Rapid Temporal Changes of Boundary Layer Winds

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[Review, Double space and format thoroughly for JAM]

Abstract

The statistical distribution of the magnitude of the vector wind change over 0.25, 0.5, 1 and 2-h periods based on data from November 1999 through August 2001 is presented. The distributions of the 2-h u and v component wind changes are also presented for comparison. The wind changes at altitudes from 500 to 3000 m were measured using the Eastern Range network of five 915 MHz Doppler radar wind profilers. Quality controlled profiles were produced every 15 minutes for up to sixty gates, each representing 101 m in altitude over the range from 130 m to 6089 m. Five levels, each constituting three consecutive gates, were selected for analysis because of their significance to aerodynamic loads during the Space Shuttle ascent roll maneuver. The distribution of the magnitude of the vector wind change is found to be lognormal consistent with earlier work in the mid-troposphere. The parameters of the distribution vary with time lag, season and altitude. The component wind changes are symmetrically distributed with near-zero means, but the kurtosis coefficient is larger than that of a Gaussian distribution.

1. Introduction

Merceret (1997) showed that the magnitude of the vector wind change over periods from 0.24 to 4-h in the mid-troposphere (6 - 17 km) is lognormally distributed and that the parameters of the distribution vary systematically with the time over which the change takes place. Recently, the Space Shuttle program requested a similar analysis of the u and v component wind change over a two hour period for altitudes between 500 and 3000 m for assessment of resulting aerodynamic effects on vehicle loads during the ascent roll maneuver. To facilitate direct comparison with the midtropospheric work, the magnitude of the vector wind change for 0.25, 0.5, 1 and 2 hours was also analyzed.

The Shuttle program needed results quickly. Fortunately, the author had access to nearly two years of carefully quality controlled data collected at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) from five 915 MHz boundary layer wind profilers. The software used for the midtropospheric study was modified to ingest the 915 MHz data and separate versions were developed to handle the magnitude or the components of the vector wind change.

Because of the time required for processing the data and documenting the results, the component analysis for the two hour wind change was run first and provided to the Shuttle program immediately upon completion. Later, the magnitude analysis was run for all four time lags to provide a direct comparison with the earlier work at higher altitudes. Additional lags were not run for the components because the additional labor required could not be justified in the absence of an operational requirement.

The existence of two years of data permitted an examination of seasonal effects on the distributions and the new software facilitated examination of the variation of the distributions with height. Neither of these was possible in the earlier study.

This paper briefly describes the data set and the analysis methodology and then presents the results. The two hour wind change analyses for the components are first presented, including a discussion of how they vary with height and season. Next, the distribution of the vector magnitude is presented and compared with that from Merceret (1997). A brief discussion section concludes the paper.

2. Data

Details of the profiler network and the data set, including an extensive discussion of the quality control (QC) methodology, are presented in Lambert and co-authors (2003). A brief summary is provided here for convenience.

The instruments are standard Radian (now Vaisala) LAP 3000® 915 MHz wind profilers with the associated LAP-XM® software. Data were collected from November 1999 through August 2001, during which time the number of gates was either 40 or 60 depending on configuration changes by the Air Force Eastern Range which owns and operates the system. The lowest gate was always at 130 m and the gate spacing was always 101 m. One of the profilers is located at TICO Airport in Titusville, Florida, directly across the Indian River from KSC. Two of the instruments are located on Merritt Island, respectively north and south of the Shuttle Landing Facility. The remaining two are located on the coast respectively at the north and south ends of CCAFS.

The data were subject to both automated and manual QC. The automated QC included tests for adequate signal to noise ratio; number of consensus members; limit checks on windspeed, direction, vertical wind and wind shear; the small median test of Carr and co-authors (1995) and contamination of the wind signal by rainfall. Any measurement that failed any test was flagged. Following automated QC, all of the data were examined using software that allowed the u and v components, or the speed or direction of either the wind or the wind change to be visualized using a color palette. Such visual examination, especially of the wind changes, proved very effective in locating and flagging the few erroneous data that remained unflagged by the automated QC. Flagged data were excluded from the analysis.

3. Analysis methodology

a. Statistics

The statistical analysis methodology is the same as that described in detail by Merceret (1997). Again, a brief summary is presented for convenience. For each selected altitude range and season (see below), the first four raw moments were computed. From them the mean, standard deviation, skewness coefficient and kurtosis coefficient were derived. These will be called the "analysis statistics" below. This was done for the u and v components of the two hour wind change and for the magnitude of the vector wind change for changes over periods of 0.25, 0.5, 1 and 2 hours.

For the magnitude of the vector wind change, six estimates of the parameters M and S of the lognormal distribution were derived from the four raw moments taken in pairs as explained in Merceret (1997). M is the mean of the logarithm of the vector wind change magnitude and S is its standard deviation. The minimum, mean, maximum and standard deviation of the six estimates were computed as objective measures of the consistency of the estimates. If the distribution were perfectly lognormal and there were no noise in the data, the standard deviation would be zero and all of the other measures would be equal to the actual values of M and S for the distribution. In addition, the cumulative probability distribution for the lognormal distribution having the mean values of M and S was plotted over the cumulative distribution of the actual data for a visual assessment of the degree of agreement.

The final products are the analysis statistics for u, v and $|\Delta V|$ plus M and S for $|\Delta V|$ as a function of height and season.

b. Stratification

The Shuttle program defines three seasons for the purpose of wind climatology. The "winter" season comprises the months December through March. The "summer season" comprises the months June through September. The remaining months constitute the "transition" season. The program requested that this stratification be used.

To reduce the workload to manageable proportions while preserving the ability to investigate the variability of the analysis statistics with height, data from gates 4 through 30 were combined into nine levels as shown in Table 1. Combining gates into levels not only reduced the workload, but it also increased the sample size in each level, thus reducing the sampling variability in the analysis statistics. Data below gate 4 and above gate 30 were not examined because they were outside of the region of interest to the Shuttle ascent roll maneuver. The analysis statistics for u and v were computed at all nine levels. The statistics for |ΔV| were computed only for the odd-numbered levels and only for summer and winter, again to reduce the labor involved.

Level	Low Gate	Mid Gate	High Gate	Low Alt (m)	Mid Alt (m)	High Alt (m)
1	4	5	6	433	534	635
2	7	8	9	736	837	938
3	10	11	12	1039	1140	1241
4	13	14	15	1342	1443	1544
5	16	17	18	1645	1746	1847
6	19	20	21	1948	2049	2150
7	22	23	24	2251	2352	2453
8	25	26	27	2554	2655	2756
9	28	29	30	2857	2958	3059

Table 1. Definition of the nine levels used in the wind change analysis.

4. Results

a. u and v 2-hr wind change components

The 2-hr wind change u and v component means were much smaller than the error of measurement of the wind profilers at all levels for all three seasons. This was expected, since any other result would require a huge change in the mean wind component between the beginning and the end of the season.

The standard deviations of both component changes ranged from 1.5 to 2.5 ms^{-1} with surprisingly little variation with season. The standard deviations increased with height and were slightly lower in the summer as shown in Table 2.

Level	u sum	v sum	u tra	v tra	u win	v win
1	1.88	1.97	1.98	2.27	1.98	2.27
2	1.73	1.86	1.93	2.11	2.04	2.14
3	1.68	1.80	1.96	2.08	2.10	2.06
4	1.74	1.81	2.01	2.11	2.11	2.12
5	1.77	1.84	2.09	2.14	2.12	2.29
6	1.82	1.91	2.12	2.20	2.17	2.38
7	1.90	1.95	2.08	2.25	2.28	2.59
8	1.96	2.00	2.14	2.30	2.43	2.73
9	1.99	2.09	2.22	2.36	2.44	2.73

Table 2. Standard deviations (ms^{-1}) of the u and v components for the summer (sum), transition (tra) and winter (win) seasons as a function of level.

The skewness coefficients, Sk, for u and v were both small ($|Sk| < 0.25$) for all levels in the summer. They were also small for u at all levels during the winter and transition seasons. For the v component, $-1.0 < Sk < -0.3$ in the winter with a mean of -0.53, and $-0.7 < Sk < -0.1$ for the transition season with a mean of -0.25. No reason for the slight v component asymmetry in the transition and winter seasons has been identified.

The kurtosis coefficient, K, is defined such that for a Gaussian distribution K=3.0. The observed values were always significantly higher than this, indicating a distribution with longer tails than a normal distribution. This is consistent with the magnitude of the vector wind change having the long tails characteristic of the lognormal distribution as shown in the next section. Table 3 presents the results by season and level.

Level	u sum	v sum	u tra	v tra	u win	v win
1	5.47	5.78	5.27	6.47	5.88	9.10
2	5.15	5.15	5.67	5.37	6.12	5.86
3	5.78	5.22	5.54	5.06	6.78	4.76
4	6.61	5.02	5.05	4.70	6.32	5.69
5	5.82	5.44	4.97	4.40	6.02	5.59
6	6.30	6.19	4.56	4.83	4.89	5.42
7	7.97	6.24	4.13	5.17	4.58	6.29
8	9.58	6.27	4.25	5.16	4.70	6.39
9	9.31	6.11	4.36	4.42	4.59	5.33

Table 3. Kurtosis coefficients of the u and v components for the summer (sum), transition (tra) and winter (win) seasons as a function of level.

The higher moments require large sample sizes for accurate estimates. Table 4 shows the sample sizes for the discussion in this section. The sample size decreases with altitude because the signal to noise ratio of the instrument decreases with altitude and fewer data pass the QC process.

Level	Summer	Transition	Winter
1	107557	153412	97951
2	107288	152063	95446
3	103721	146056	86828
4	98351	130835	74313
5	92057	109099	59429
6	83034	87499	46500
7	72533	68877	36875
8	60171	52012	26785
9	46351	38096	17726

Table 4. Sample size as a function of level and season

b. Magnitude of the vector wind change

As with the midtropospheric wind changes reported by Merceret (1997), the magnitude of the vector wind change for 0.25, 0.5, 1 and 2 hour lag times was found to be lognormally distributed. Figure 1 shows an example. The means of the six values of M and S derived from the moment pairs as described above were used to generate the model lognormal distribution shown in the figure along with the measured data. The standard deviation of the six estimates of M was 0.0055 and the standard deviation of the estimates of S was 0.0038. This indicates that all of the moment pairs are consistent, confirming the visual impression given by the figure that the measured distribution is lognormal.

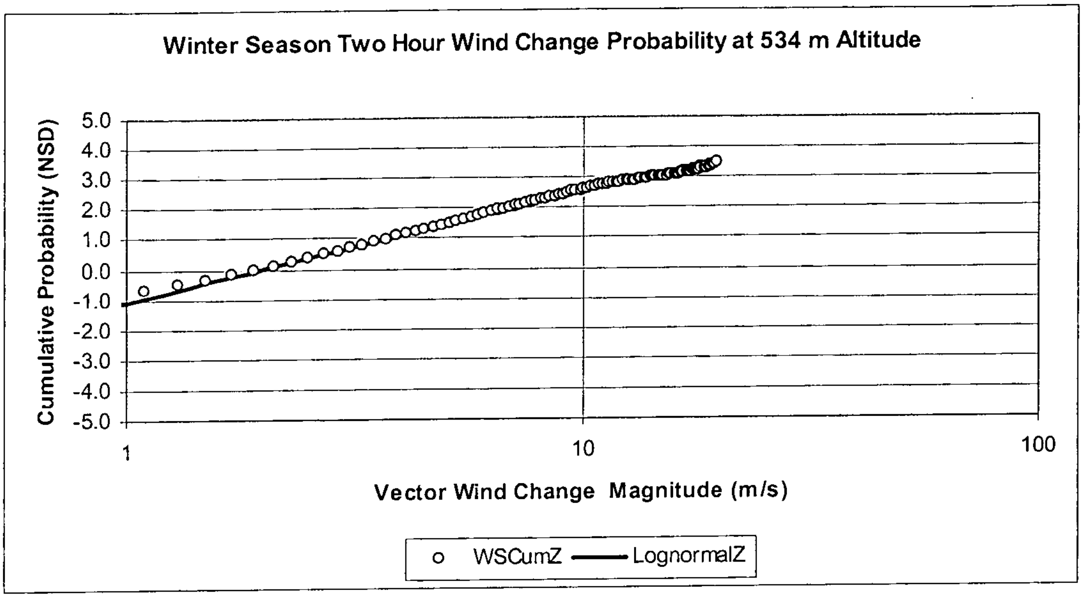

Figure 1. The cumulative probability distribution for level 1 at two hours lag in the winter season. The open circles are the measured data. The solid line, mostly hidden under the data, is the calculated lognormal distribution with M = 0.689742 and S = 0.64049.

The mean and standard deviation of $|\Delta V|$ as well as the lognormal parameters M and S varied with season, height and lag time. Figure 2 shows the variation of the mean vector wind change as a function of altitude for the four lag times examined for the winter and summer seasons. Figures 3, 4 and 5 show the same information for the standard deviation and the lognormal parameters M and S respectively.

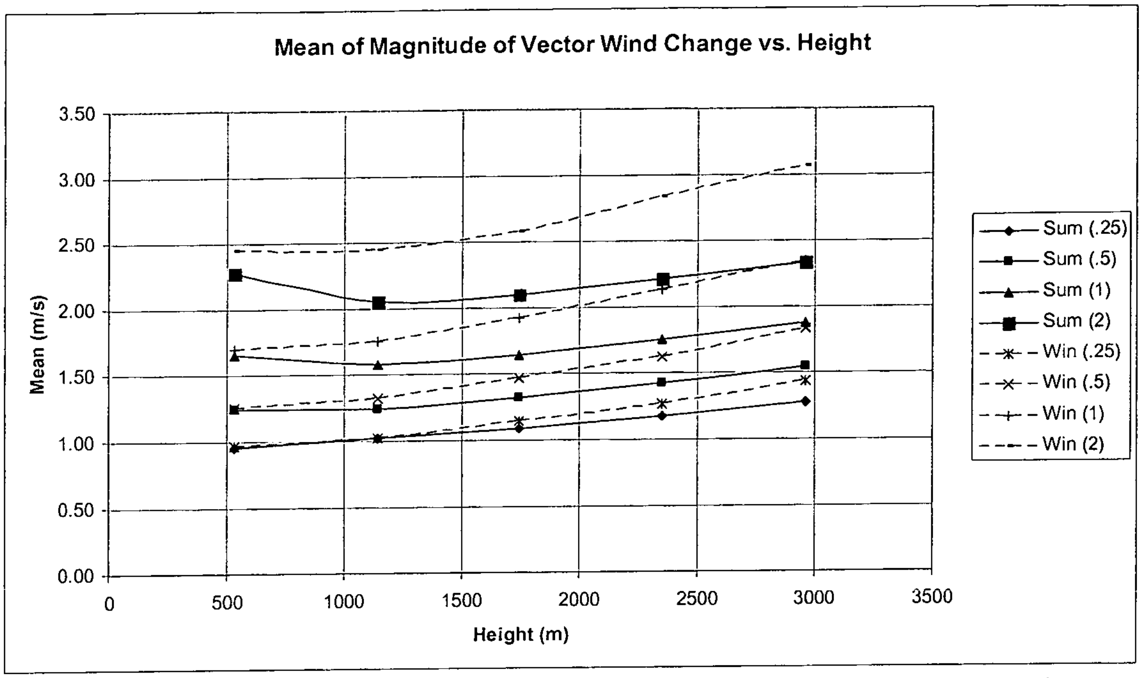

Figure 2. Average of the magnitude of the vector wind change as a function of height. In the legend, "Sum" denotes summer while "Win" denotes winter. The number in parenthesis in the legend denotes the lag time in hours.

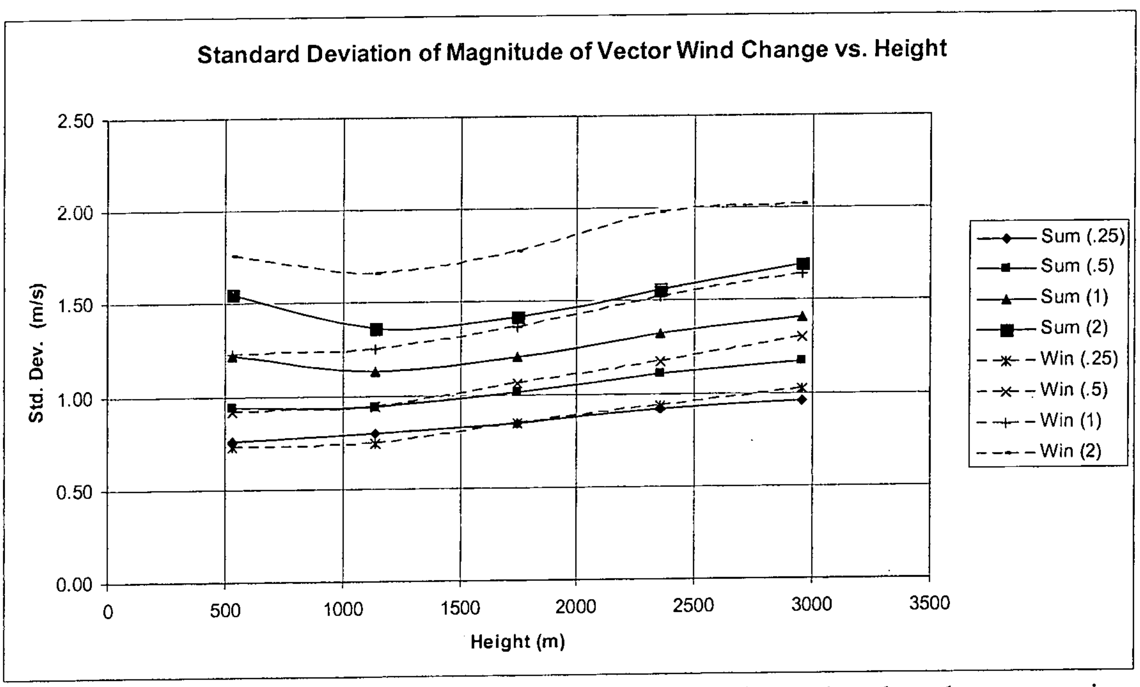

Figure 3. Same as Figure 2 except that the standard deviation rather than the average is presented.

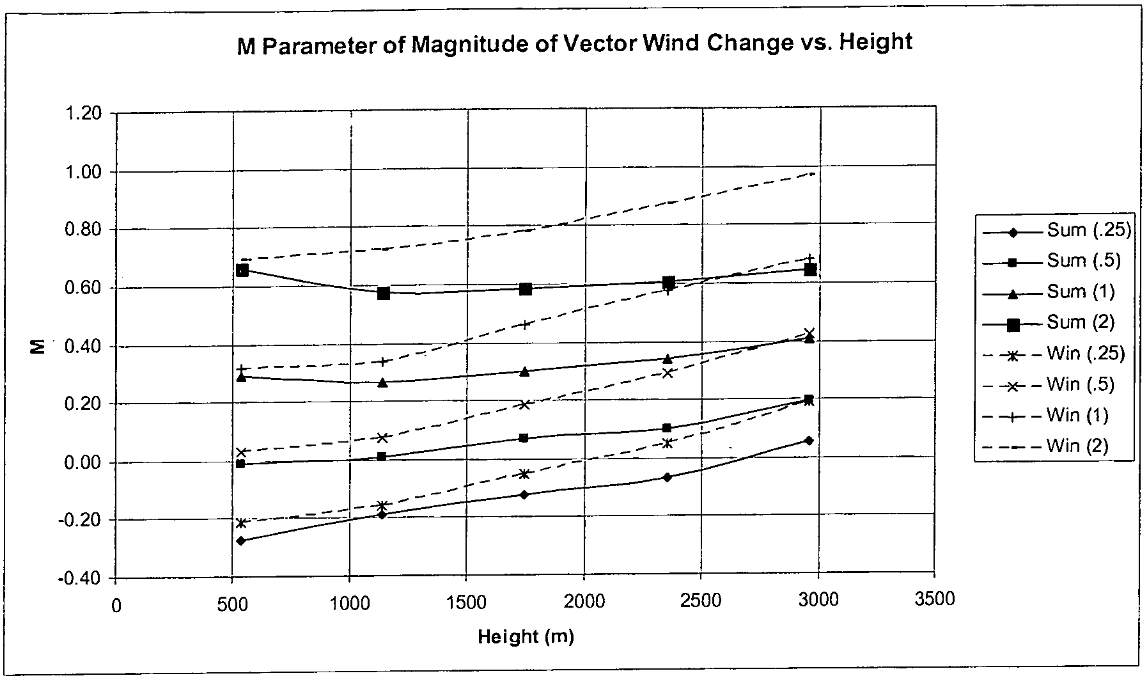

Figure 4. Same as Figure 2 except that the lognormal parameter M for $|\Delta V|$ measured in ms^{-1} is presented.

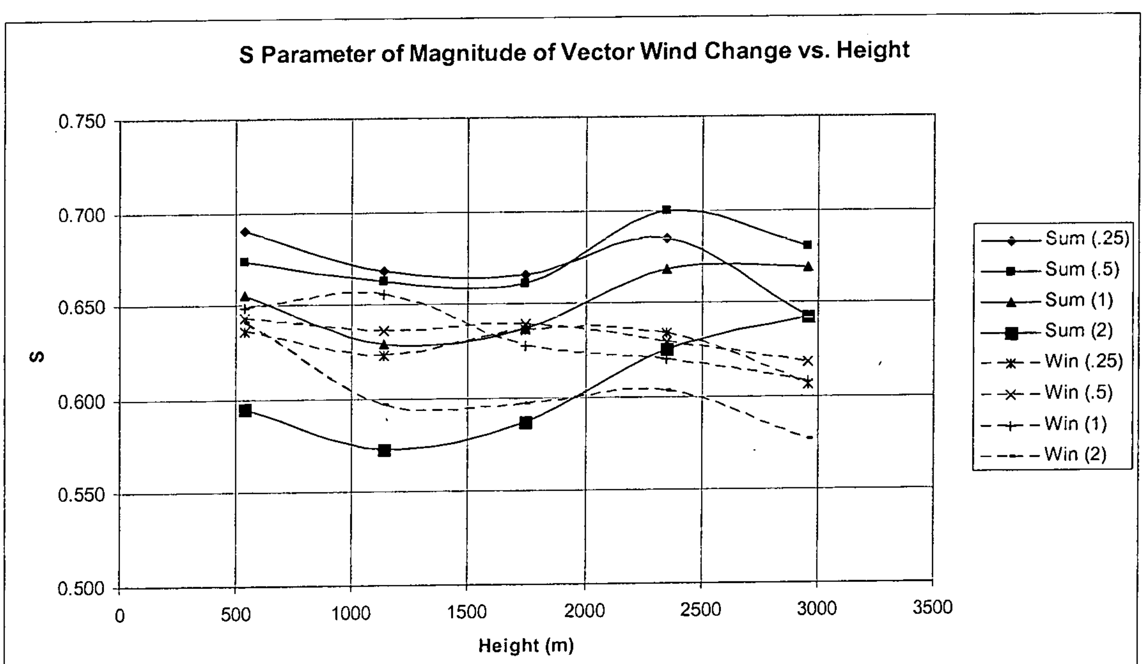

Figure 5. Same as Figure 4 except that the parameter S is presented.

Merceret (1997) found that M increased nearly linearly with the logarithm of the lag time, ΔT, with a correlation coefficient r^2>0.9. He found S to decrease with increasing log ΔT, but the linear relationship was weaker (r^2>0.4). The boundary layer data presented here demonstrate a similar relationship for M as may be seen from Figure 6. The curve for the winter season at the highest level (2958 m) is nearly identical to

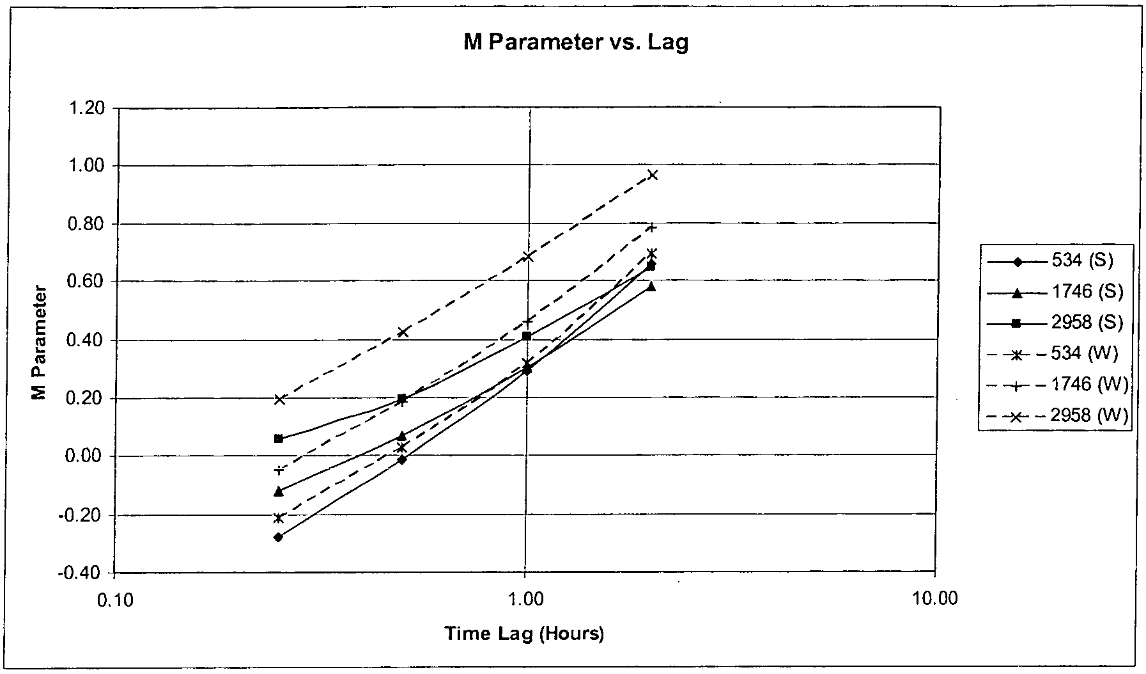

Figure 6. M parameter as a function of time lag, ΔT, for selected altitudes. The S and W in parentheses in the legend respectively denote summer and winter seasons.

the equivalent curve presented in Fig. 3 of Merceret (1997) for higher altitudes. The linear least squares fits for all six curves have $r^2>0.98$.

The S parameter does not show the same kind of regularity found in the previous study as may be seen from Figure 7. Although there is still a strong tendency

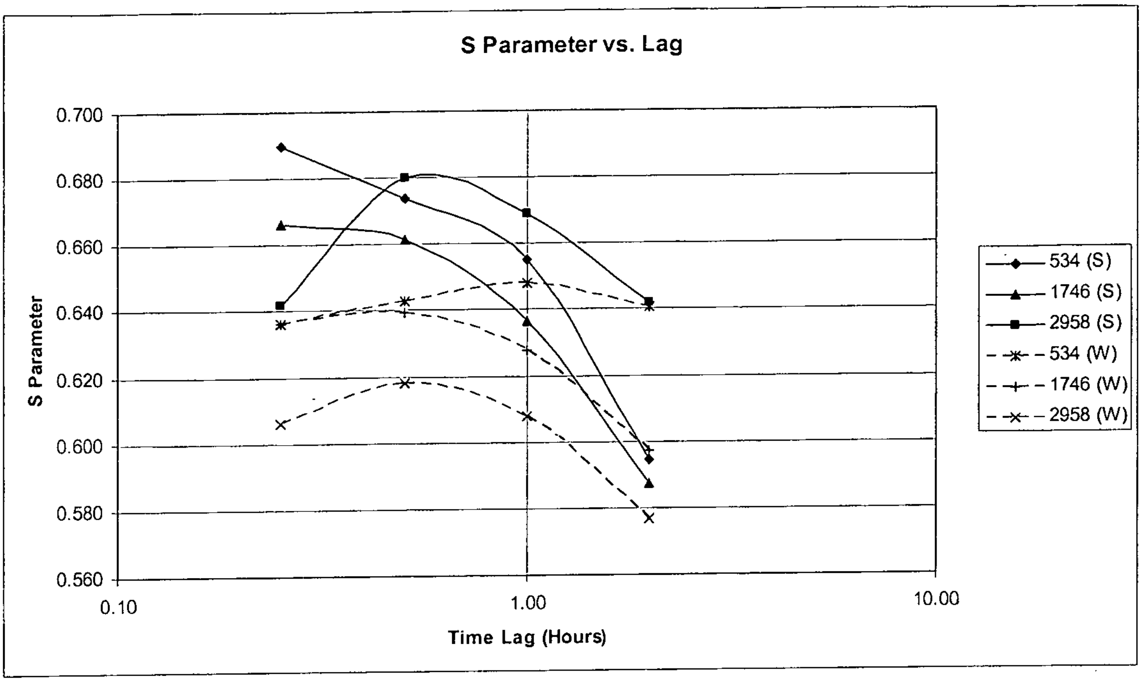

Figure 7. Same as Figure 6 except the S parameter is shown.

for S to decrease with increasing log ΔT, the relationship is neither linear nor always monotonic. Figure 7 is on an expanded scale, so one must take care not to over interpret it. In fact, except for 2958(S) and 534(W) the linear least squares fits for these curves have $r^2 > 0.5$. In any case, S remains within 0.63 +/- 0.06 throughout all seasons, levels and lags. The range in the earlier study was about 0.65 +/- 0.1, so the results here are consistent although not as neat.

5. Discussion

The probability distributions of the component velocity differences presented in section 4a are consistent with the findings of Castaing and co-authors (1990) for component velocity differences in high Reynolds number (Re) wind tunnel turbulence. Specifically, they found that the skewness was always negative. They also found that the tails of the distribution were longer than Gaussian, implying a Kurtosis greater than 3. They related these features to vortex stretching and the intermittency of the high Re flow. This study goes beyond those basic results by examining the variation of these statistics with height and season in the atmospheric boundary layer (ABL).

There is nothing in the boundary layer literature presenting the probability distribution of the magnitude of the vector wind change over time with which to compare the results of section 4b. On the other hand, updraft/downdraft dimensions and the size of convective plumes in the ABL were found to be lognormally distributed respectively by Humphrey and List (1980) and Lopez (1977). Wind changes at all altitudes, and the sizes of the up/down drafts and plumes all have one thing in common: they are the result of the non-linear interaction of multiple independent forcing functions. When applied to an output generated from the product, rather than the sum, of multiple independent processes, the central limit theorem produces a lognormal distribution. The non-linearity of the equations of motion provides the necessary multiplicative processes. This study confirms that the lognormal distribution found in the mid troposphere continues to apply in the ABL and extends the analysis to examine the variation of the parameters of the distribution with height and season.

Acknowledgments

The author thanks Paul Wahner of Computer Sciences Raytheon for providing the raw wind profiler data and Jennifer Ward of NASA for assistance in the data processing. Mention of a proprietary product or service does not constitute an endorsement thereof by the author, the National Aeronautics and Space Administration or the American Meteorological Society.

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Tables

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4	1.74	1.81	2.01	2.11	2.11	2.12
5	1.77	1.84	2.09	2.14	2.12	2.29
6	1.82	1.91	2.12	2.20	2.17	2.38
7	1.90	1.95	2.08	2.25	2.28	2.59
8	1.96	2.00	2.14	2.30	2.43	2.73
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Table 2. Standard deviations (ms^{-1}) of the u and v components for the summer (sum), transition (tra) and winter (win) seasons as a function of level.

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3	5.78	5.22	5.54	5.06	6.78	4.76
4	6.61	5.02	5.05	4.70	6.32	5.69
5	5.82	5.44	4.97	4.40	6.02	5.59
6	6.30	6.19	4.56	4.83	4.89	5.42
7	7.97	6.24	4.13	5.17	4.58	6.29
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8	60171	52012	26785
9	46351	38096	17726

Table 4. Sample size as a function of level and season

Figure Captions

Figure 1. The cumulative probability distribution for level 1 at two hours lag in the winter season. The open circles are the measured data. The solid line, mostly hidden under the data, is the calculated lognormal distribution with M = 0.689742 and S = 0.64049.

Figure 2. Average of the magnitude of the vector wind change as a function of height. In the legend, "Sum" denotes summer while "Win" denotes winter. The number in parenthesis in the legend denotes the lag time in hours.

Figure 3. Same as Figure 2 except that the standard deviation rather than the average is presented.

Figure 4. Same as Figure 2 except that the lognormal parameter M for $|\Delta V|$ measured in ms^{-1} is presented.

Figure 5. Same as Figure 4 except that the parameter S is presented.

Figure 6. M parameter as a function of time lag, ΔT, for selected altitudes. The S and W in parentheses in the legend respectively denote summer and winter seasons.

Figure 7. Same as Figure 6 except the S parameter is shown.

Figures

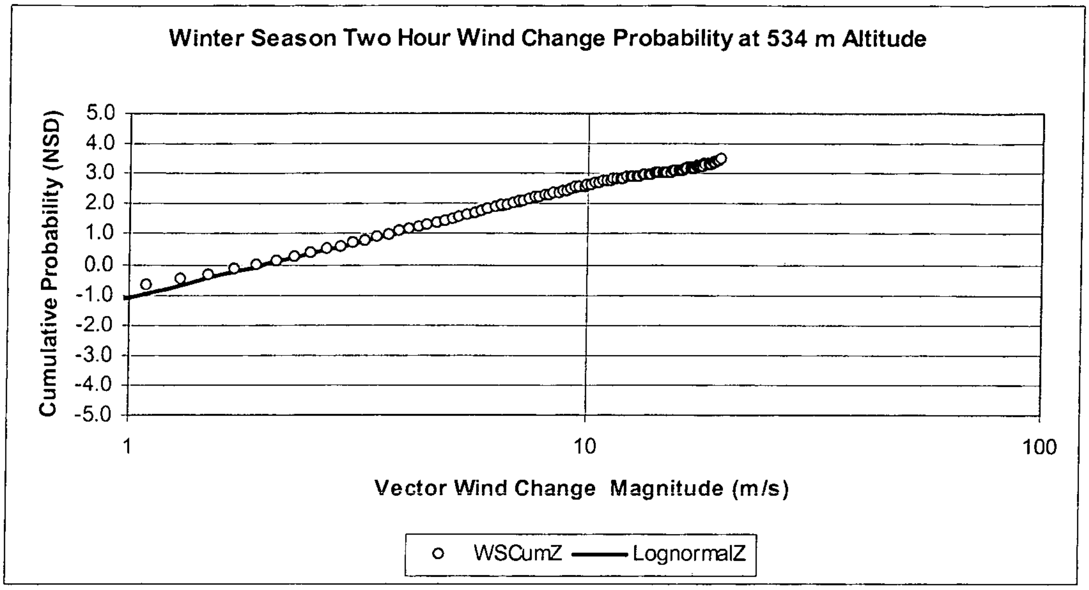
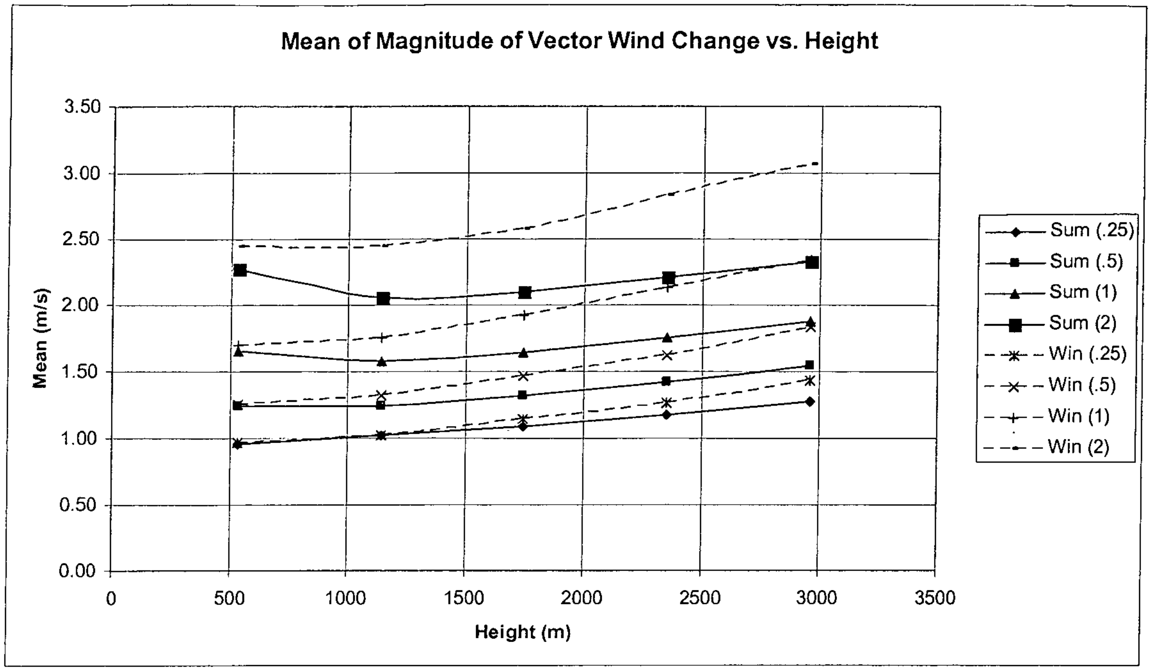
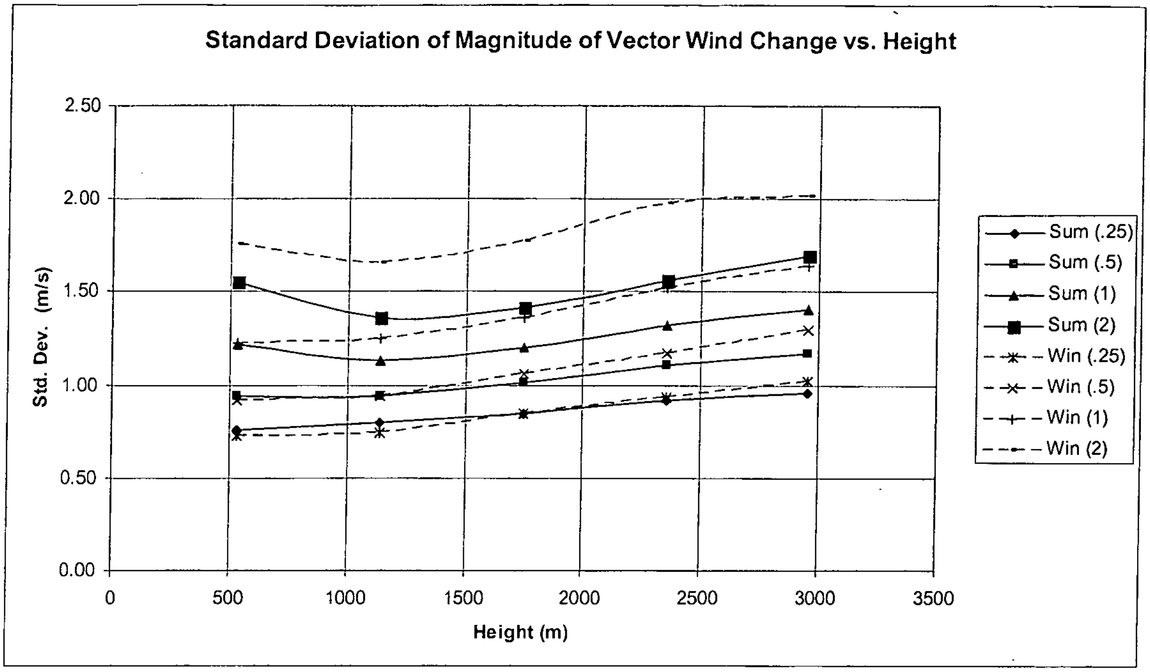


Fig. 1



Mean of Magnitude of Vector Wind Change vs. Height
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Mean (m/s)
0
500
1000
1500
2000
2500
3000
3500
Height (m)
Sum (.25)
Sum (.5)
Sum (1)
Sum (2)
Win (.25)
Win (.5)
Win (1)
Win (2)

Fig. 2



Standard Deviation of Magnitude of Vector Wind Change vs. Height
2.50
2.00
1.50
1.00
0.50
0.00
Std. Dev. (m/s)
0
500
1000
1500
2000
2500
3000
3500
Height (m)
Sum (.25)
Sum (.5)
Sum (1)
Sum (2)
Win (.25)
Win (.5)
Win (1)
Win (2)

Fig. 3

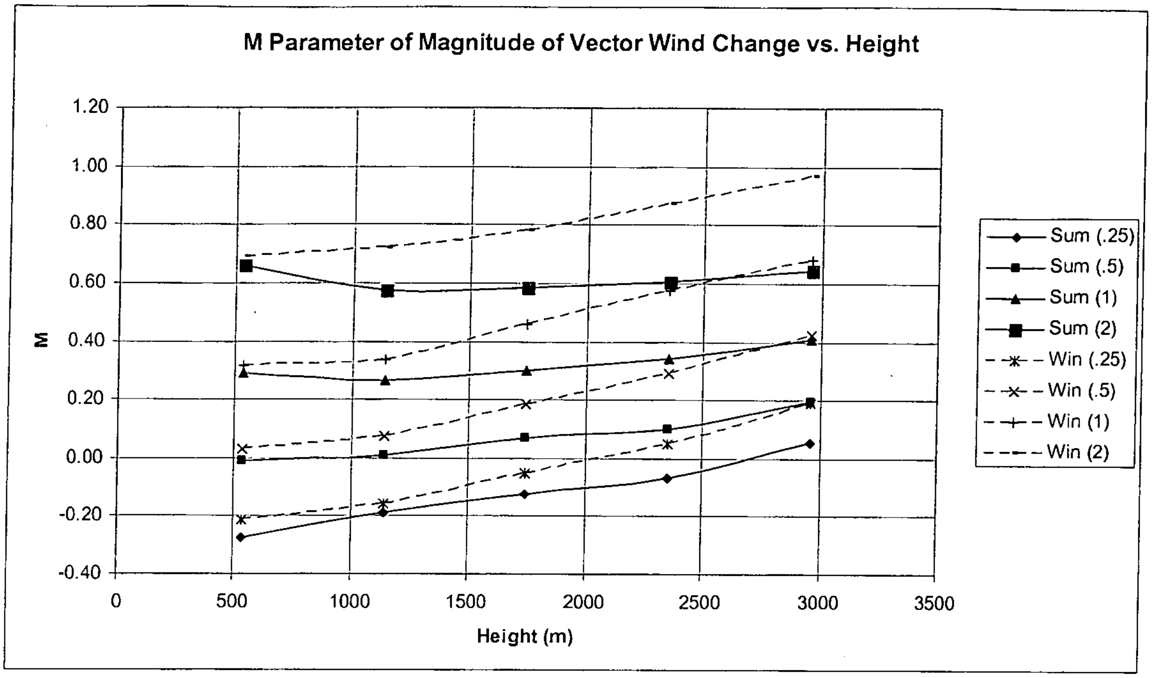

M Parameter of Magnitude of Vector Wind Change vs. Height
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
M
0
500
1000
1500
2000
2500
3000
3500
Height (m)
Sum (.25)
Sum (.5)
Sum (1)
Sum (2)
Win (.25)
Win (.5)
Win (1)
Win (2)

Fig. 4

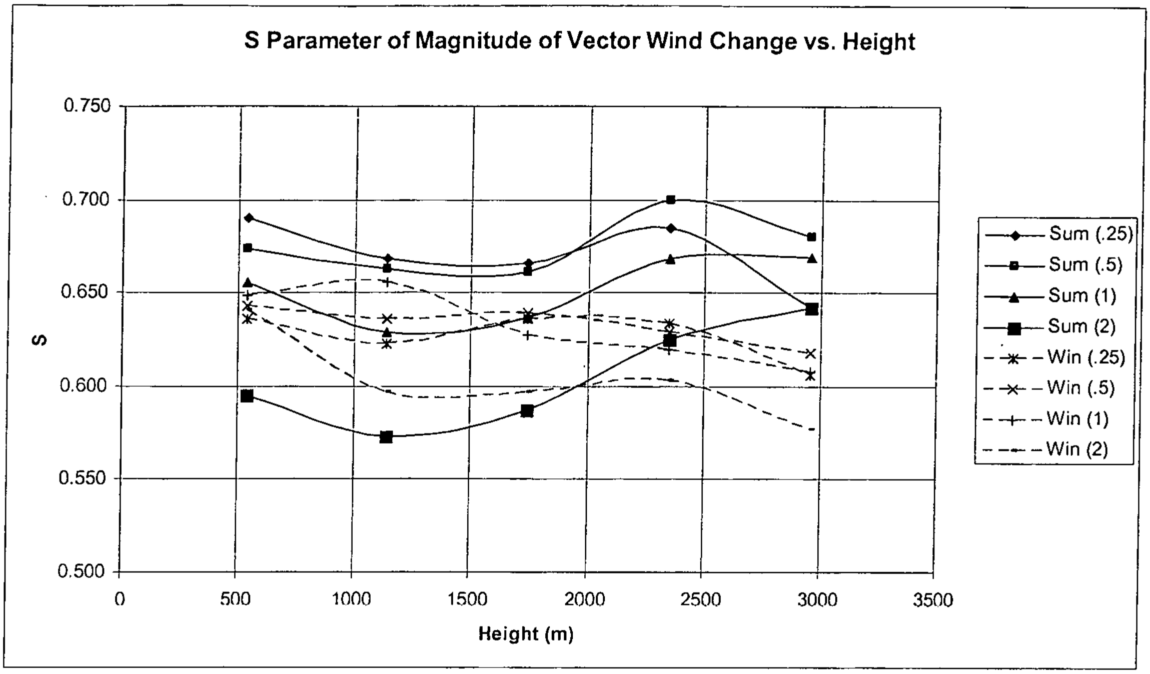
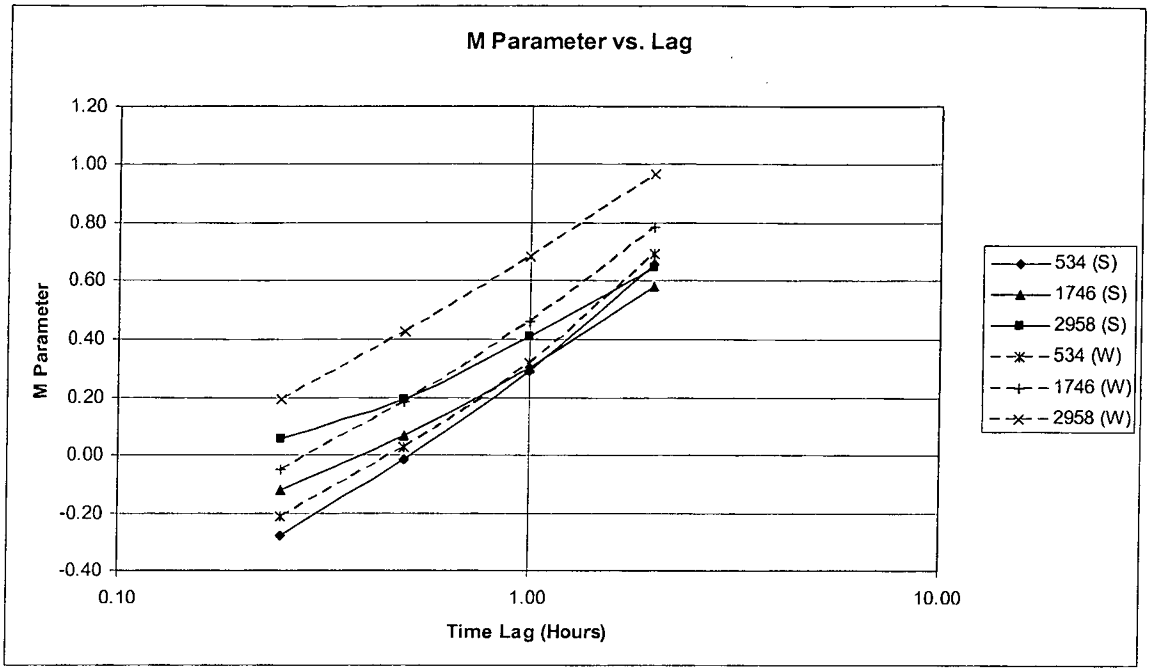
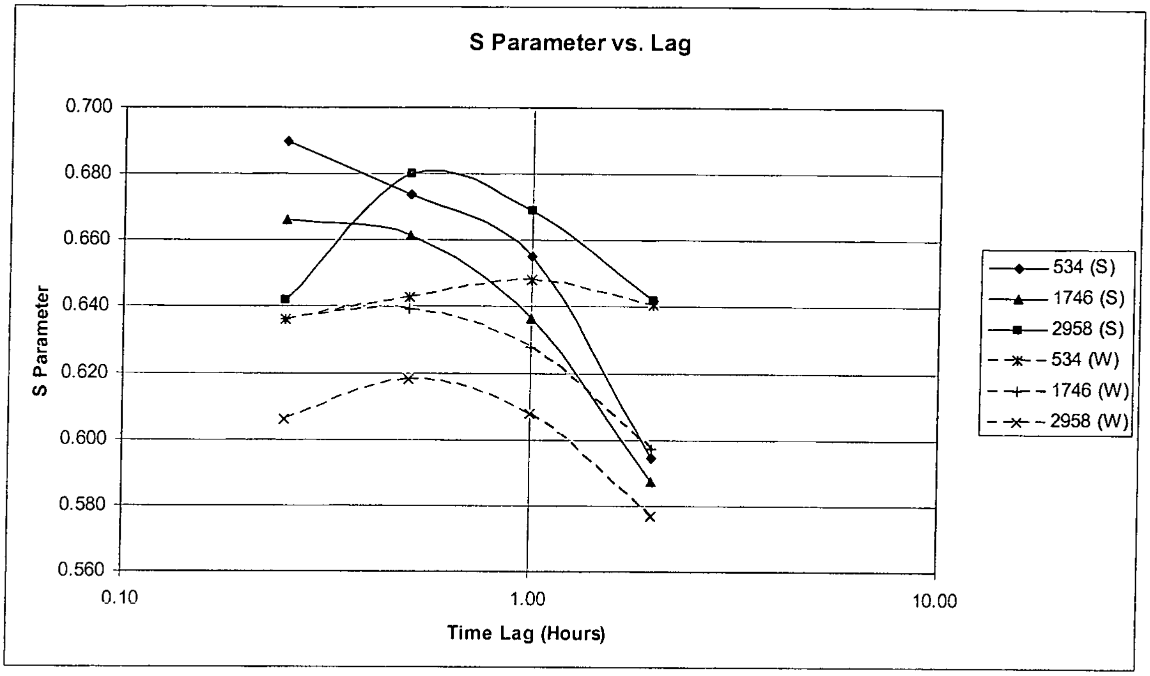

S Parameter of Magnitude of Vector Wind Change vs. Height
0.750
0.700
0.650
0.600
0.550
0.500
S
0
500
1000
1500
2000
2500
3000
3500
Height (m)
Sum (.25)
Sum (.5)
Sum (1)
Sum (2)
Win (.25)
Win (.5)
Win (1)
Win (2)

Fig. 5



M Parameter vs. Lag
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
M Parameter
0.10
1.00
10.00
Time Lag (Hours)
534 (S)
1746 (S)
2958 (S)
534 (W)
1746 (W)
2958 (W)

Fig. 6



S Parameter vs. Lag
0.700
0.680
0.660
0.640
0.620
0.600
0.580
0.560
S Parameter
0.10
1.00
10.00
Time Lag (Hours)
534 (S)
1746 (S)
2958 (S)
534 (W)
1746 (W)
2958 (W)

Fig. 7