity and signal strength evenly spaced at eight minute intervals.

A second data set, covering a 13 hour period, was obtained at higher spatial resolution with three quarters of the final system in operation in February 1982. Three of the quarters were in oblique operation with 1.2 Mw in a single 1.1° beam. Data acquisition hardware limited the February experiment to the operation of a single beam (Carter et al., 1980) and the eastward directed beam was chosen.

Profiles with a height resolution of 750 m were obtained every 25 seconds during this experiment. Visual inspection of the data revealed a thirteen hour period during which there was no obvious contamination of the data by airplanes or other interference. A simple 5 point smoothing filter was applied to the uncontaminated data and a portion of the data set is shown in Figure 1.

For all of the data, the measured Doppler shift, due to the projection of the motion of the refractive irregularities in the direction of the radar beam, were converted to horizontal wind speeds by assuming zero vertical motion. This zero vertical wind assumption becomes more valid as the averaging time increases and may be invalid for the high resolution data set. Since no independent measurements were made of the vertical motion during the high resolution experiment, it is not possible to accurately

remove the vertical wind component from the data. However, vertical wind speeds are usually smaller by a factor of 10 to 100 than horizontal wind speeds and therefore the measured radial speed is mainly due to the horizontal motion of the atmosphere.

The measured signal strengths were converted to estimates of C_n^2 , the radio refractivity turbulence structure constant, using the method of Nastrom et al., (1981a). The resultant estimates of C_n^2 can be used to infer turbulence intensity at scale sizes corresponding to half the radar wavelength (Tatarski, 1971), which is 3 m for the Poker Flat radar. The signal strengths are obtained from the Doppler power spectra using algorithms described in Clark and Carter (1980). The relevant quantity used in the C_n^2 calculation is the signal-to-noise ratio (S/N) from each height in each beam. By scaling the S/N to the estimated cosmic noise power that is received by the radar the actual power returned to the radar was obtained. (See also Van Zandt et al., 1978 and Green et al., 1979). The formula used for this conversion was

$$C_n^2 = \frac{64}{.38 \pi} \frac{\lambda^{1/3}}{A_e \alpha^2} \frac{r^2}{\Delta r} \frac{1}{P_t} \frac{S}{N} \frac{N}{\text{min noise}} \frac{2.5 \times (10^{-15}) \text{ watts}}{NCI}$$

where, for the Poker Flat radar,

$\lambda = 6 \text{ m}$

$\alpha = \text{system efficiency} \sim .63$

$A_e = \text{effective antenna area} = (10^4 \text{ or } 3(10^4)\text{m}^2) \times \cos 15^\circ$

$r = \text{radial distance to radar sample volume}$

$\Delta r = \text{height of sample volume}$

$P_t = \text{transmitted power}$

$\text{min noise} = \text{is the minimum spectral noise level recorded during a sidereal day}$

NCI = number of coherent integrations per spectra (affects the spectral bandwidth and thus the magnitude of the noise level)

2.5 (10⁻¹⁵) watts = estimated minimum cosmic plus system noise power.

C_n^2 , which is a measure of the mean square deviation of the radio refractive index over a unit distance, can be related to the energy of inertial subrange turbulence by the following simplified arguments (Ottersten, 1972 and Gage et al., 1980). The inertial subrange refers to the portion of the turbulence energy spectrum covering fluctuation scale sizes of tens of meters down to millimeters over which ϵ is constant and proportional to the turbulent energy density. ϵ is the rate at which energy transfers from one scale size to the next smaller scale size, or cascades, through the inertial subrange.

The radio refractive index has been empirically determined to be a function of pressure, temperature and water vapor pressure in the atmosphere below 50 kms (Bean and Dutton, 1966). Above 50 km electron density becomes a dominant factor in the refractive index (Balsley and Gage, 1980). Water vapor pressure is usually unmeasurable by radiosondes above about 7 km over Fairbanks, Alaska. This means that above 7 km and below 50 km changes in the refractive index (equivalently, changes in C_n^2) are due to changes in the ratio of pressure to temperature or changes in density.

Arguing that the wind shears produce refractive index (density) fluctuations at the same rate that they produce turbulence, Ottersten (1969) showed that C_n^2 was proportional to $\epsilon^{2/3}$ and inversely proportional to the strength of the wind shears. Gage et al., (1980) produced a simplified relationship between C_n^2 and ϵ by using the turbulence model of Van Zandt et al. (1978) to determine the statistical distribution of wind shear layers capable of producing turbulence. Gage et al.'s result is

$$\epsilon = A (T/P)^3 (C_n^2)^{3/2}$$

where T is temperature in °K, P is pressure in millibars and A is a constant with the value of 1.1×10^{22} in the troposphere and 3.4×10^{21} in the stratosphere. The factor of 4 change in A is due to the difference in stability between the stratosphere and troposphere. Gage et al. (1980) further state that climatological values of T and P may be used without introducing much error in an estimate of ϵ .

Finally, in the inertial subrange, ϵ is constant and related to turbulent energy density by a 2/3 power law relationship. The scale size of the fluctuations that are felt as CAT are larger (on the order of hundreds of meters and greater) than scale sizes in the inertial subrange. However, all of the energy cascading through the inertial subrange has come from scale sizes larger than the largest size in the subrange so it is reasonable to assume that an increase in ϵ and a corresponding increase in energy density in the inertial subrange follows from an increase in the turbulent energy at larger scale sizes. Since a measurement of C_n^2 can yield an estimate of ϵ which in turn is related to turbulent energy density, it is possible to use a time sequence of C_n^2 measurements to infer the temporal behavior of the intensity of clear air turbulence.

Analysis

The availability of continuous measurements of the horizontal wind velocity and estimates of turbulence intensity from the Poker Flat MST radar made it possible to study the development of turbulence in relationship to wind shears over depths on the order of the radar height resolution. Only measurements obtained between the altitudes of 7 and 15 km were used here. Below 7 km, ground clutter and water vapor fluctuations made it difficult to

obtain accurate C_n^2 estimates. Above 15 km, the signal to noise ratio is usually very small and useful data could only be obtained by averaging over longer periods than were used in this study. The increase in power and antenna area prior to the February 1982 experiment made it possible to receive strong signals up to an altitude of about 20 km and data from those heights was incorporated in the analysis of that experiment. The method used to examine the relationship between shears and turbulence has been to compute time-lagged cross correlation coefficients using various length time series of wind speed, wind shear and C_n^2 measurements. The results indicate that there exists a good correlation between C_n^2 and wind speed over long periods of time but that the correlation between C_n^2 and wind shear is strongest only for hour long periods. The correlation peaks for C_n^2 lagging wind shear by about 10 minutes.

Time-lagged cross correlations were computed using the wind speed, wind shear and C_n^2 time series that had been smoothed by a 16 minute running average. Initially, data taken during the passage of a strong (speeds greater than 50 m/s) jet stream over the radar was examined. With this data, cross correlation coefficients greater than 0.6 were found for wind speed and C_n^2 at zero lag and for shear leading C_n^2 with a lag of two hours. Again, it appeared that the development of C_n^2 was directly connected to changes in wind speed but now it seemed that shears measured at one point affected turbulence that passed over the radar hours later with a spatial separation of hundreds of kilometers between the correlated shear and C_n^2 regions. In order to verify this long range behavior, cross correlations for 10 other jet stream passages were computed and then averaged together to improve the confidence levels of the correlations.

Periods for analysis were selected by requiring the wind speed to increase to greater than 35 m/s, corresponding to the passage of the leading edge of a jet stream over the radar. These periods were selected because the large scale shears associated with jet streams could be resolved using the coarse resolution of the Poker Flat MST radar. Only periods during which the wind speed was increasing were chosen in order to study the onset of clear air turbulence in hopes of predicting the occurrence of turbulence.

After computing time-lagged cross correlation coefficients for the selected events, the coefficients from each event were averaged together with respect to height above the ground. That is, all correlations between wind speed and C_n^2 in the 2.2 km volume centered at 8.2 km were averaged together, as were those at 10.3 km, etc. The resultant averages showed there was no significant correlation between wind speed and C_n^2 or between wind shear and C_n^2 at any height. The good correlations previously obtained (Nastrom et al., 1981b) and the expected relationship between turbulence and jet stream shears made this null result difficult to explain.

Since shears are greatest above and below the jet stream core and numerous aircraft probings of jet streams have shown that turbulence is most intense above and below the core (Ludlam, 1980 and Vinnichenko et al., 1981), the averaging of coefficients was next done with respect to the level of the maximum wind independent of the altitude of the maximum wind. (Approximately half of the events used in the average had the maximum located in the sample volume centered at 8.2 km and the maximum wind was in the 10.3 km volume for the other half.) This procedure did yield significant correlations of wind speed and shear with C_n^2 as will be shown below.

The average time-lagged cross correlations of wind speed and C_n^2 at the level of the maximum wind, the level 2.2 km above the maximum and the level 4.4 km above the maximum is shown in Figure 2. It can be seen that fluctuations in C_n^2 are independent of wind speed fluctuations in the 2 km height range containing the maximum wind. This cannot be construed to mean that the jet stream core is smooth because the C_n^2 magnitude at the maximum wind level was in the same range as the C_n^2 estimates above and below that altitude and all the values of C_n^2 were elevated above the values recorded on calm days. One possible explanation of the zero correlation is that the turbulence at the maximum wind level was not generated locally but was advected to that level from regions above or below the maximum. Testing of this hypothesis must await an increase in the height resolution of the radar in order to determine the source of the turbulence appearing at the maximum wind level.

Correlations at heights 2.2 and 4.4 km above the maximum wind are very similar with a peak correlation between wind speed and C_n^2 of about 0.4 occurring at zero lag. These correlations are based on 1-2 days worth of data that had been smoothed with a 16 minute running average. No correlations were obtained below the jet stream core because only data at or above the 8.2 km sample volume were used in this study.

Figure 3 presents the results of the correlation of shear with C_n^2 . The lower curve is the correlation of the wind shear determined between the level of the maximum wind and the region 2.2 km above the maximum wind with the average of the C_n^2 values from both regions. Again, little or no correlation is seen. The measured shears over that region were often weak which could possibly be an artifact of the coarse height resolution. The radar measures the average wind speed over a 2.2 km high region and therefore,

smooths the wind speed profile and underestimates both wind speed and shears. Thus, the null correlation in this height range may be due to an underestimate of the wind shears above the jet core that are producing turbulence.

The upper curve of Figure 3 is the correlation of the shear between the volumes 2.2 and 4.4 km above the maximum wind level with the average C_n^2 value from both heights. For this region, there is a significant correlation of about 0.4 near zero lag. It can be seen that the peak of the shear correlation is not as good as the speed and C_n^2 correlation peaks (curves 2 and 3 of Figure 2). The exact positions of the peaks in Figures 2 and 3 cannot be determined from the curves because the data smoothing has introduced an uncertainty in the time axis of 30 minutes and there exists an uncertainty in the correlations of ± 0.06 (95% confidence level).

This statistical analysis indicates that a relationship exists between wind speed and C_n^2 such that an increase in speed is often accompanied by an increase in C_n^2 , while an increase in wind shear 2-4 km above the maximum wind is often associated with an increase in C_n^2 .

More evidence for the shear and C_n^2 relation was obtained from the high resolution experiment run on February 28, 1982. Again, time-lagged cross correlations were computed with the time series from each height and for each hour analyzed independently.

Potential temperature profiles, calculated from data obtained by National Weather Service (NWS) radiosondes launched from Fairbanks International Airport 50 km south of the radar, are shown in Figure 4. As can be seen, the height of the tropopause, determined by the NWS, slowly rose about 1.5 km in elevation in 24 hours corresponding to the movement of a jet stream southward over Fairbanks. Before 00 UT 1 March, the maximum wind was less than 30 m/s and thus did not meet the criteria for a maximum

wind level to be reported on radiosonde data transmissions by the NWS. However, from the radar data the level of the maximum wind descended, over the same period, as well as increased in strength to greater than 30 m/s.

The Poker Flat MST radar was running from 0300 UT until 1700 UT on February 28 in a high spatial and temporal resolution mode. A profile with 750 m range resolution was recorded every 25 seconds. The radar was under construction at that time and the hardware constraints were such that the high resolution data could only be obtained from a single beam. Wind speed and signal strength measurements were obtained from the beam directed 15° off zenith and 64° east of north. Figure 5 is a time sequence of the 64°E wind component profiles obtained by averaging the radar data for the hour beginning at the times shown. The descent and strengthening of the maximum wind can be clearly seen in this figure.

Correlations of speed and shear with C_n^2 were computed for each hour and each 750 m interval between 7 and 20 km. Smoothing of the wind shear data was accomplished by computing shears from the wind speeds immediately above and below the radar sample volume from which the corresponding C_n^2 data was obtained. The correlations between wind speed and C_n^2 were not significantly different from zero, in general, indicating that fluctuations in C_n^2 or turbulence intensity were independent of wind speed fluctuations over one hour periods. However, a correlation coefficient of .76 (95% confidence limits of $\pm .16$) was found for wind shear leading C_n^2 by 10 minutes during the 1400-1500 UT period at a height of 9 km (see the relationship between shear and C_n^2 in Figure 1). As can be seen from Figure 5, this was near the time at which the maximum wind descended below the tropopause. Part of the observed 10 minute delay between shear and C_n^2 is due to the time necessary for the turbulence to cascade from the production scale sizes down

to the 3 m scale size at which the Poker Flat radar samples the turbulence. A precise determination of this propagation delay would require simultaneously sampling the atmosphere at a scale size other than 3 m.

In an attempt to verify the long period speed - C_n^2 correlations found previously, wind shear and speed were correlated with C_n^2 over the whole 13 hour period. Wind speed and C_n^2 were again significantly correlated at several heights and weaker shear - C_n^2 correlations were observed. Using this longer time series did produce a significant negative correlation between wind speed and C_n^2 at a height of 8.3 km. This height is the location of the maximum wind after 1400 UT. Thus, over the 13 hours that the wind speed at 8.3 km was increasing the magnitude of C_n^2 was decreasing and was 5 dB less than C_n^2 at heights 1-2 km above and below 8 km by 1700 UT. In this instance, the jet stream core was less turbulent than the surrounding atmosphere.

DISCUSSION

This paper deals with two aspects of the development of clear air turbulence which can be inferred from radar measurements of C_n^2 . One is that strong wind speeds are associated with large values of C_n^2 and the other is the widely variable correlation between wind shear (the usual mechanism for turbulence production) and C_n^2 .

Correlations computed using long-term (day to month long) time sequences of wind and C_n^2 measurements made by the Poker Flat MST radar have shown that wind speed and C_n^2 are better correlated than wind shear and C_n^2 .

Nastrom, Balsley and Gage (1981b) found a strong correlation between wind speed and C_n^2 but no consistent relation between wind shear and C_n^2 . They studied three, approximately month long, periods of data obtained during the 1980-1981 winter. Each point in their time series was an average

of three hours of wind speed and C_n^2 measurements. They found wind speed - C_n^2 correlation coefficients of .82, .59 and .86 (95% confidence limits of about $\pm .2$) at zero lag but the wind shear - C_n^2 coefficients were .63, -.43 and .64. Nastrom et al. also showed that C_n^2 at different altitudes correlated best with wind speed at the height of jet streams present during the study period. From these correlations they concluded that the speed of the jet stream influences the level of turbulence, possibly through vertically propagating gravity waves or by the presence of intense baroclinic regions associated with jet streams. The poor correlations between shear and C_n^2 were said to be due to the coarse (2.2 km) resolution of the radar which prevented meaningful computation of the magnitude of the wind shear. However, experiments and theory have shown that shears are required to convert the energy of motion of a fluid into turbulent energy so a better correlation between shear and C_n^2 would be expected. Good correlation can be found between wind shear and C_n^2 by performing time-lagged cross correlations (which show shear leading C_n^2) and by using short periods of data (on the order of an hour). Examination of a 13 hour period of high time and spatial resolution radar data revealed only one instance of wind shear and C_n^2 correlation. This happened near the time that the maximum wind descended from the stratosphere to the less stable troposphere.

The wind speed - C_n^2 correlations, that show turbulence is associated with jet streams, can be explained by saying that associated with high wind speeds are large wind shears and since turbulence is associated with wind shears, high turbulence is associated with high wind speeds. The fact that Nastrom et al. (1981b) see less correlation between shear and C_n^2 could possibly be due to the elimination of the strong, but short-lived

wind shears by the radar's 2.2 km spatial averaging and also by the three hour long time averages that were used in their work.

In the work reported here, correlations of approximately equal magnitude were found for wind speed and wind shear with C_n^2 using 16 minute time averages and 2.2 km spatial averages. These correlations were found in regions above the level of the maximum wind and not at the level of the maximum wind for periods in which wind speed increased as a jet stream passed over the radar. Thus, by using higher time resolution data sequences and using the height of the maximum wind as a reference level, statistically significant correlations of wind shear and C_n^2 were obtained.

The statistical significance of these correlations was improved over the correlation for a single observation by averaging correlations from several jet stream passages. The correlation was nearly zero when the averages were computed with respect to height above the ground, but were non-zero when done with respect to the level of the maximum wind regardless of altitude above the surface. Obviously, the level of the maximum wind fluctuates by more than 2 km from jet stream to jet stream, but the region in which shear-induced turbulence (as observed with a 2 km spatial resolution) is found seems to have a more nearly constant position with respect to the maximum wind level. This agrees well with aircraft observations of turbulence near jet streams (Ludlam, 1980 and Vinnichenko et al., 1981) which have produced cross-sections of jet streams with the regions of most frequent and most intense turbulence located 1-2 km above and below the jet core (level of maximum wind, which is known only to within 2.2 km using the Poker Flat data).

The largest correlation between wind shear and C_n^2 was found using the highest time and spatial resolution data available from the Poker Flat MST

radar. That correlation suggests that an increase in wind shear leads C_n^2 by about 10 minutes. This correlation was found only in the radar sample volume between the level of the maximum wind and the tropopause and only during the hour after the maximum wind had descended below the tropopause.

During that hour the eddy dissipation rate, ϵ , attained a spatial average (over the 750 m layer sampled) value of about $5 \times 10^{-4} \text{ m}^2 \text{ sec}^{-3}$ (using Gage et al.'s (1980) formula) or a turbulence intensity of less than light (Trout and Panofsky, 1969). A C_n^2 magnitude of $1 \times 10^{-17} \text{ m}^{-2/3}$ over a 2.2 km layer has been associated with moderate CAT on the basis of six pilot reports of CAT in the vicinity of Poker Flat (Smith, 1982). Using the previously mentioned formula of Gage et al. (1980) and the turbulence intensity - eddy dissipation rate categories of Trout and Panofsky (1969), Smith concluded that approximately 0.03 of the 2.2 km high radar sample volume was turbulent. This agrees well with the 0.1 factor found by Van Zandt et al. (1978) and the range of 0.01 to 0.1 of a 1 km high volume found by Gage et al. (1980) to be turbulent. Assuming that 0.03 of a 2.2 km high volume is turbulent implies that approximately 1/10th of a 750 m high volume is turbulent. If only 1/10th of the sampled volume can produce a value of ϵ of $5 \times 10^{-4} \text{ m}^2 \text{ sec}^{-3}$ then over the portion of the volume that is turbulent the eddy dissipation rate is $50 \times 10^{-4} \text{ m}^2 \text{ sec}^{-3}$ which corresponds to light turbulence (Trout and Panofsky, 1969). In this one instance, it may have been possible to predict an increase in C_n^2 and the presence of light turbulence based on examination of the shear time series.

The implication of the correlations of these three different time series is that the wind shears that lead directly to turbulence can be resolved only with short time and spatial sampling intervals. The observed correlations between shears are strongest at lags of about 10 minutes and

only over short time periods (order of an hour) and the shears are probably averaged out over long periods of weeks.

Stronger correlations are observed between wind shear and C_n^2 when higher spatial resolution is used. The measured shears were less than the shear needed to produce a Richardson number of 1/4 by about a factor of 4. Thus, it is unlikely that the observed shears were directly responsible for increases in C_n^2 . Possibly, the thin (10's of meters) shear layers in which intense turbulence is found (Woodman, 1980; Crane, 1980) appear in direct proportion to the shear that is measured over kilometer scales, but the direct link between shears and C_n^2 can only be studied by sampling the atmosphere with resolution equal to the thin layers in which turbulence is generated.

The Fairbanks office of the National Weather Service forecasts clear air turbulence to be in the region between the tropopause and the level of maximum wind when that level is below the tropopause and the Richardson number is about 1. The Poker Flat data examined to date has supported the forecasts (Smith, 1982) in that regions with C_n^2 values greater than a value corresponding to moderate CAT were always found in the forecast area for some time during the forecast. The high resolution data discussed above also places the most intense turbulence between the maximum wind and the tropopause. However, this assumes a constant or gradually increasing altitude for the tropopause which is probably not correct for a maximum wind traversing the tropopause. It should be possible in the future to more accurately locate the tropopause with a vertically pointed radar beam and the technique of Gage and Green (1981). The stability information provided by that technique would greatly improve the study of turbulence development and the source of the turbulence by allowing more

accurate calculation of Richardson numbers, and revealing the changes in stability associated with the descent of the maximum wind. With such data, the NWS forecasts could locate the possible CAT regions more precisely in time and altitude.

The potential of an MST radar, with just 750 m resolution, for aiding in forecasts of CAT by locating regions of high C_n^2 and enabling one to watch the development of wind shears can be seen in the discussion of the February experiment.

CONCLUSIONS

Evidence for a long term, direct relationship between wind speed and turbulence near the tropopause has been presented. However, laboratory experiments and theory imply the direct relationship should be more evident between wind shears and turbulence. Correlations of wind speed and shear with a turbulence parameter, C_n^2 , were presented for three different time resolution data sequences and two different spatial resolutions. The correlations between wind shear and C_n^2 improve as the resolution improves while the wind speed and C_n^2 correlations become weaker. Thus, to accurately study the development of turbulence, high resolution is required, while, low resolution is adequate to infer average turbulence conditions and determine a threshold for the development of clear air turbulence.

With a height resolution of 750 m, it was possible to observe the development of CAT as a region of wind shear above a weak jet stream core descended below the tropopause. This observation lends support to the Fairbanks NWS CAT forecast model which indicates CAT occurs most often between the tropopause and the maximum wind level, when that level is below the tropopause. It was also possible to identify the jet stream core as being less turbulent than the regions immediately above and below the core.

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FIGURE CAPTIONS

- Figure 1. 3 hour segments of the eastward (64°E) wind component, C_n^2 and the eastward shear component at an altitude of 9 km from the February 28, 1982, radar experiment. The spatial resolution was 750 m and the time resolution was 23 s. A 5 pt. smoothing function has been applied to the data.
- Figure 2. Time-lagged cross correlations of wind speed with C_n^2 averaged with respect to the level of the maximum wind. The correlations are at 1) the level of the maximum wind, 2) 2.2 km above the maximum wind, 3) 4.4 km above the maximum. Positive lags correspond to speed leading C_n^2 . Error bar gives 95% confidence limits.
- Figure 3. Cross correlations of wind shear between the altitudes 1) of the maximum wind and 2.2 km above the maximum and 2) 2.2 km and 4.4 km above the maximum wind with an average C_n^2 from both of the respective altitudes. Error bar gives 95% confidence limits.
- Figure 4. Potential temperature profiles calculated from NWS radiosondes launched from Fairbanks, Alaska covering the period of the February 28, 1982 experiment.
- Figure 5. Hour average profiles of the component of the horizontal wind in the 64°E direction sampled by the Poker Flat MST radar. Time in UT is at the top of each profile. The wind was mainly directed south westward during the experiment.

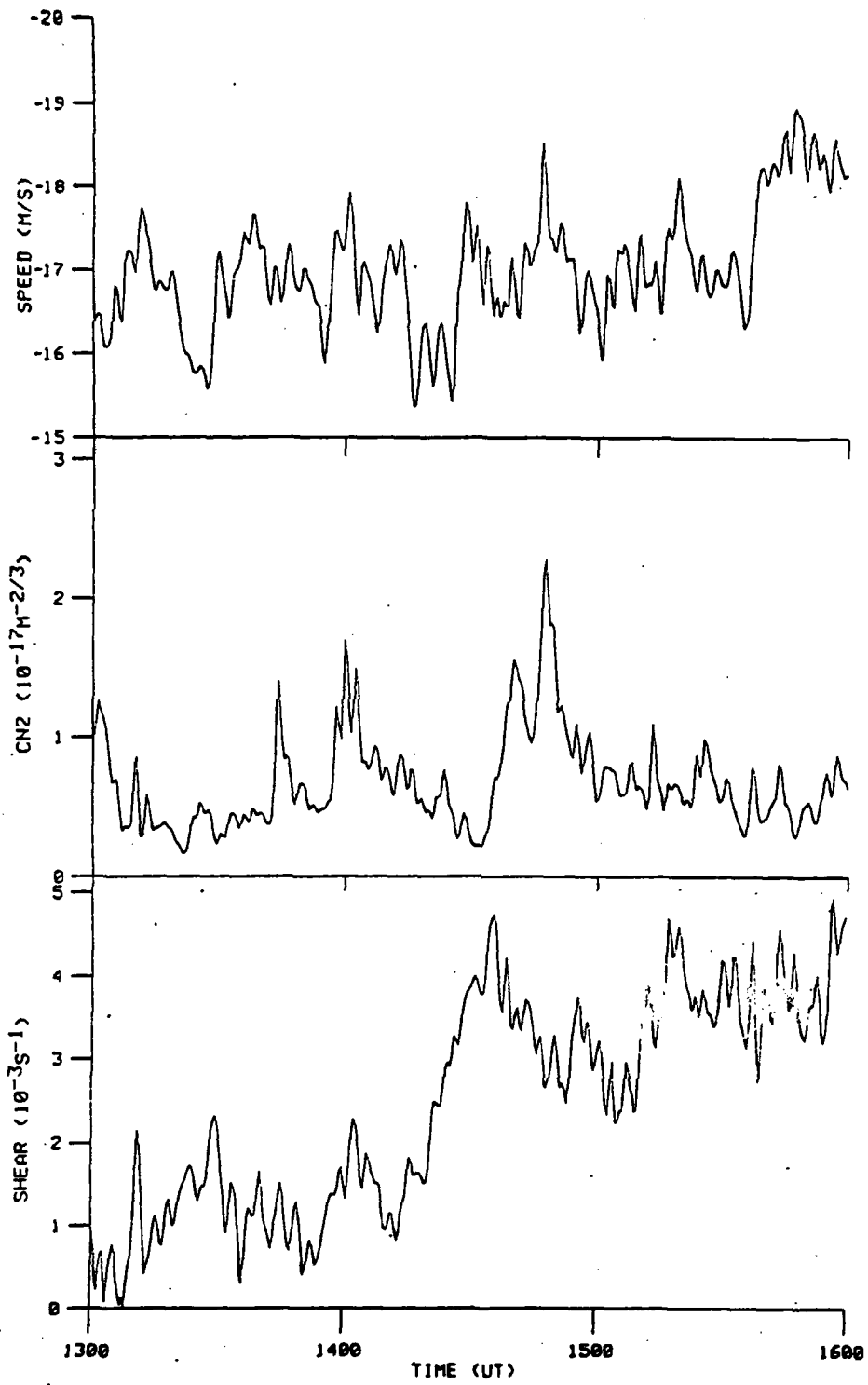


Figure 1.

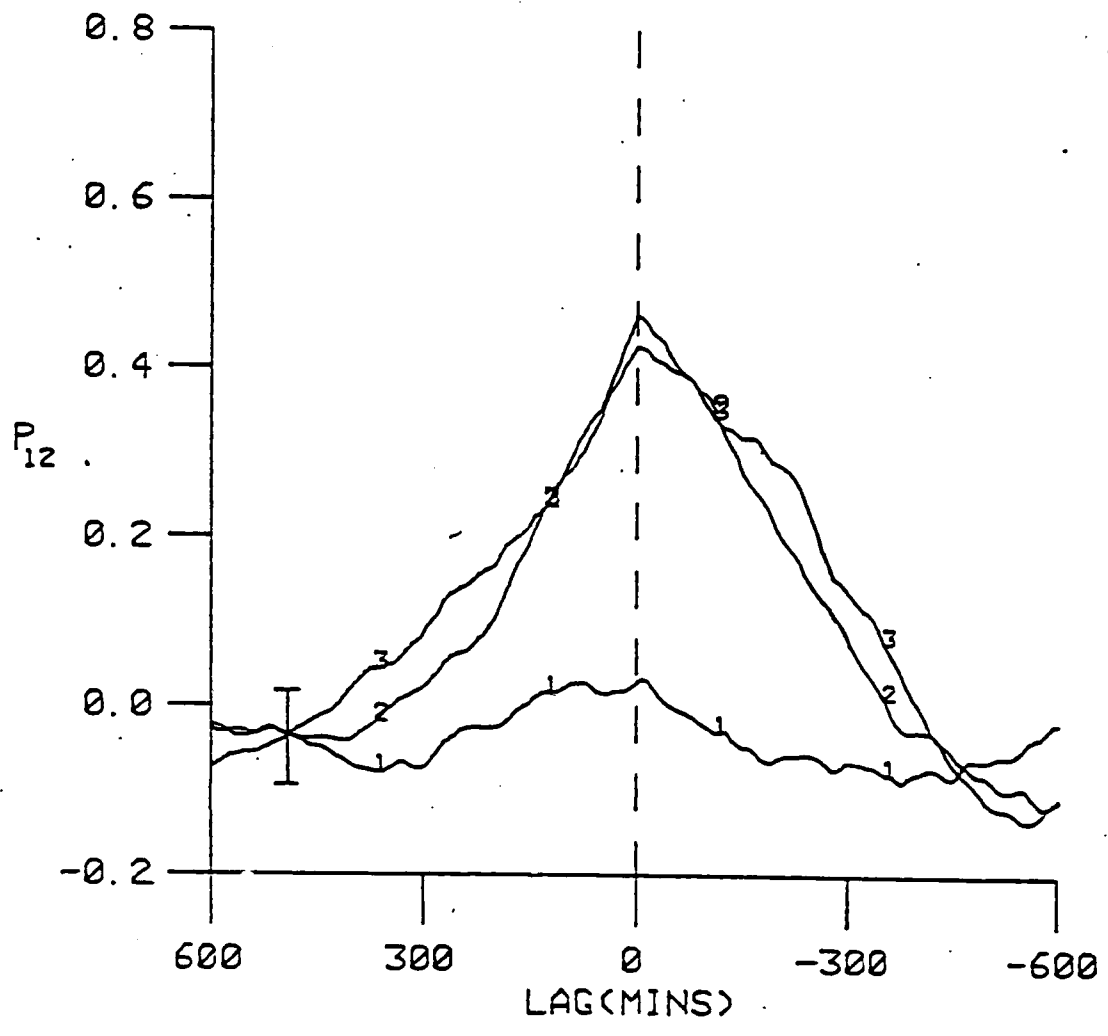


Figure 2.

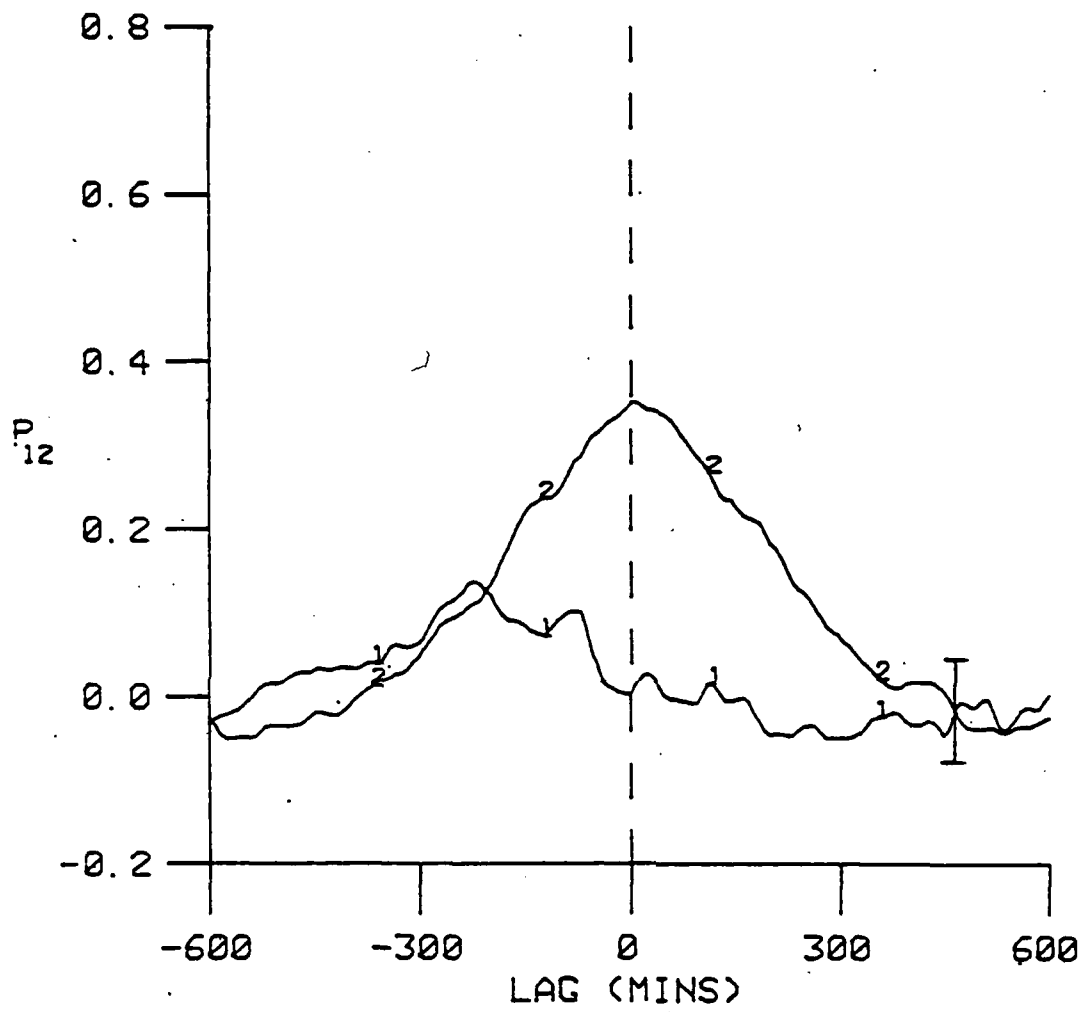


Figure 3.

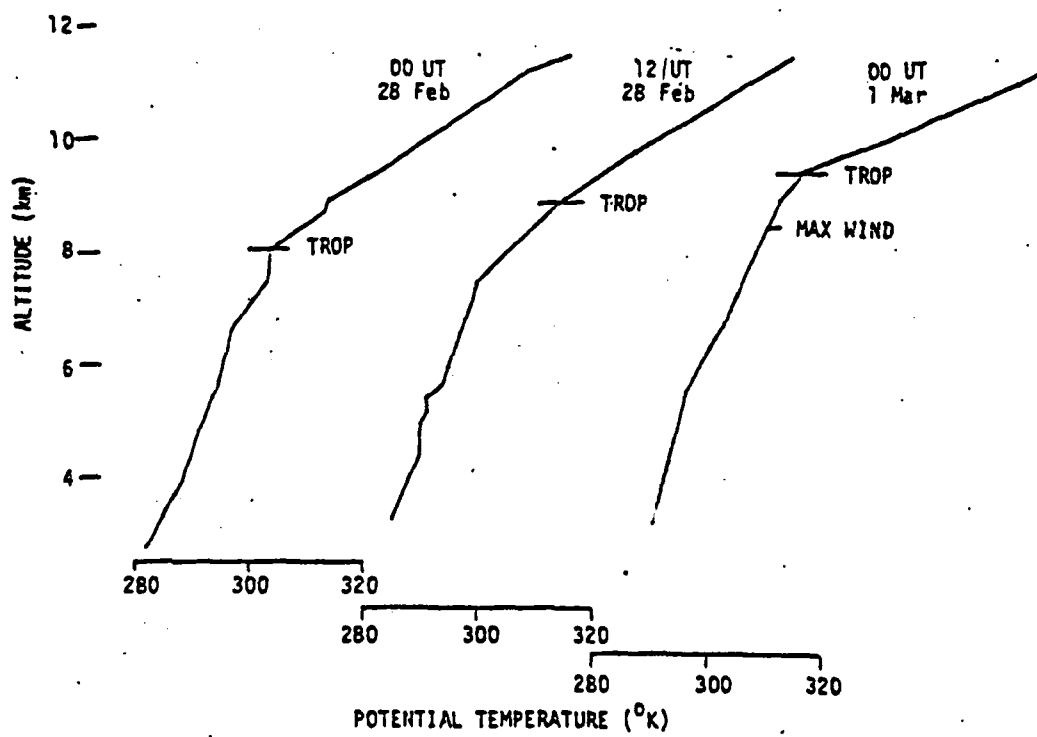


Figure 4.

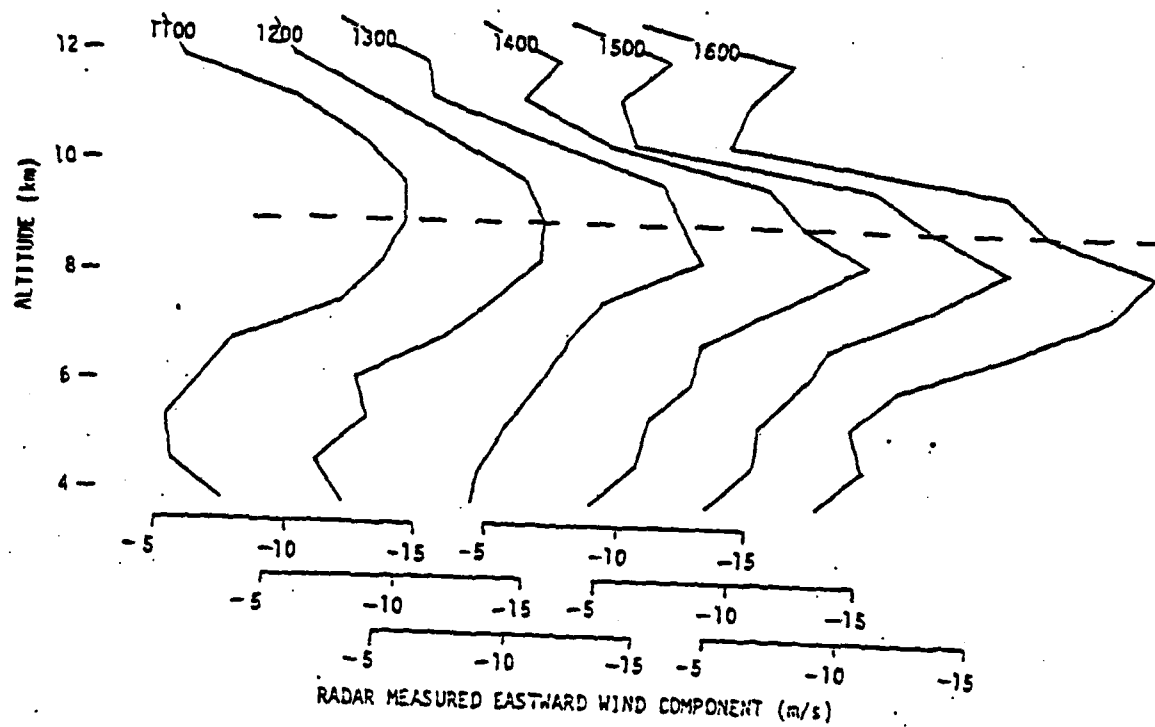


Figure 5.

PUBLICATIONS:

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