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**Spatial Correlation and Coherence of Boundary Layer Winds Near Cape Canaveral
Florida**

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Abstract

The spatial correlation and coherence of winds over separation distances from 8.5 to 31 km based on central Florida data from November 1999 through August 2001 are presented. The winds at altitudes from 500 to 3000 m were measured using a network of five radar wind profilers. The goal was to determine the extent to which the profilers may be considered independent data sources. 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 containing three consecutive gates, were selected for analysis. These levels covered the range from 433 to 3059 m. The results show that the profilers are independent for features having time scales of less than one hour in the winter or two hours in the summer. This does not depend significantly on height. Because the size of the network coincides with the “spectral gap” in the boundary layer, the result also does not depend on the spacing of the profilers within the network.

1. Introduction

This paper presents measurements of time-lagged cross-correlations and frequency spectral coherence of wind speeds obtained by a network of boundary layer wind profilers. Autocorrelations for time-separated wind profiles and coherence spectra in wave-number space obtained at a single spatial point are relatively easy to obtain: examples may be found in Merceret (2000) and Spiekermann and co-authors (2000). Spatial cross-correlations and coherences require a network of profilers with relatively close spacing, and such networks are rare. This study was motivated by inquiries about the independence of the data from the five boundary layer wind profilers in the network operated by the Air Force's Eastern Range (ER) at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS). It uses the same wind profile data base used for a statistical analysis by Merceret (2006). The goal was to provide objective guidance to decision-makers regarding the meteorological value of having multiple profilers in such a limited spatial domain. If the data are redundant at scales of interest for operational and safety applications, then cost savings may be obtained by reducing the number of profilers or eliminating all but one.

Section 2 describes the profiler network and data. Section 3 presents the analysis methodology. The results of the analysis are presented in Section 4 and are followed by a brief discussion in Section 5.

2. Instrumentation and 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 ER. The lowest gate was always near 130 m and the gate spacing was always 101 m. The radar wind profilers are numbered RWP1 through RWP5. Their locations are shown in Figure 1 and the distances between them are shown in Table 1.

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 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. Quantities Measured

The primary measurements reported here are cross correlations at time lag, L , and coherence spectra as a function of frequency between wind speeds (not wind components) measured at pairs of locations separated by known fixed distances, D , as noted above. The temporal autocorrelations and power spectra as a function of frequency for individual profilers and levels are also reported.

The correlation is the standard Pearson product-moment correlation $R_{xy}(D, L)$ (Wilks, 1995, eq. 3.17) with $x(0, t_0)$ being the windspeed at the first profiler of the pair at time t_0 and $y(D, t_0+L)$ being the windspeed at the second profiler at time $t_0 + L$. The lag, L , ranges from - 120 minutes to 120 minutes in fifteen minute intervals. In order to limit the sampling error of the estimates to a reasonable size, no correlation was accepted unless the sample size at each lag was at least 100. This provided a 95% confidence interval of about 0.04 for $R_{xy} = 0.9$ increasing to 0.15 as R_{xy} decreases to 0.3 (Otnes and Enochson, 1978, Sec. 7.6)

The coherence $C_{xy}(D, f)$ is the same as that presented in Merceret (2000) except in the frequency domain rather than the wave-number domain with spatial rather than

temporal separation between the profiles. Profiles were available every fifteen minutes and 32 points were used in the Fast Fourier transforms, thus requiring a record length of 8 hours per spectrum. The error of the estimates was limited by requiring at least 16 spectral estimates in each coherence value. The resulting 95% confidence interval is from 0.74 to 0.95 for a measured $C_{xy} = 0.9$. The interval widens rapidly, especially on the low side, as the coherence decreases. For a measured C_{xy} of 0.3, the limits are from 0.00 to 0.59 (Otnes and Enochson, 1978, Sec. 9.5). Unfortunately, to significantly improve the low side of the confidence interval would require prohibitive sample sizes.

b. Stratifications

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 for the earlier work from which this study is derived. The transition season was not included in this analysis.

In addition to the season, the data were stratified by time of day in order to capture diurnal effects. This stratification has four categories:

- summer day (SD) (1300 - 2200 UTC),
- summer night (SN) (0200 - 0700 UTC),
- winter day (WD) (1400 - 1900 UTC) and
- winter night (WN) (0200 - 0900 UTC).

For local time subtract 4 hours from UTC in the summer and 5 hours in the winter. These time blocks assured that all data attributed to "day" were taken during daylight and all data attributed to "night" were taken in darkness even when lagged for the purposes of computing the cross correlations.

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 the nine levels presented in Merceret (2006). For this analysis, only the odd numbered levels were used. These are shown in Table 2. 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 results.

Finally, an attempt was made to develop a wind direction stratification. Cases for which the wind direction was within 20 degrees (in either direction) of the line between a pair of profilers were denoted "along wind" cases. Cases within 20 degrees (in either direction) of the perpendicular to the line between the profilers were denoted "cross wind" cases. "All-wind" cases were processed without regard to the wind direction and included the along wind, cross wind, and all other cases. Unfortunately, the sample size for both the along wind cases and the cross wind cases proved too small to be very useful. This will be discussed further in Section 4 below. Except for that brief discussion, the remainder of this paper is based on the all-wind cases.

4. Results

a. Along and crosswind analysis

The sample sizes for the along-wind and cross-wind stratifications were typically an order of magnitude smaller than for the all-wind stratification. This resulted in no valid coherence data for either the along-wind or the cross-wind stratification. Valid cross-correlations were obtained in a limited number of cases. Given that there are five levels (1, 3, 5, 7 and 9) and four time stratifications (WN, WD, SN and SD) there are twenty possible combinations. Valid directional stratifications were obtained in only seven of these: WN1, WN3, WD1, SD1, SD3, SD5, and SD7. There were no data for summer nights and except for summer days, there were no data above level 3. The primary driving factor is that in order to produce valid directionally stratified data, the wind direction must remain within the forty degree angle centered on a line between two profilers (or its perpendicular) for the time required to produce a correlation (4 hours) or spectrum (8 hours). The natural variability of the wind direction is large enough that this does not occur often.

An examination of the available data indicates that the along-wind and cross-wind correlations do not differ in a systematic way. Their differences are generally within the error of estimate of the measurement except for summer days at the 8.5 km separation. In order to show this in the most compact way, the average over all lags and separation distances was computed for the following differences in correlations: all - along, all - cross and along - cross. Table 3 shows the results along with the standard deviation and sample size associated with each average. Where the standard deviation shown is small,

the along-wind, cross-wind and all-wind correlations are roughly equivalent. An example is shown in Figure 2.

Every case in Table 3 where the standard deviation of a difference is greater than or equal to 0.1 is a summer daytime case at a separation of 8.5 km. In the SD3 stratification, both large standard deviations are due entirely to the 8.5 km crosswind correlation which is pathological as shown in Figure 3. All of the directional correlations for the 8.5 km spacing are shown in Figure 4. In the SD1, SD5 and SD7 stratifications, the 8.5 km along wind correlation is significantly larger than the cross wind correlation. Levels one and five have nearly identical correlations and level seven differs only slightly from these two levels. At level three, not only is the cross-wind correlation erratic, but the along wind correlation is distinctly lower than that of the other three levels at all lags.

In the single case, summer days at 8.5 km spacing, where there are systematic differences between the along and cross-wind correlations, the most likely reason is the summer daytime sea-breeze. Typical sea-breeze propagation speeds are from five to ten meters per second, corresponding to about 15 to 30 minutes to travel 8.5 km. No obvious skewing of the peak correlation by that amount appears in the data, but the central peak near zero lag is so broad and gentle that such skewing would be hard to detect even if present. The distinct behavior of level three (near 1 km altitude) is consistent with it being near or just above the altitude of the transition region between the surface landward-directed sea-breeze flow and the ambient air aloft (Laird and co-authors, 1995; Zhong and Takle, 1993).

The lack of any directionally stratified data for summer nights, its availability at only the lowest levels during the winter, and the absence of any systematic difference between the along and cross-wind directions in these cases prevents any further meaningful analysis of the directional data.

b. All-wind correlation

1) Autocorrelations

The autocorrelations for each of the five profilers were similar but not identical for any given season, time and level. Except for summer nights, the differences were generally small.

For summer nights, there were significant differences at every level, but no consistent pattern or explanation could be found for them. Figure 5 shows level 7 as an example. Level 9 is similar to level 7 in that RWP 2 and 3 were distinctly less correlated at larger lag than the other profilers. At levels 3 and 5, RWP 2, 3 and 5 are grouped together at a lower correlation than RWP 1 and 4. Level 3 is shown in Figure 6. At level 1, RWP 1, 2 and 3 form a group with RWP 4 significantly higher and RWP 5 significantly lower as shown in Figure 7. The terrain and site locations do not seem to account for this behavior. Although RWP 2 and 3 behave alike at all levels, RWP 2 is on coast with few significant structures or trees whereas RWP 3 is in the center of Merritt Island in the KSC industrial area where both structures and trees are present. RWP 1 is located near the coast in a setting similar to RWP 2 except for a considerable number of nearby trees. RWP 4 is located in a forested area where the upwind fetch is primarily

over water for northeasterly winds and primarily over land for winds from the southwest. RWP 5 is located on the mainland at a commercial airport surrounded by trees.

The autocorrelations did not vary systematically with height for any season or time of day, but there was a marked variation with season at each level. Summertime autocorrelations were always smaller than those in the winter. An example is presented in Figure 8.

2) Cross correlations

The cross-correlations produced several interesting findings. Probably the most significant is that they do not vary systematically with separation distance over the range from 8.5 to 31 km examined in this study. The consequences of this will be discussed in Section 5 in conjunction with the coherence results of Section 4.c. Figure 9, which is typical, shows that while there is no significant systematic trend with separation distance at any lag, there can be noticeable variability among profiler pairs that are nearly the same distance apart. This variability is on the order of 0.05, and is generally within the sampling error of the measurement.

The second finding is that the cross-correlations can be a function of altitude, but the effect is strongly dependent on season and time of day. The only stratification with a clear and consistent pattern is summer days. As shown in Figure 10, the coherence decreases as the altitude increases for the smaller lags and for most levels at the larger lags. On the other hand, winter nights show little difference in correlation with altitude

and what difference there is shows no consistent pattern as may be seen in Figure 11.

Summer nights and winter days both behave like winter nights with the following exceptions:

- SN level 9 correlates lower by 0.1 than levels 3,5 and 7 at all lags
- SN level 1 correlates well with levels 3, 5 and 7 for lags less than 40 minutes in magnitude, but for larger lags it decreases until it matches level 9 for lag magnitudes (see bullet above) greater than 80.
- WD level 1 is less well correlated than the other levels. The difference ranges from about 0.02 near zero lag to about 0.1 at +/- 120 minutes.

Possible explanations for this behavior are discussed later in this section.

The third finding is that regardless of time of day or altitude, the cross-correlations are lower in the summer than in the winter. Figure 12 shows level 5, typical of the atmosphere above the surface layer, while Figure 13 shows level 1, the lowest level.

The second and third findings are consistent with the atmospheric forcing over central Florida. In the winter, the wind field is synoptically driven. In the summer the flow is dominated by local seabreeze and riverbreeze circulations complicated by convection.

Winter nights generally provide the most stable atmospheric thermal stratification whereas summer days are generally the most unstable with the other two stratifications in between. As noted in Section 4a above, summer days usually have strong afternoon sea-

breezes that have a semi-coherent onshore flow in the lower levels with a weaker, more diffuse return flow aloft. Summer nights frequently have a weak and shallow off-shore-directed land-breeze, often confined well below level 1 but sometimes extending to that level (Case and co-authors, 2005; Zhong and Takle 1992, 1993). Modeling studies of this complex circulation by Zhong and Takle (1993) show considerable structure with time scales of one to two hours at horizontal scales comparable to the separation distances between the profilers. On winter nights when these locally-induced structures are weak, the correlations at each level are most-likely dominated by the large scale pressure-gradient-driven flow which is coherent over the entire depth of the boundary layer. This is consistent with the lack of any systematic variation with height in the correlations.

Summer days are characterized by convectively driven local circulations embedded in the synoptic flow. The synoptic flow is frequently sheared, and additional vertical shear results from the sea-land-breeze circulation. Near the surface, the profilers are affected primarily by the local horizontal circulations arising in their immediate vicinity. Above the surface layer, the effects of thermally driven convection become significant across a broad range of horizontal and vertical scales including strong contributions to the variance at scales smaller than the spacing between the profilers (Plank, 1969; Lopez and co-authors, 1984). As the altitude increases, the effects of advection in the sheared flow aloft become more important in the presence of the convective vertical mixing. At the higher altitudes, the wind profile is a product of non-linear interactions over a much larger geographical area, also resulting in increased variance. The behavior of the SN correlations supports this hypothesis. The convective

structure decays in the late afternoon and early evening (Lopez and co-authors, 1984). At small lags, the correlations are based on times close enough together that advective and non-linear mixing effects have not had time to overwhelm the semi-coherent local structure. As the time difference becomes larger, the two flow regimes being correlated are still being locally generated, but under different thermal conditions. The behavior of WD correlations is also consistent with this hypothesis. In the winter, local thermally driven circulations continue to occur, but they are weak and shallow, and do not frequently include a night land-breeze (Case and co-authors, 2005).

c. All-wind power and coherence spectra

Power and coherence spectra are only available for winter nights (WN) and summer days (SD) because the required minimum record length of 12 hours to generate each spectrum was longer than the period of daylight during the winter or the period of darkness during the summer.

1) Power spectra

The power spectra displayed conventional boundary layer power-law behavior as shown in Figure 14 which is typical. The reference line in the figure has an inertial subrange slope of $-5/3$ for comparison. At the higher altitudes during the summer the spectral slope sometimes flattened out near the Nyquist frequency. There are two possible causes for the spectral flattening, both of which may be contributing. The first is low signal to noise ratio, which tends to produce a flat “white noise” spectrum. The second is spectral aliasing due to frequency content above the Nyquist frequency. Since by the nature of the radar profiler’s method of operation no pre-sampling analog filtering is

possible, some aliasing is unavoidable. A “worst case” is shown in Figure 15. This is probably due to summertime buoyant production of convective scale variance.

2) Coherence spectra

The coherence spectra have the same general characteristics for both seasons at all separations and levels. Generally, the coherence is greater than 0.4 and can be more than 0.8 at the lowest frequency, 3.47×10^{-5} Hz, which corresponds to a period of about 8 hours. The coherence decreases roughly linearly with the logarithm of the frequency until it falls below 0.2 at a frequency that depends on season, level and separation distance. At higher frequencies, the coherence fluctuates randomly between 0 and about 0.3, which is within the confidence interval of any value less than 0.2.

As expected, at the smaller separations the coherence was generally larger at a given frequency, and coherences greater than 0.3 extended to higher frequencies in both seasons. Figure 16 shows the coherence for winter nights at level 1. Figure 17 shows the corresponding summer daytime data. The main difference is that the SD coherence drops off more rapidly as the frequency increases. This is consistent with the presence of more local convectively-generated structure on horizontal scales smaller than the separation between the profilers during summer days, as was also expected. The frequency at which the WN coherence falls below 0.3 is about 3×10^{-4} Hz corresponding to a period of 0.9 hours. The corresponding SD frequency is about half that, corresponding to a period near 2 hours.

For a fixed separation distance there is no clear pattern of variation of coherence with height. Figure 18 shows both seasons at a separation distance of 18 km. The other distances behave similarly. The summer values are generally smaller as noted above, but within either season, the curves for the different levels approach or even cross one another and no consistent height ordering occurs.

5. Discussion

Section 4.b. (2) showed that the correlations are independent of the separation distances. This requires that the coherent part of the flow field be at scales larger than, rather than similar to, those distances. It also requires that the incoherent part of the flow have most of its variance at scales smaller than, rather than similar to, the separation distances. Thus, there must be a “spectral gap” at the scale of the profiler network. The concept of a spectral gap is well established in boundary layer meteorology, and in frequency space it occurs at frequencies equivalent to periods from tens of minutes to several hours as shown, for example, in Figure 2.2 of Stull (1988). For advective wind speeds of 5 to 10 m s⁻¹ which are typical of the Cape Canaveral area, the corresponding spatial scales are from less than three to more than 60 km. These scales completely cover the 8.5 to 31 km range of separations used in this study.

The coherence results in section 4.c.(2) are consistent with a spectral gap at these frequencies. The coherence is large at the lowest frequency corresponding to a period of 8 hours but declines logarithmically with frequency until there is no detectable coherence for periods less than one to two hours depending on the season. Since the power

spectrum is also declining rapidly over the same spectral region as shown in section 4.c.(1), the amount of coherent variance present at time scales of less than two hours is negligible compared to that at longer time scales.

The presence of the spectral gap simplifies using the results to answer the question motivating the study: to what extent are the measurements taken by the profilers in the network independent? The answer is that for features with time scales less than two hours, they are essentially independent. For features with time scales longer than two hours they become coherent, becoming highly coherent for time scales longer than four hours. This result depends somewhat on season, with the scales of motion over which independence is maintained are about a factor of two larger in the convective season. It does not depend much on height.

In an environment often dominated by rapidly moving sea-breeze, land-breeze and thunderstorm outflow boundaries, phenomena on the scale of two hours or less can be highly important to spaceport operations. Toxic hazard assessment models can be highly sensitive to small changes in wind direction in both the horizontal and the vertical (Boyd and co-authors, 2006; Sullivan and co-authors, 1993). Boyd and co-authors (2002) give an example where RWP 1, 2 and 3 had easterly winds but RWP 4 had more northeasterly flow near the surface becoming easterly only at higher altitudes. The difference was enough to allow a launch that would have violated toxic hazard constraints if the full spatial distribution had not been known. Thus, the results presented

here strongly suggest that reducing the number of profilers in the network will remove information at scales of operational interest.

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Table Captions

Table 1. Distance and bearing between pairs of instruments in the ER boundary layer profiler network.

Table 2. Definition of the five levels used in the analysis.

Table 3. Average, standard deviation and sample size for differences between all-wind, along-wind and cross-wind correlations for available stratifications and levels. WN1 denotes Winter Night Level 1 and so forth where S = Summer, D = Day.

Tables

Profiler Pair	Distance (km)	Bearing (deg)
2,3	8.45	238
3,5	14.42	243
3,4	15.07	339
2,4	15.86	307
1,3	16.03	328
1,2	18.09	356
4,5	21.93	200
1,5	22.46	288
2,5	22.85	241
1,4	30.97	333

Table 1. Distance and bearing between pairs of instruments in the ER boundary layer profiler network.

Level	Low Gate	Mid Gate	High Gate	Low Alt (m)	Mid Alt (m)	High Alt (m)
1	4	5	6	433	534	635
3	10	11	12	1039	1140	1241
5	16	17	18	1645	1746	1847
7	22	23	24	2251	2352	2453
9	28	29	30	2857	2958	3059

Table 2. Definition of the five levels used in the analysis.

Quantity	WN1	WN3	WD1	SD1	SD3	SD5	SD7
All - Along Avg	0.014	0.021	0.006	0.026	0.028	0.053	0.046
All - Along Std Dev	0.061	0.029	0.051	0.068	0.047	0.115	0.113
All - Along Count	170	170	119	119	119	85	85
All - Cross Avg	0.018	0.005	-0.010	0.033	-0.030	0.029	0.017
All - Cross Std Dev	0.053	0.018	0.032	0.086	0.148	0.093	0.042
All - Cross Count	170	170	119	119	136	119	85
Along - Cross Avg	0.003	-0.016	-0.010	0.028	-0.045	-0.066	0.015
Along - Cross Std Dev	0.089	0.037	0.064	0.100	0.132	0.158	0.067
Along - Cross Count	170	170	102	68	102	85	68

Table 3. Average, standard deviation and sample size for differences between all-wind, along-wind and cross-wind correlations for available stratifications and levels. WN1 denotes Winter Night Level 1 and so forth where S = Summer, D = Day.

Figure Captions

Figure 1. Locations of the five boundary layer profilers used in this study. The profilers are numbered as follows: South Cape = 1, False Cape = 2, Merritt Island = 3, Mosquito Lagoon = 4 and TICO = 5.

Figure 2. All-wind, along-wind and cross-wind correlations at levels one and three for winter nights.

Figure 3. Cross-wind correlations at level 3 for summer days at separations of 8.5, 16, 18.1, 22.9 and 31 km.

Figure 4. Along and cross wind correlations for summer days at 8.5 km spacing. The two character identifiers denote the level (1 through 7) and along-wind (A) or cross-wind (C).

Figure 5. Autocorrelations for all five RWP for summer nights at level seven.

Figure 6. Autocorrelations for all five RWP for summer nights at level three.

Figure 7. Autocorrelations for all five RWP for summer nights at level one.

Figure 8. RWP1 level 5 autocorrelation as a function of season and time of day.

Figure 9. Cross-correlations for winter nights at level 1 as a function of separation distance for selected lags.

Figure 10. Summer day cross-correlations at 18 km spacing for various levels.

Figure 11. Winter night cross-correlations at 18 km spacing for various levels.

Figure 12. Level 5 correlations at 18 km spacing for seasonal and temporal stratifications.

Figure 13. Level 1 correlations at 18 km spacing for seasonal and temporal stratifications.

Figure 14. Power Spectra for all five profilers for winter nights at level 3. A reference line with a slope of $-5/3$ is included.

Figure 15. Power Spectra for RWP 1, 2 and 4 for summer days at level 7. A reference line with a slope of $-5/3$ is included. RWP 3 and 5 are not included because they did not meet the minimum sample size criterion.

Figure 16. Coherence spectra for winter nights at level 1 for various separation distances (km).

Figure 17. Coherence spectra for summer days at level 1 for various separation distances (km).

Figure 18. Coherence spectra for a separation distances of 18 km for winter nights (WN) levels 1 through 5 and summer days (SD) levels 1 through 7. Higher levels did not meet the required minimum sample size.

Figures

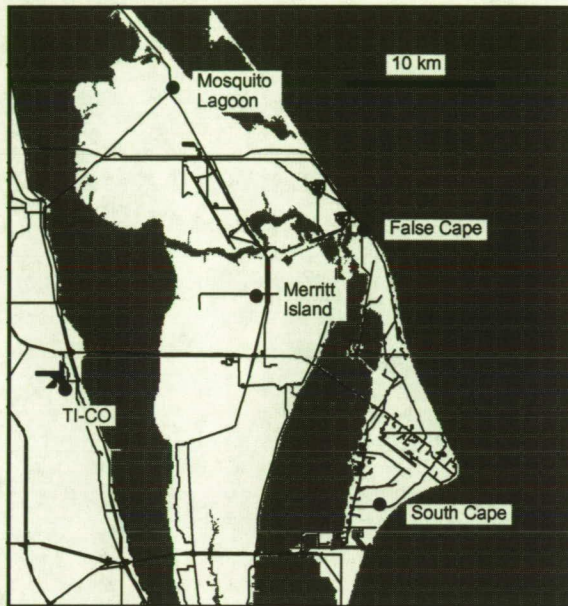


Figure 1. Locations of the five boundary layer profilers used in this study. The profilers are numbered as follows: South Cape = 1, False Cape = 2, Merritt Island = 3, Mosquito Lagoon = 4 and TICO = 5.

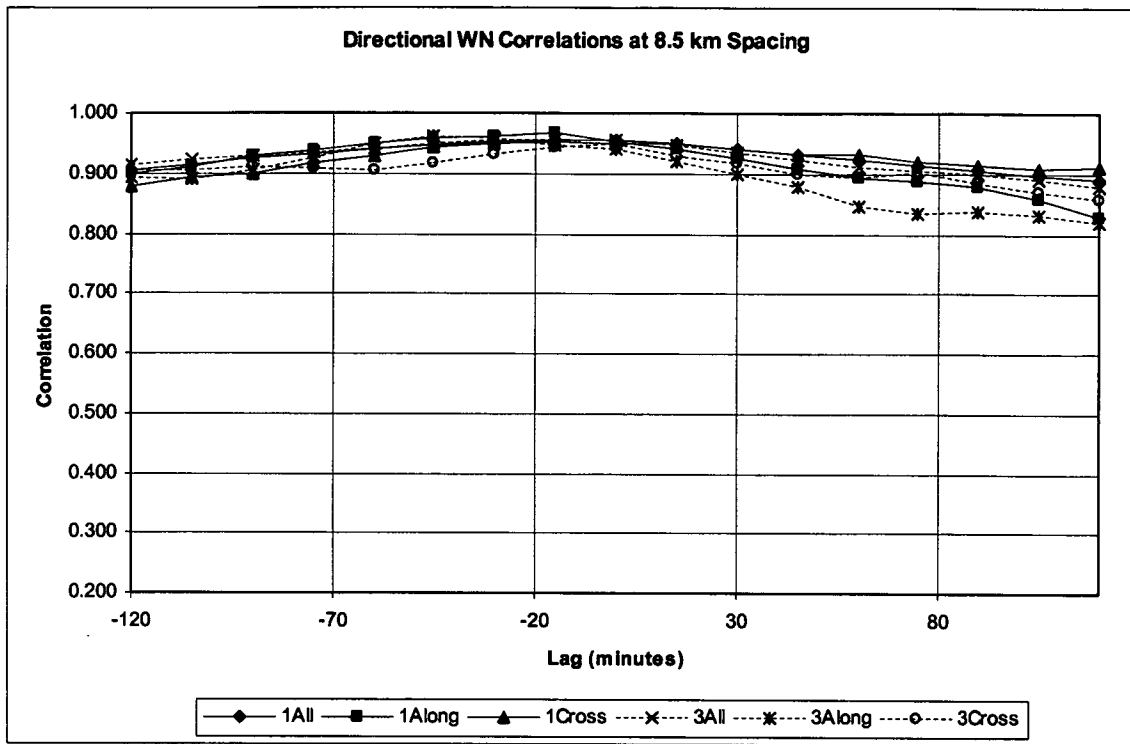


Figure 2. All-wind, along-wind and cross-wind correlations at levels one and three for winter nights.

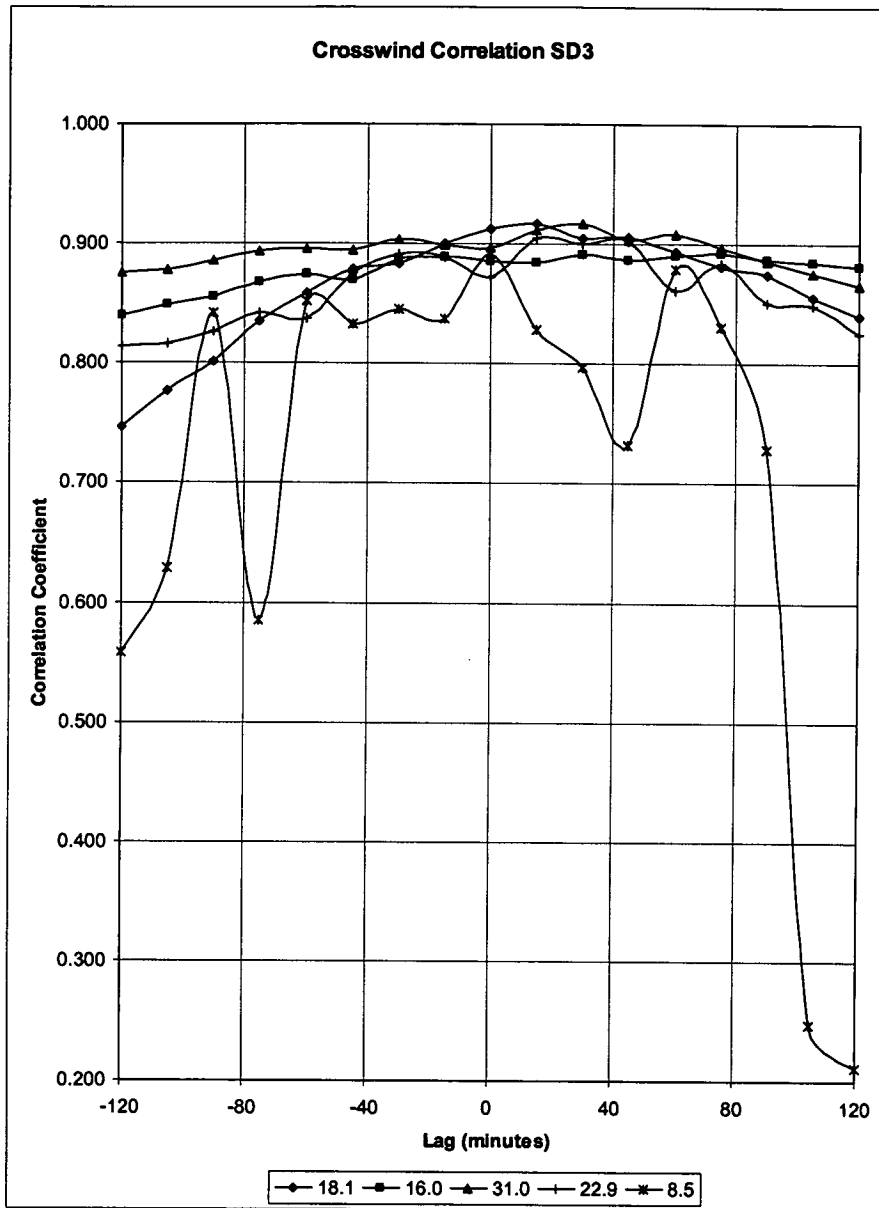


Figure 3. Cross-wind correlations at level 3 for summer days at separations of 8.5, 16, 18.1, 22.9 and 31 km.

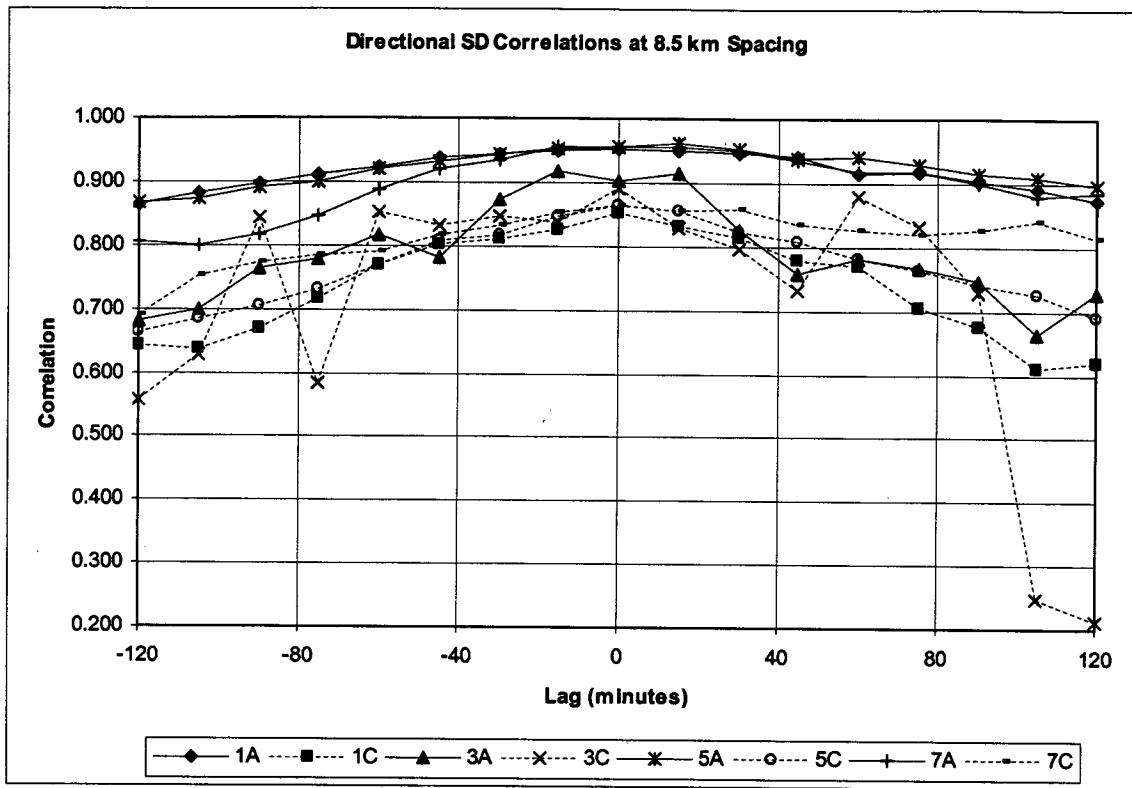


Figure 4. Along and cross wind correlations for summer days at 8.5 km spacing. The two character identifiers denote the level (1 through 7) and along-wind (A) or cross-wind (C).

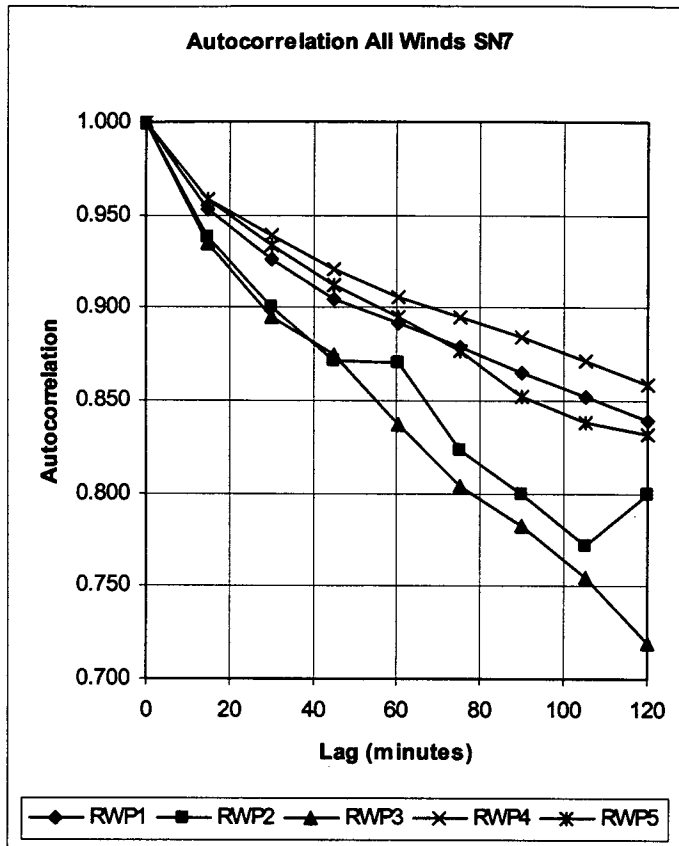


Figure 5. Autocorrelations for all five RWP for summer nights at level seven.

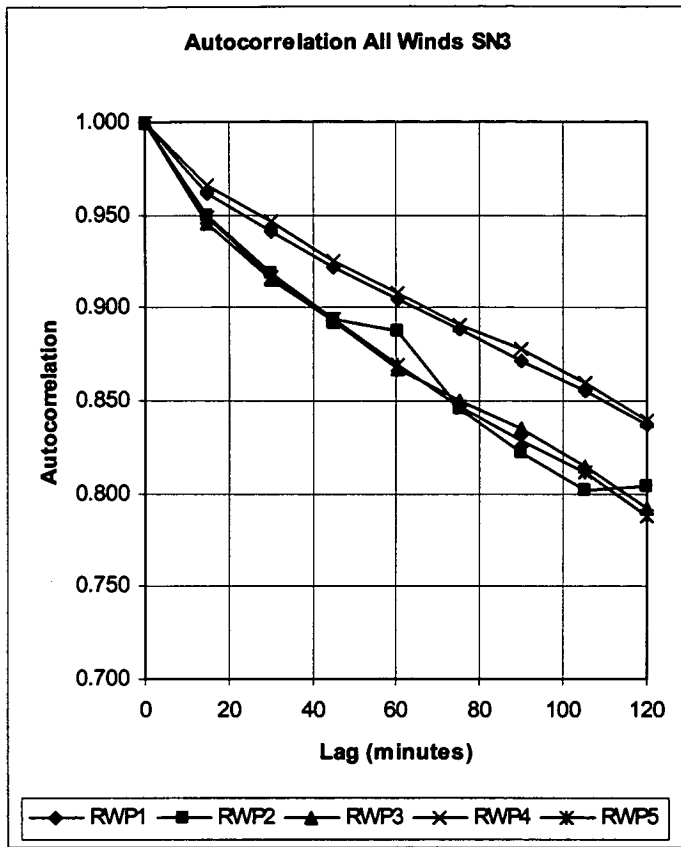


Figure 6. Autocorrelations for all five RWP for summer nights at level three.

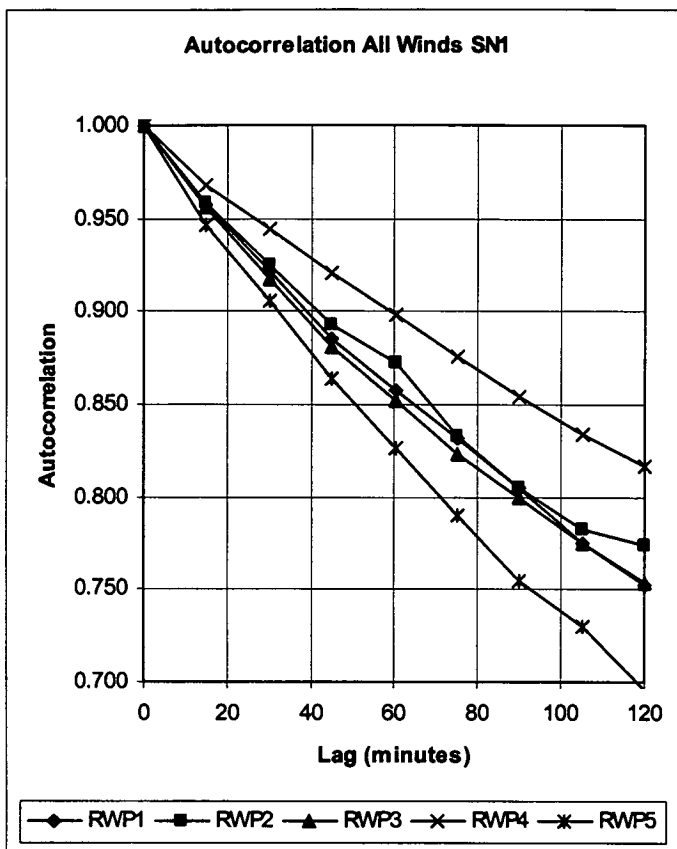


Figure 7. Autocorrelations for all five RWP for summer nights at level one.

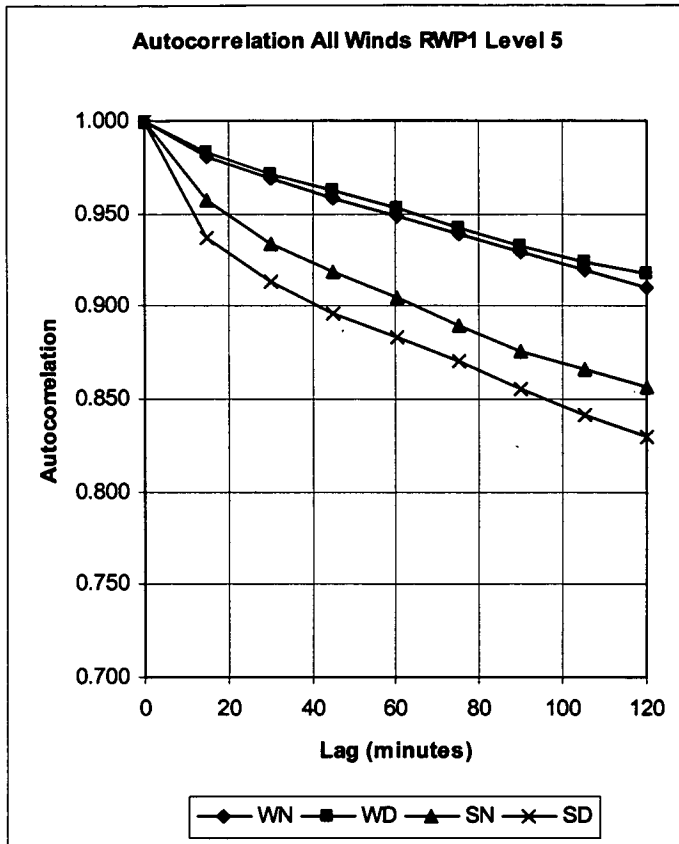


Figure 8. RWP1 level 5 autocorrelation as a function of season and time of day.

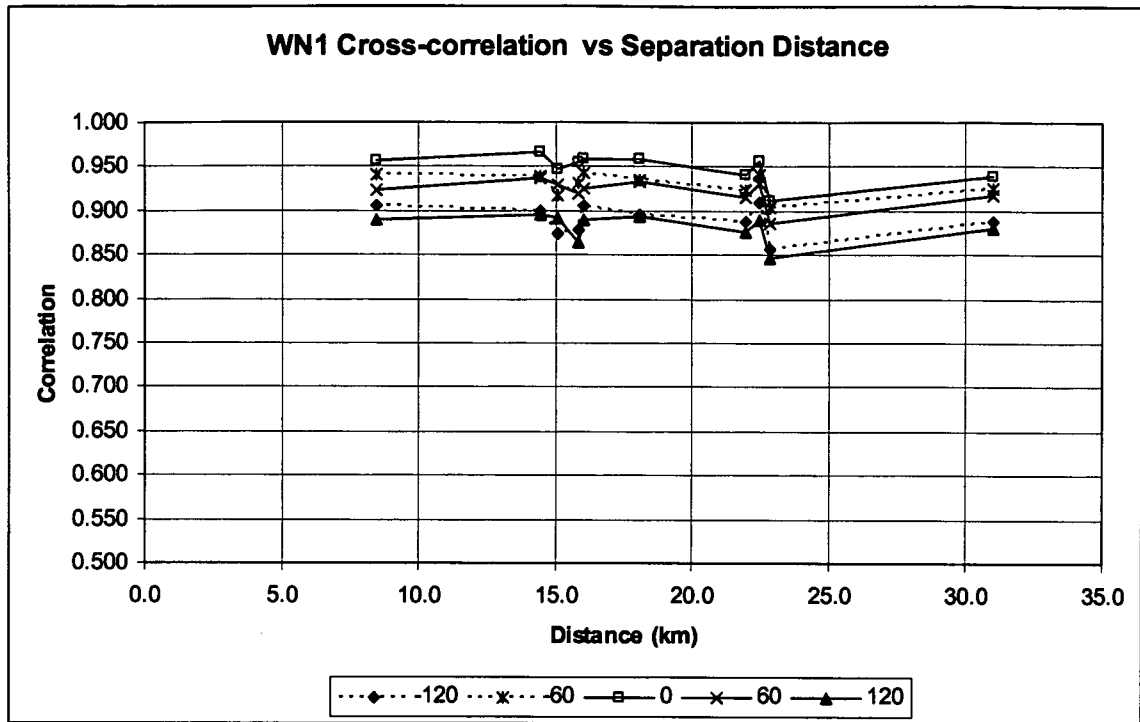


Figure 9. Cross-correlations for winter nights at level 1 as a function of separation distance for selected lags.

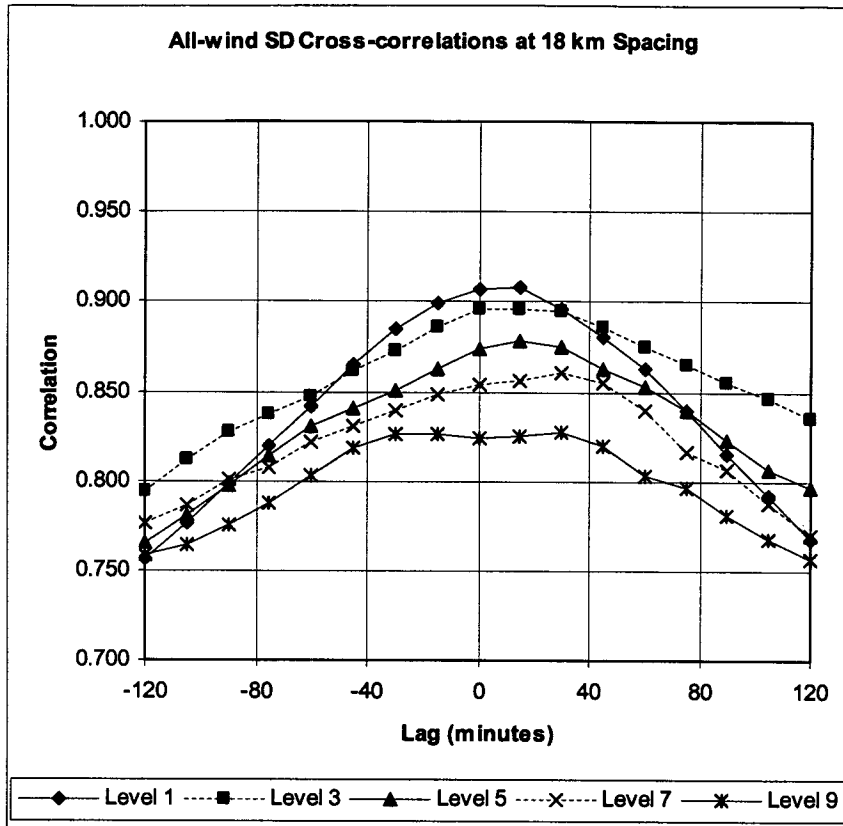


Figure 10. Summer day cross-correlations at 18 km spacing for various levels.

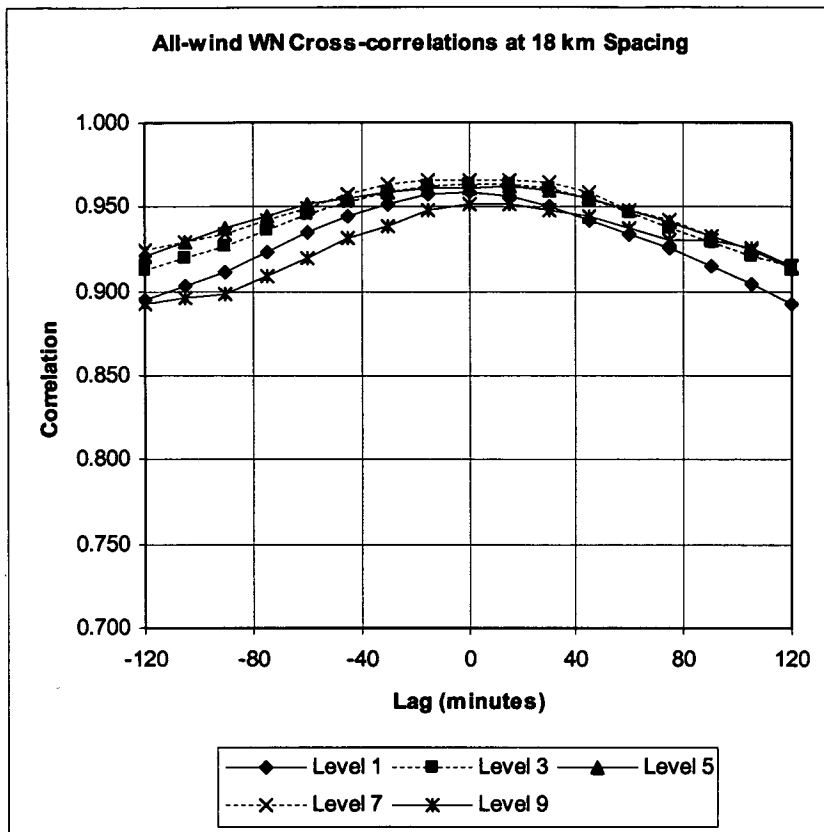


Figure 11. Winter night cross-correlations at 18 km spacing for various levels.

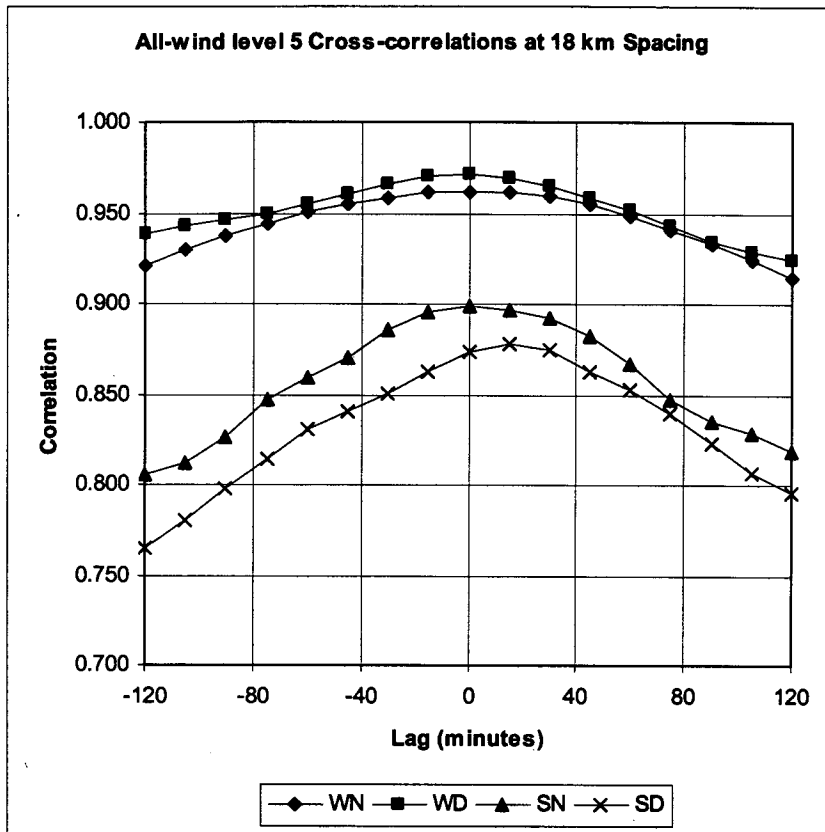


Figure 12. Level 5 correlations at 18 km spacing for seasonal and temporal stratifications.

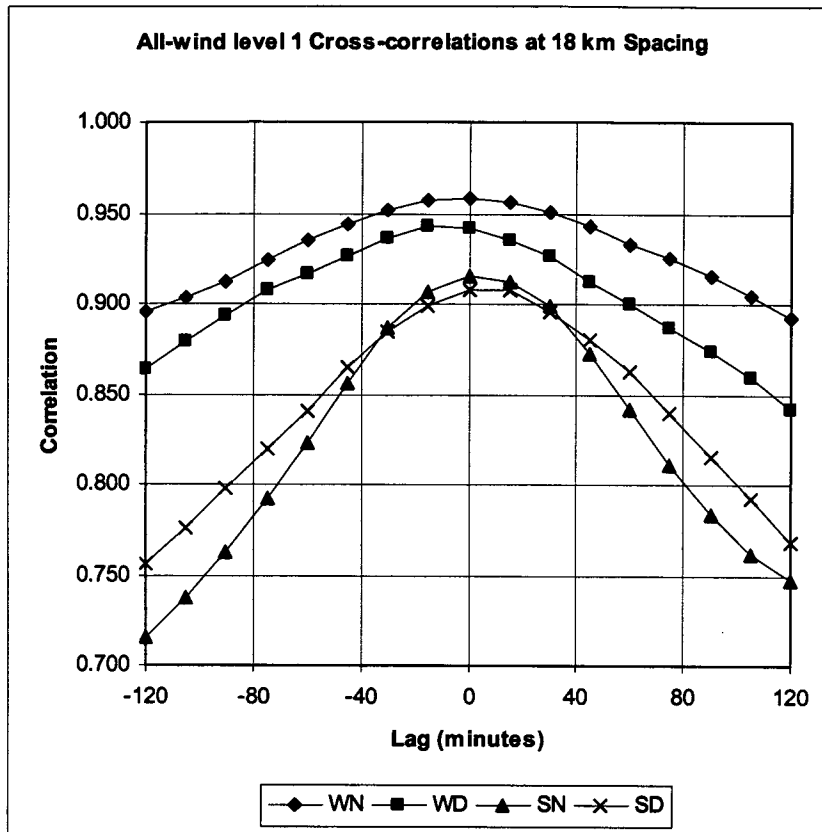


Figure 13. Level 1 correlations at 18 km spacing for seasonal and temporal stratifications.

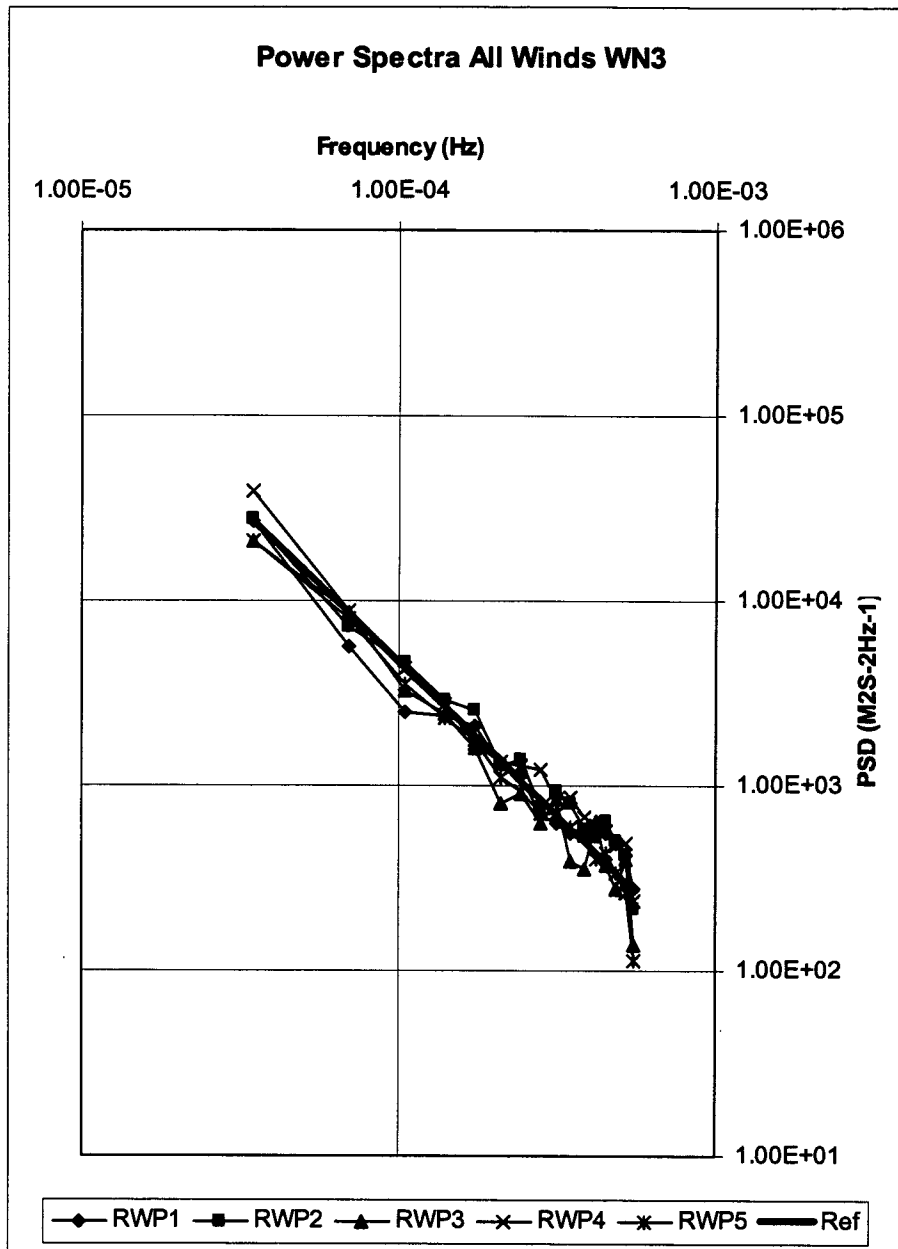


Figure 14. Power Spectra for all five profilers for winter nights at level 3. A reference line with a slope of $-5/3$ is included.

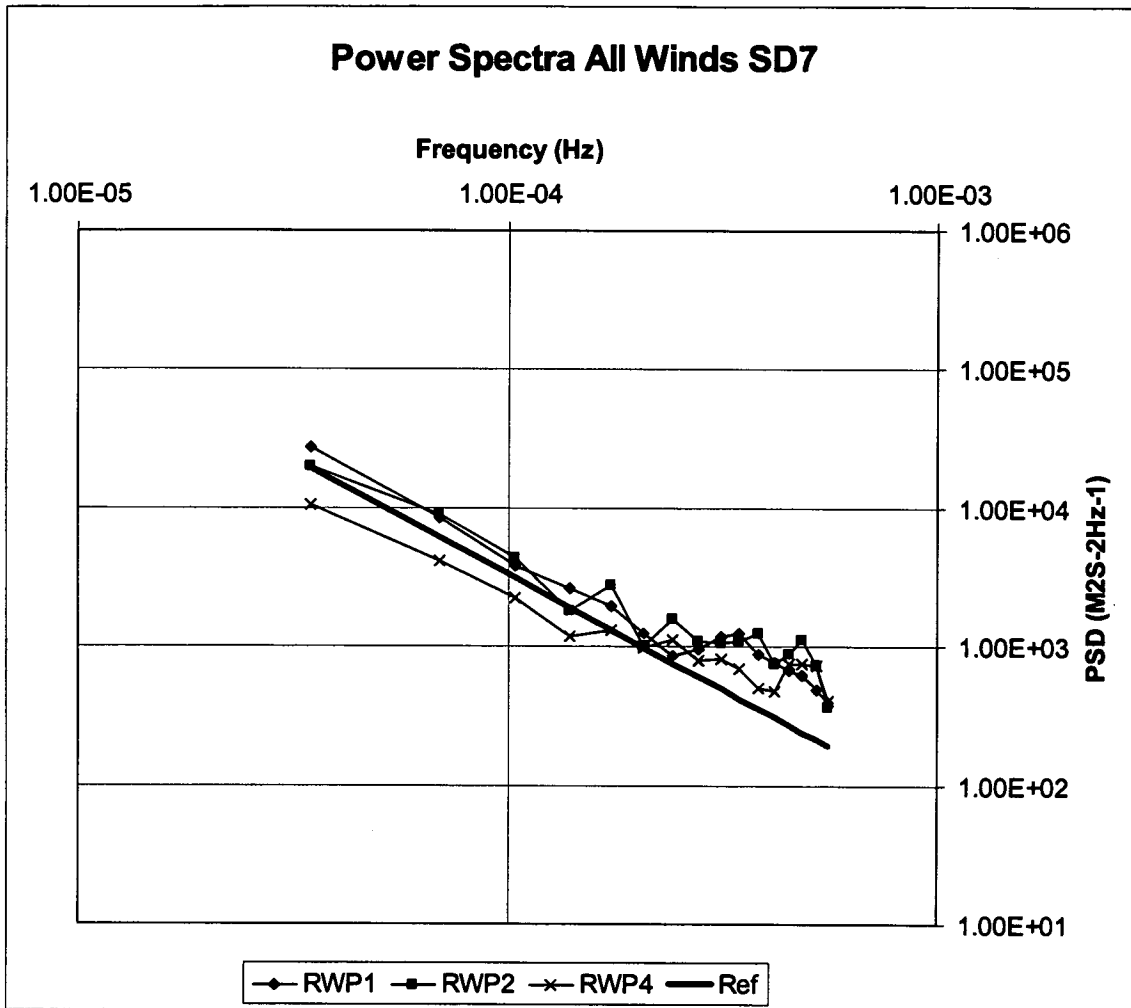


Figure 15. Power Spectra for RWP 1, 2 and 4 for summer days at level 7. A reference line with a slope of $-5/3$ is included. RWP 3 and 5 are not included because they did not meet the minimum sample size criterion.

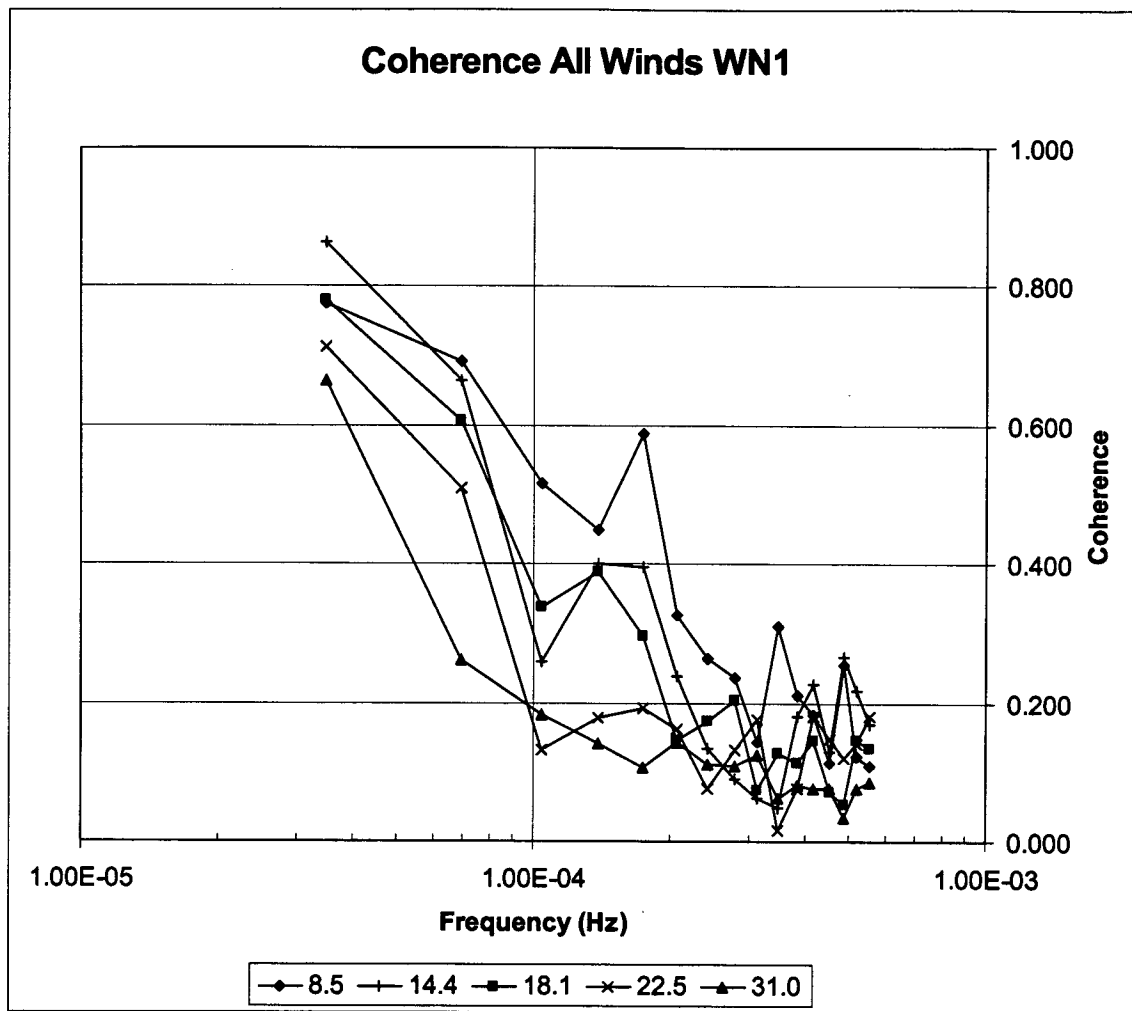


Figure 16. Coherence spectra for winter nights at level 1 for various separation distances (km).

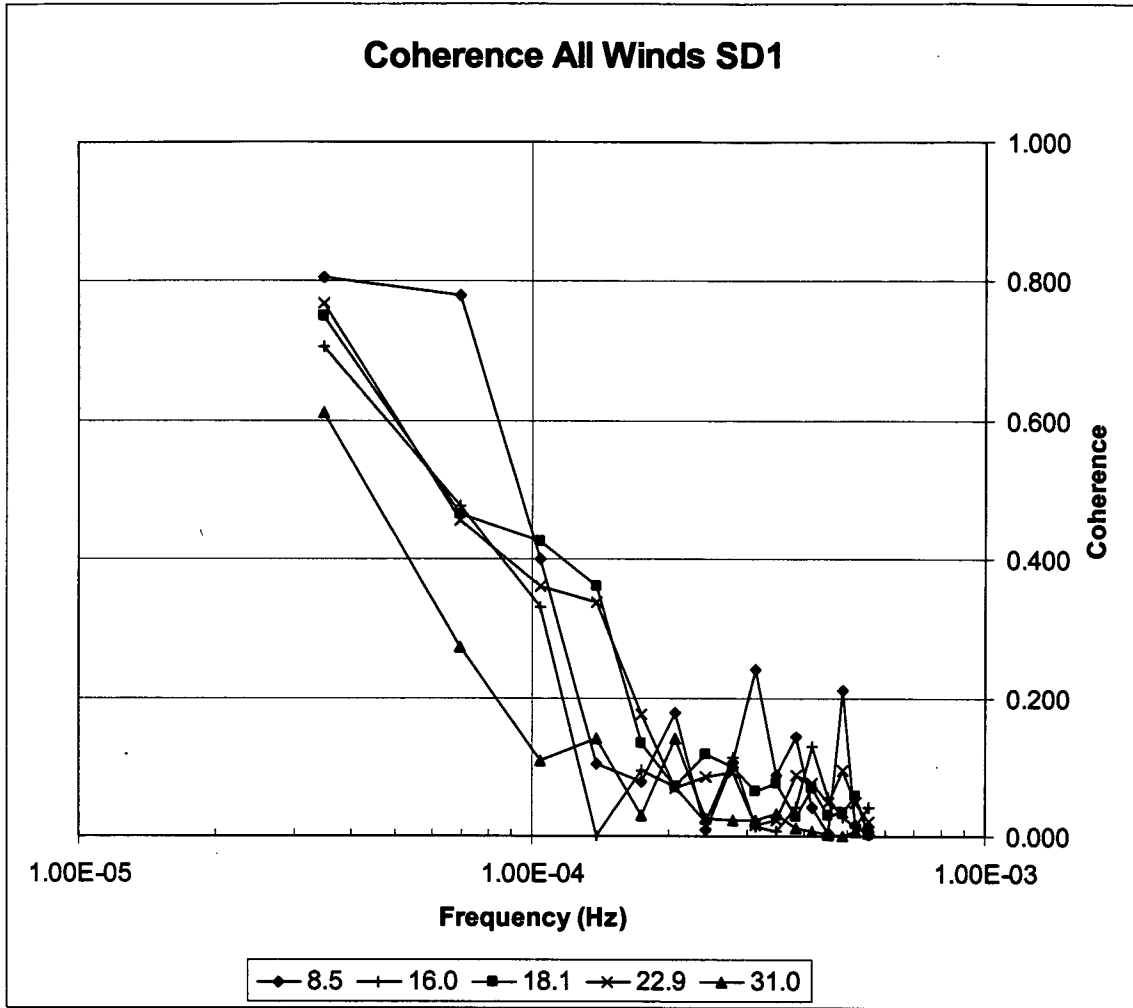


Figure 17. Coherence spectra for summer days at level 1 for various separation distances (km).

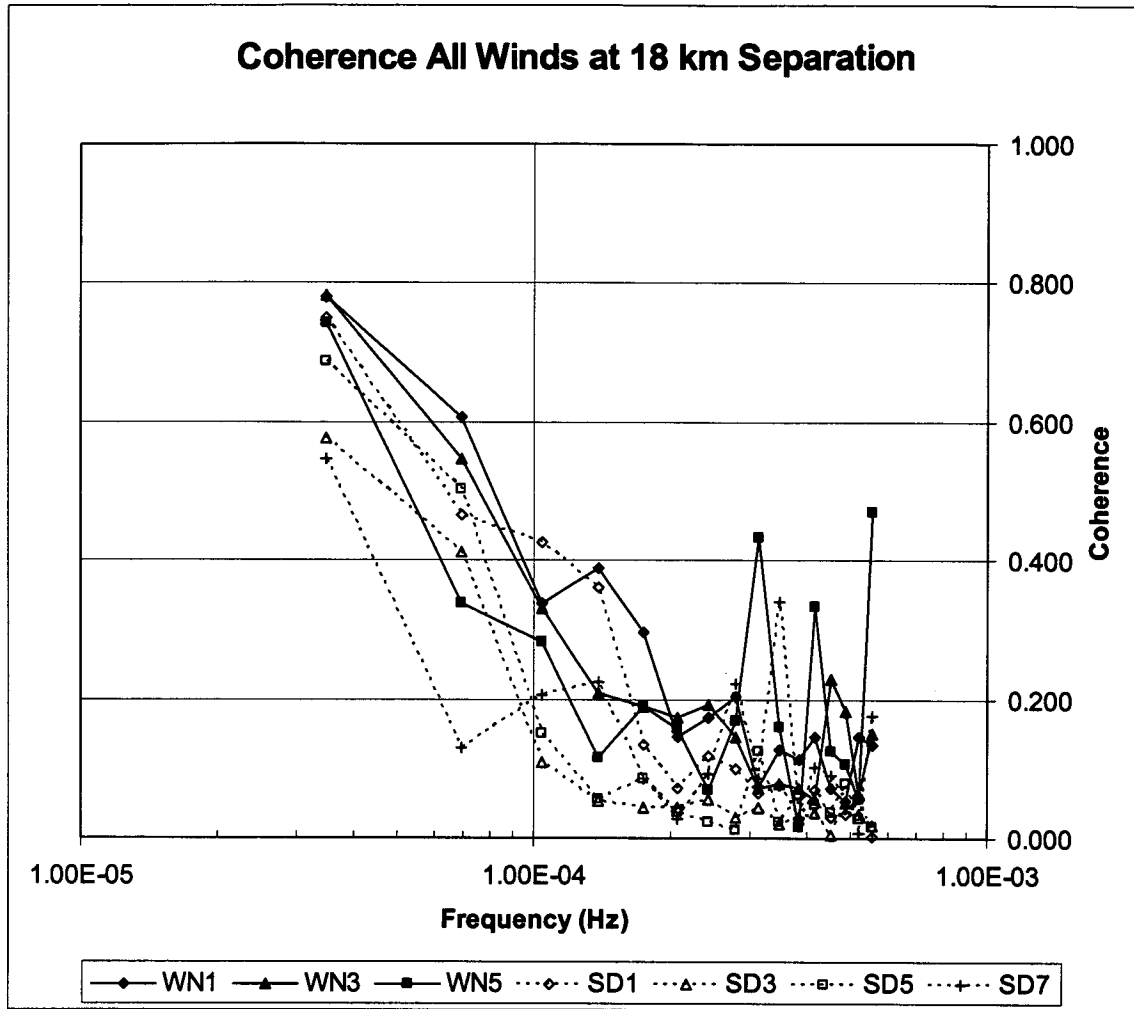


Figure 18. Coherence spectra for a separation distances of 18 km for winter nights (WN) levels 1 through 5 and summer days (SD) levels 1 through 7. Higher levels did not meet the required minimum sample size.