

NOTES AND CORRESPONDENCE

Rapid Temporal Changes of Boundary Layer Winds

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ABSTRACT

The statistical distribution of the magnitude of the vector wind change over 0.25-, 0.5-, 1-, and 2-h periods based on central Florida data from November 1999 through August 2001 is presented. The distributions of the 2-h u and v wind-component 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 min for up to 60 gates, each representing 101 m in altitude over the range from 130 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 midtroposphere. 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

The space shuttle program recently requested a statistical analysis of the u and v wind-component change over a 2-h period for altitudes between 500 and 3000 m for assessment of resulting aerodynamic effects on vehicle loads during the ascent roll maneuver. The statistical properties of these components were needed to develop safety margins for the use of wind profiles taken 2 h before launch to calculate launch-time aerodynamic loads during the roll maneuver.

Merceret (1997) previously developed similar statistics for the magnitude of the vector wind change $|\Delta\mathbf{V}|$ over periods from 0.25 to 4 h in the midtroposphere (6–17 km) to assess the probability of dangerous wind changes in the region of maximum dynamic pressure during ascent. Those results showed that $|\Delta\mathbf{V}|$ is lognormally distributed and that the distribution parameters vary systematically as a function of lag time. This meant that risk figures based on the mean and variance of the wind changes using the assumption of Gaussian

statistics were seriously underestimated (Merceret 1998). To determine whether this is the case in the boundary layer, statistics of $|\Delta\mathbf{V}|$ for 0.25, 0.5, 1, and 2 h were generated in addition to the 2-h statistics for u and v . 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. In addition, the availability of 2 yr of research-grade 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 things was possible in the earlier study.

This paper briefly describes the dataset and the analysis method and then presents the results. The 2-h wind-change analysis for the components is presented first, including a discussion of how they vary with height and season. Next, the distribution of the vector magnitude is presented and is compared with that from Merceret (1997). A brief discussion concludes the paper.

2. Data

Details of the profiler network and the dataset, including an extensive discussion of the quality-control

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(QC) method, are presented in Lambert et al. (2003). A brief summary is provided here for convenience.

The instruments are standard Radian (now Vaisala, Inc.) model LAP 3000 915-MHz wind profilers with the associated proprietary LAP-XM software. Data were collected from November of 1999 through August of 2001, during which time the number of gates was either 40 or 60, depending on configuration changes by the U.S. Air Force Eastern Range, which owns and operates the system. The lowest gate was always near 130 m and the gate spacing was always 101 m. One of the profilers is located at Spacecoast Regional Airport in Titusville, Florida, directly across the Indian River from Kennedy Space Center. 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 Cape Canaveral Air Force Station.

The data were subject to both automated and manual QC. The automated QC included tests for adequate signal-to-noise ratio; the number of individual profiles in the “consensus” profile reported by LAP-XM; limit checks on wind speed, direction, vertical wind, and wind shear; the small median test of Carr et al. (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 the 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 method

a. Statistics

The statistical analysis method is the same as that described in detail by Merceret (1997). A brief summary is presented for convenience. For each selected altitude range and season (see below), the first four raw statistical moments were computed. From them, the mean, standard deviation, skewness coefficient, and kurtosis coefficient were derived. These “analysis statistics” were computed for the u and v components of the 2-h wind change and for the magnitude of the vector wind change for changes over periods of 0.25, 0.5, 1, and 2 h.

For the magnitude of the vector wind change, an additional analysis was performed. To determine whether the lognormal distribution found at higher al-

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

Level	Low gate	Middle gate	High gate	Low alt (m)	Middle 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

titudes applied in the boundary layer, the statistical moments for $|\Delta\mathbf{V}|$ were used to derive the parameters μ and σ of a lognormal distribution, where μ is the mean of the logarithm of $|\Delta\mathbf{V}|$ and σ is its standard deviation. Six estimates of the parameters μ and σ were derived from the four raw moments taken in pairs, as explained in Merceret (1997). 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, then all six estimates would be the same. In that case, the variance of the estimates would be zero and all of the other measures would be equal to the actual value of the parameter. The size of the variance and the spread among the mean, minimum, and maximum of the six estimates are a measure of their departure from lognormality. In addition, the cumulative probability distribution for the lognormal distribution having the mean values of μ and σ 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 $|\Delta\mathbf{V}|$ plus the lognormal parameters for $|\Delta\mathbf{V}|$ as a function of height and season.

b. Stratification

The shuttle program defines three seasons for the purpose of a climatological description of wind. The “winter” season comprises December–March. The “summer season” comprises June–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 4–30 were combined into nine levels as shown in Table 1. Combining gates into levels not only reduced the

workload but 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 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 $|\Delta\mathbf{V}|$ were computed only for the odd-numbered levels and only for summer and winter, again to reduce the labor involved.

4. Results

a. u and v 2-h wind-change components

The 2-h 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. The standard deviations of both component changes ranged from 1.5 to 2.5 m s⁻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.

The higher moments require large sample sizes for accurate estimates. Table 3 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.

The skewness coefficients S (not shown) for u and v were both small ($|S| < 0.25$) 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, $-1.0 < S < -0.3$ in the winter, with a mean of -0.53 , and $-0.7 < S < -0.1$ for the transition season, with a mean of -0.25 . No cause 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

TABLE 2. Standard deviations (m s⁻¹) of the u and v components for the summer (sum), transition (tra), and winter (win) seasons as a function of level.

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 3. Sample size as a function of level and season.

Level	Summer	Transition	Winter
1	107 557	153 412	97 951
2	107 288	152 063	95 446
3	103 721	146 056	86 828
4	98 351	130 835	74 313
5	92 057	109 099	59 429
6	83 034	87 499	46 500
7	72 533	68 877	36 875
8	60 171	52 012	26 785
9	46 351	38 096	17 726

ranged from 4.4 to 9.6, 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. There was no systematic variation with altitude or 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-h lag times was found to be lognormally distributed. Figure 1 shows an example. The means of the six values of μ and σ derived from the moment pairs as described above were used to generate the model lognormal distribution shown in the figure (solid line) along with the measured data. The standard deviation of the six estimates of μ was 0.0055, and the standard deviation of the estimates of σ was 0.0038. This result indicates that all of the moment pairs are consistent, confirming the visual impression given by the figure that the measured distribution is lognormal.

The mean and standard deviation of $|\Delta\mathbf{V}|$ as well as the lognormal parameters varied with season, height,

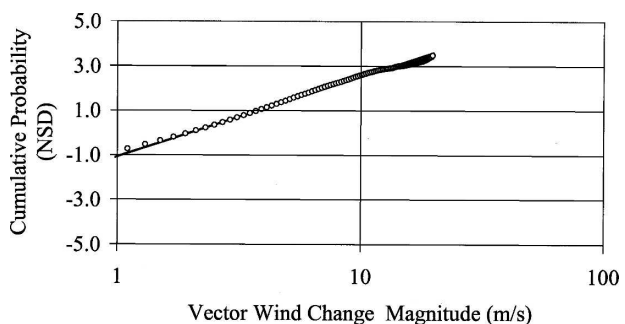


FIG. 1. The wind-change cumulative probability distribution for level 1 (534 m alt) at 2-h lag in the winter season. The open circles are the measured data. The solid line, mostly hidden under the data, is the calculated lognormal distribution with $\mu = 0.689 742$ and $\sigma = 0.640 49$. The units "NSD" refer to normalized standard deviations.

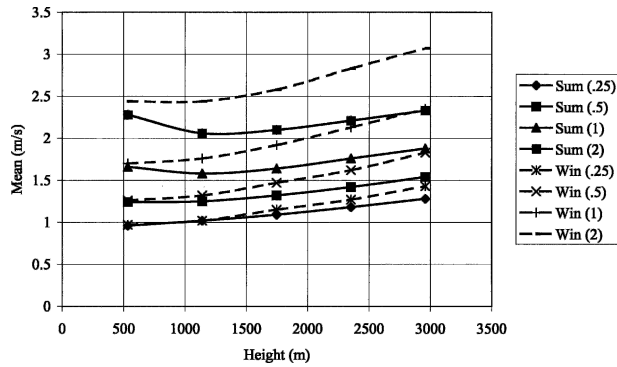


FIG. 2. The average of the magnitude of the vector wind changes as a function of height. In the legend, “Sum” denotes summer and “Win” denotes winter. The number in parentheses in the legend denotes the lag time (h).

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. The wintertime values are somewhat larger than the corresponding summer values, and the values and the seasonal differences both tend to increase slightly with altitude. The standard deviation (not shown) behaves similarly, as does the lognormal parameter μ shown in Fig. 3.

Merceret (1997) found that μ increased nearly linearly with the logarithm of the lag time ΔT , with a correlation coefficient $r^2 > 0.9$. He found σ to decrease with increasing $\log \Delta T$, but the linear relationship was weaker ($r^2 > 0.4$). The boundary layer data presented here demonstrate a similar relationship for μ , as may be seen from Fig. 4. The curve for the winter season at the highest level (2958 m) is nearly identical to 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 σ parameter does not show the same kind of

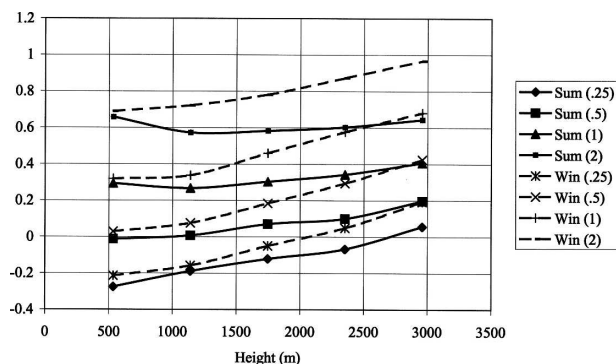


FIG. 3. Same as Fig. 2, except that the lognormal parameter μ for $|\Delta V|$ (m s^{-1}) is presented.

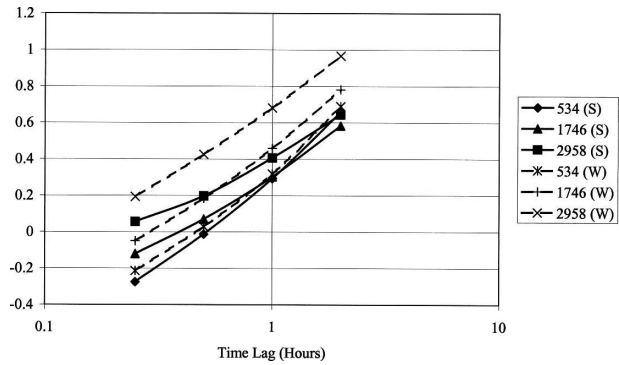


FIG. 4. The μ parameter as a function of time lag ΔT for selected altitudes. The S and W in parentheses in the legend respectively denote summer and winter seasons.

regularity found in the previous study, as may be seen from Fig. 5. Although there is still a tendency for σ to decrease with increasing $\log \Delta T$ for $\Delta T > 30$ min, the relationship is neither linear nor reliable. Figure 5 is on an expanded scale; thus one must take care not to overinterpret it. In any case, σ remains within 0.63 ± 0.06 throughout all seasons, levels, and lags. The range in the earlier study was about 0.65 ± 0.1 ; thus the results here are consistent.

5. Discussion

The probability distributions of the component velocity differences presented in section 4a are consistent with the findings of Castaing et al. (1990) for component velocity differences in high-Reynolds number (Re) wind-tunnel turbulence. 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

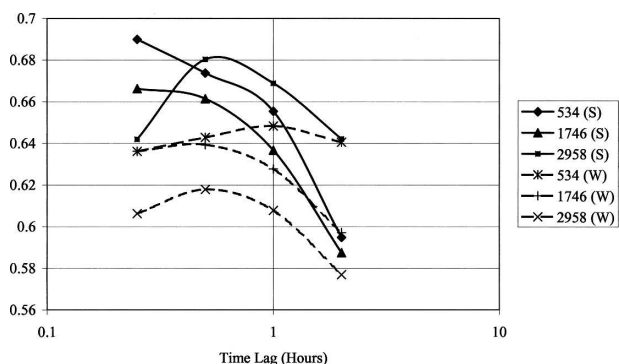


FIG. 5. Same as Fig. 4, but for the σ parameter.

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, wind changes at all altitudes involve nonlinear interactions. When applied to an output generated from the product, rather than the sum, of multiple variables, the central limit theorem produces a lognormal distribution. The nonlinearity of the equations of motion describes the multiplicative processes necessary to produce a lognormal distribution. This study confirms that the lognormal distribution found in the midtroposphere continues to apply in the ABL and extends the analysis to examine the variation of the parameters of the distribution with height and season.

The u and v statistics have been used along with an extensive database of "Jimsphere" balloon measurements archived by the Natural Environments Branch at the Marshall Space Flight Center to develop appropriate procedures for handling shuttle day-of-launch wind loads in the roll-maneuver region.

For risk analysis, the key result is that the lognormal parameter σ has the same value in the boundary layer as it does higher up. This result means that in the boundary layer, as well as higher in the atmosphere, the risk of large wind changes is greater than is estimated from the observed variance in the wind speed changes using the common Gaussian assumption. Indeed, the "three sigma" wind change is about 13 times more likely to occur with the actual lognormal distribution

than with the presumed Gaussian distribution having the same standard deviation (Merceret 1998). Because the relative risk is determined entirely by σ and is independent of μ (Merceret 1998), the risk analysis for the "max Q" region presented in Merceret (1997, 1998) may be applied quantitatively in the boundary layer as well.

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REFERENCES

- Carr, F. H., P. L. Spencer, C. A. Doswell III, and J. D. Powell, 1995: A comparison of two objective analysis techniques for profiler time-height data. *Mon. Wea. Rev.*, **123**, 2165–2180.
- Castaing, B., Y. Gagne, and E. J. Hopfinger, 1990: Velocity probability density fluctuations of high Reynolds number turbulence. *Physica D*, **46**, 177–200.
- Lambert, W. C., F. J. Merceret, G. E. Taylor, and J. G. Ward, 2003: Performance characteristics of five 915-MHz wind profilers and an associated automated quality control algorithm in an operational environment. *J. Atmos. Oceanic Technol.*, **20**, 1488–1495.
- Merceret, F. J., 1997: Rapid temporal changes of midtropospheric winds. *J. Appl. Meteor.*, **36**, 1567–1575.
- , 1998: Risk assessment consequences of the lognormal distribution of mid-tropospheric winds. *J. Spacecraft Rockets*, **35** (1), 111–112.