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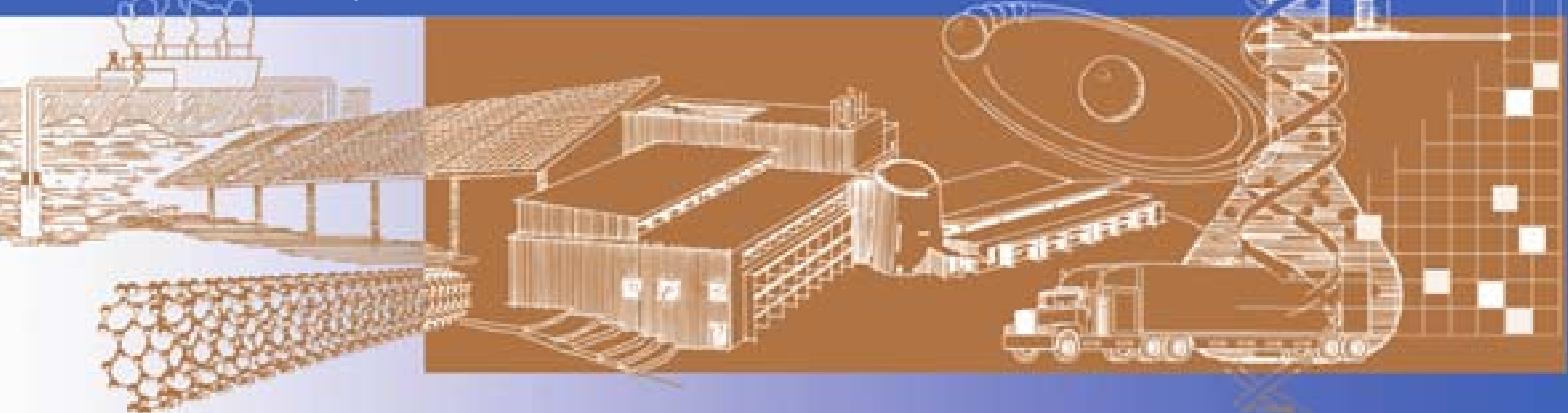

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Coastal and Marine Tall-Tower Data Analysis

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Background

To achieve the goal of producing 20% of the United States' electricity from wind energy, wind farm locations will have to include many different types of terrain and geography. The structure of the lower atmospheric boundary layer, 0-200 meters (m) above the surface, varies significantly among different terrains and wind climates. It is important to closely analyze the wind characteristics at modern wind turbine hub-heights (70 m to 100 m above the surface) in as many regions as possible to reduce uncertainty about the resource and enhance wind farm design. Though still not common, an increasing number of tall (70-m+) towers have been outfitted with anemometers and vanes at several levels. These data have helped fill the gap of wind characteristic knowledge throughout the United States. This study analyzed wind characteristics at tall tower sites in coastal and marine environments in the eastern United States. This study follows previous analyses of tall-tower data that concentrated on data from specific states (Schwartz and Elliott, 2005) and studied wind shear characteristics at towers in the Central Plains of the United States (Schwartz and Elliott, 2006). Four towers were used in the study. The towers were located: 1) on the shore of Lake Erie; 2) on an island in the Delaware Bay/River estuary; 3) in an oceanic-side sound about 15 km from the Massachusetts shore; and 4) along an inland sound opposite a barrier island in coastal North Carolina. Figure 1 shows the locations and names of the four towers. Three towers had the highest measurement level between 90 m and 120 m. The highest level on the ocean tower was 60 m. Because of the proprietary nature of the data from several towers, wind speed information from the towers will not be discussed in this paper. This analysis emphasizes wind shear characteristics, similar to what was presented in the Central Plains tall-tower study, plus some information on the prevailing wind direction and diurnal and seasonal wind patterns.

Approach

The overall data quality, data recovery rates, and minimal tower flow interference were the criteria used to create high-quality data sets from each tall-tower location used in this study. The technique of analyzing wind speed and frequency by direction data was again used to identify interference with the air flow caused by tower effects at each site. The details of this technique have been discussed in previous papers (Schwartz and Elliott, 2006). The wind shear exponent α (alpha) is very sensitive to flow distortions caused by the tower or equipment at a measurement site. We believe the directly measured alpha values of the measurement levels used for this study to be within a 0.05 range of accuracy. A measured 0.2 alpha value likely represents an envelope of values between 0.175 and 0.225.

The analysis used wind speed data at each tower from the lower levels ranging from 40 m to 60 m up to its highest anemometer for the wind shear information. Wind shear characteristics were calculated by averaging all alpha values from individual measurements between levels with speeds of at least 3.0 meters per second (m/s) occurring at the same time. Analyzed wind shear characteristics include annual average alpha values, diurnal and seasonal variability, shear variation by prevailing wind direction, and the distribution of alpha values.

Analysis Results

Table 1 shows the four tall towers used in the study, the levels on each tower used for analysis, the periods-of-record, and the annual average alpha value for the study levels. The periods-of-record at the four towers vary widely. Approximately 4 to 5 years of measurement data were

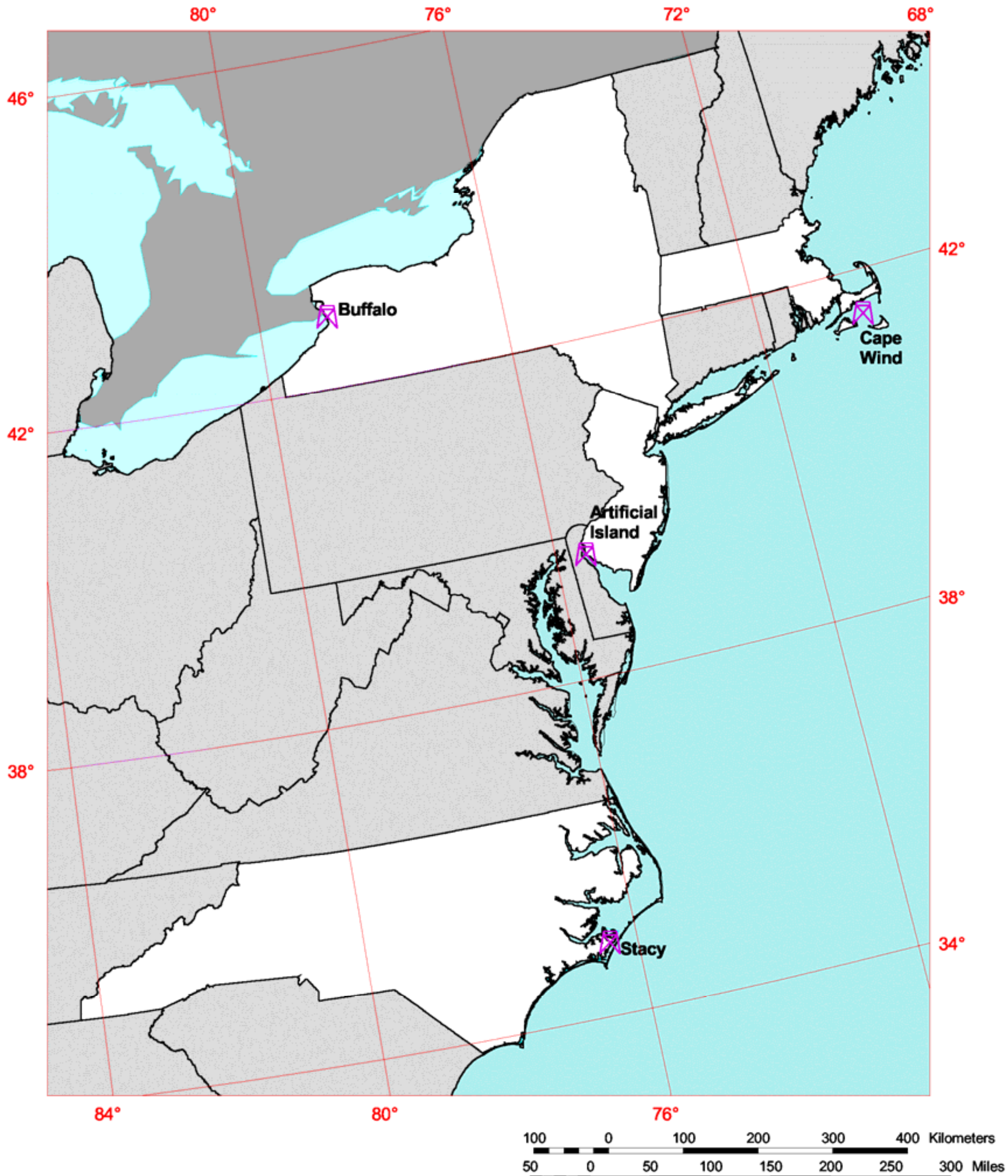

Figure 1. Location of tall-tower study stations

available at the Artificial Island and Cape Wind towers. In contrast, under a year of data was available for the Buffalo and Stacy tall-tower locations. The shorter periods-of-record increase the uncertainty of the shear statistics but we believe the general trends discussed in this paper would still be valid for longer measurement periods.

Annual Average

The annual alpha values for the four towers ranged from 0.147 to 0.272. These values are not significantly different from those derived in previous studies of inland tall-tower sites. The

Table 1. Names, anemometer heights, periods-of-record, and annual average alpha values for tall-tower stations. Anemometer heights in bold were used to calculate shear statistics.

Site Name	**Anemometer Heights**	**From**	**To**	**Shear (α)**
Buffalo, NY	(28), **59, 110**	04-01-2003	06-30-2004	0.148
Artificial_Island, NJ	(10), **46, 91**	01-01-1999	09-30-2004	0.200
Cape Wind, MA	(20), **40, 60**	04-03-2003	03-31-2007	0.147
Stacy, NC	**62**,(92), **120**	07-09-2006	02-28-2007	0.272

similarity of shear values to inland sites is not surprising at the three stations (Buffalo, Artificial Island, and Stacy) located next to a large land mass. However, the shear value at Cape Wind (which is well offshore) is larger than what might be anticipated for an ocean location. As will be discussed later, the structure of the marine boundary layer in the vicinity of the Cape Wind tower during certain seasons seems to be the major factor in the relatively large shear between 40 and 60 m at that site.

Diurnal Variability

Figure 2 shows the annual diurnal pattern for the four tall-tower stations. The diurnal variability at three towers - Buffalo, Artificial Island, and Stacy- are similar to inland sites. The alpha values are between 0.10 and 0.15 during the day and range from 0.2 to 0.35 at night. Buffalo's low overall shear among the three towers can be attributed to its lower nighttime shear. The diurnal shear pattern at the Cape Wind tower was flat with alpha values around 0.15 between 40 m and 60 m. Unfortunately, it is impossible to determine the shear pattern up to 100 m above the ocean surface without measurement data for levels higher than 60 m.

Seasonal Variability

There are two distinct patterns in the seasonal variability, as shown in Figure 3. The maximum shear values at Buffalo and Cape Wind occur in the spring and early summer. Artificial Island has a slight maximum during late autumn and early winter. There is a slight indication of a winter maximum also at Stacy. However, spring measurements at Stacy were not available, so no definite conclusions can be made at this time. The patterns on Figure 3 are based on a 6-week running average of alpha values.

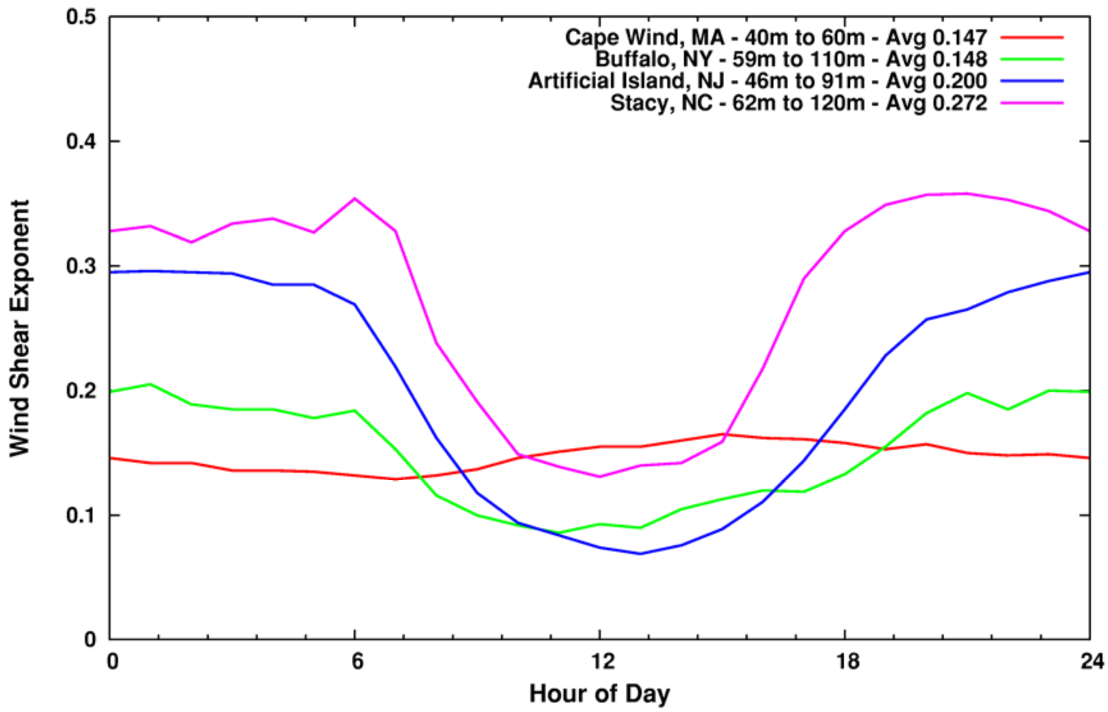

Figure 2. Annual diurnal wind shear pattern at the four tall-tower stations. Annual average alpha values are presented at top.

Distribution of Shear Values

Figure 4 shows the distribution of the annual shear values at the four towers. Cape Wind and Buffalo towers have peaks in the shear values just below zero and just above zero, respectively. Though the negative shear peak at Cape Wind may be misleading because of small speed differentials in a narrow vertical layer plus anemometer variations and tower flow effects, both Buffalo and Cape Wind have more instances of very low shear compared to Artificial Island and Stacy. Buffalo and Cape Wind also had narrower distributions than the other two towers. The alpha values at Artificial Island have a peak between 0.15 and 0.20 with a gradual decrease toward higher shear values. Stacy had the broadest distribution with a similar frequency of occurrences from near zero to about 0.40. Stacy also exhibited greater frequencies of shear values greater than 0.40 compared to the other towers.

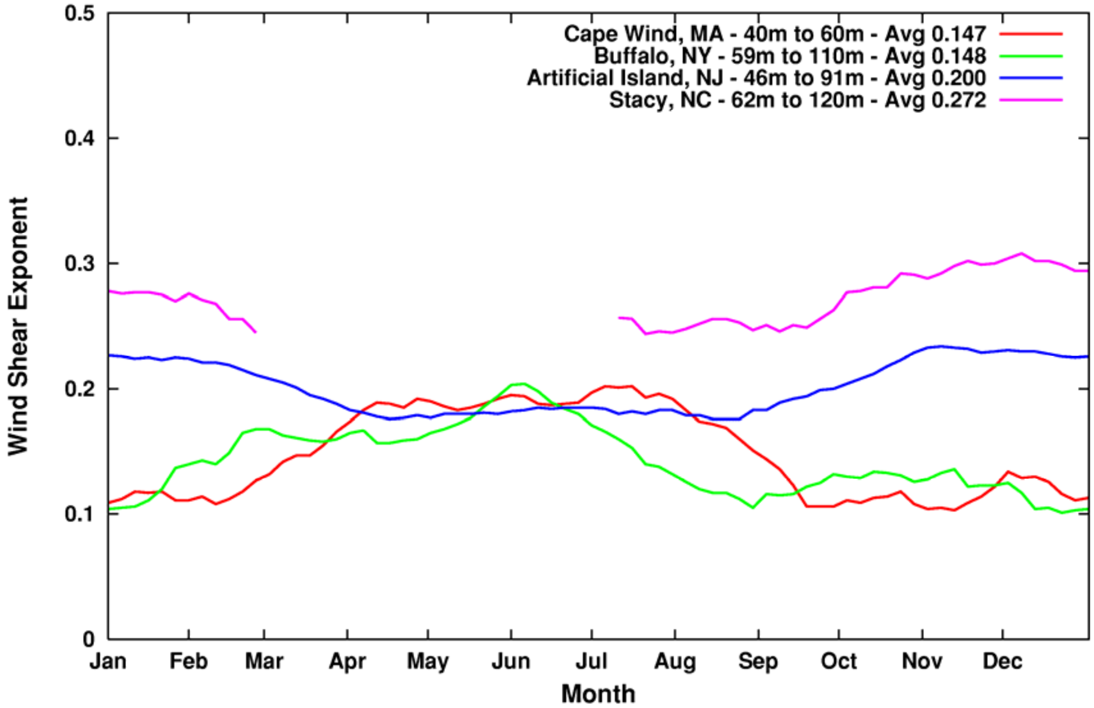

Figure 3. Seasonal wind shear pattern at the four tall-tower stations.

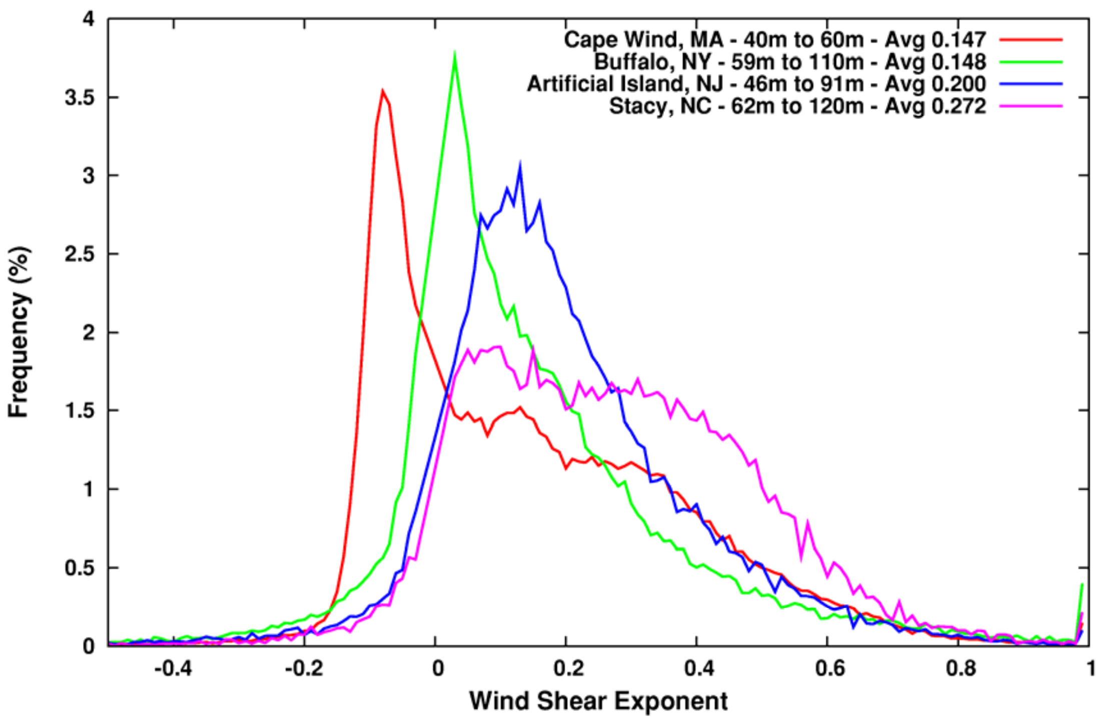

Figure 4. Distribution of annual wind shear values at the four tall-tower stations.

Shear Variability by Wind Direction

The annual values of shear by wind direction plots (wind shear roses) for the four towers are shown in Figure 5 through Figure 8. The values plotted every 10 degrees are a 30-degree running average of alpha values. The shaded areas represent the prevailing wind direction(s) during the warm and cool seasons. The prevailing wind directions are also labeled as having a land or marine fetch. The analysis of shear by direction at the four towers revealed perhaps the most interesting aspect of coastal and marine tall- tower wind climatology.

The most striking feature of these plots is how different are the shear by direction patterns at each tall-tower location. A common feature at all stations is the prevailing winds during the warm season from the southwest. The shear exponent at Buffalo is low (0.15 – 0.20) compared to the 0.25-0.30 shears measured at the other towers.

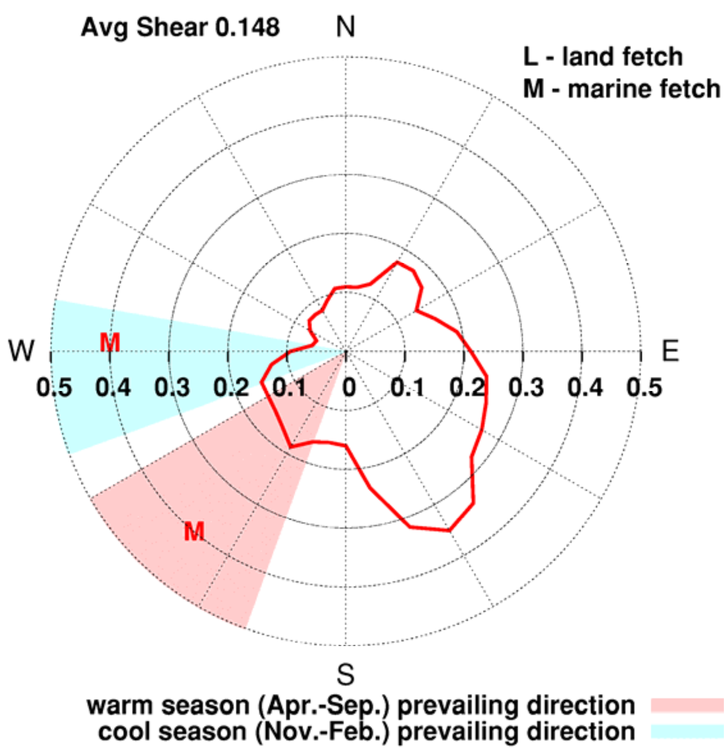

Figure 5. Wind shear rose (annual alpha values by wind direction) for Buffalo, NY.

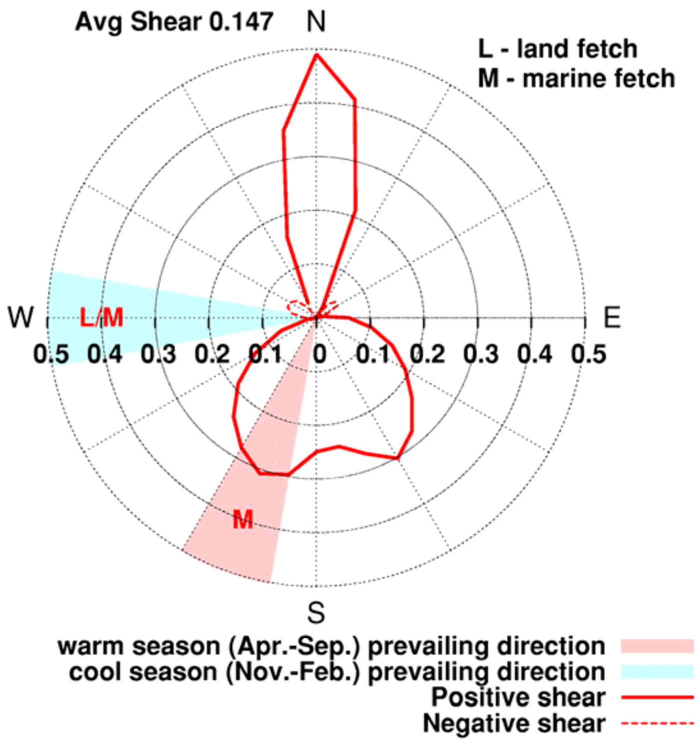

Figure 6. Wind shear rose for Cape Wind, MA.

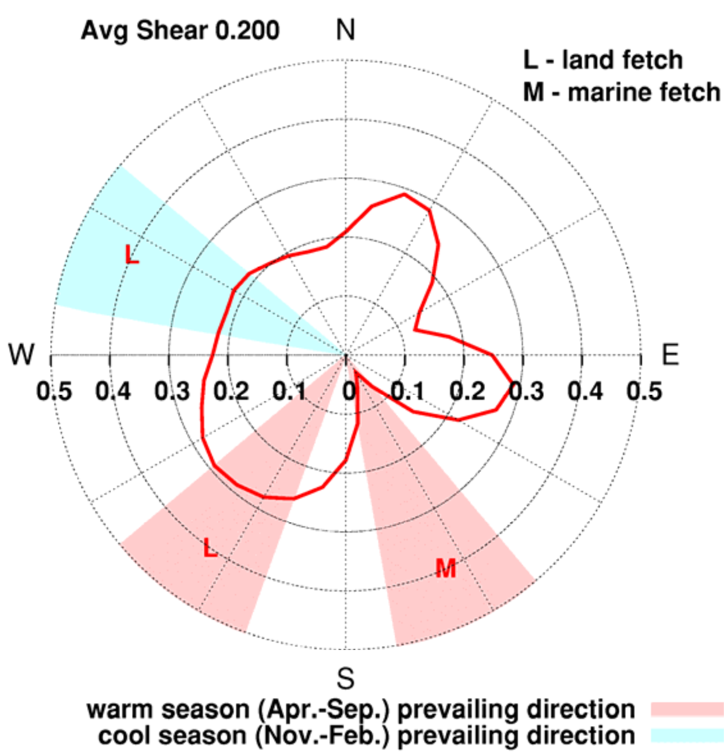

Figure 7. Wind shear rose for Artificial Island, NJ.

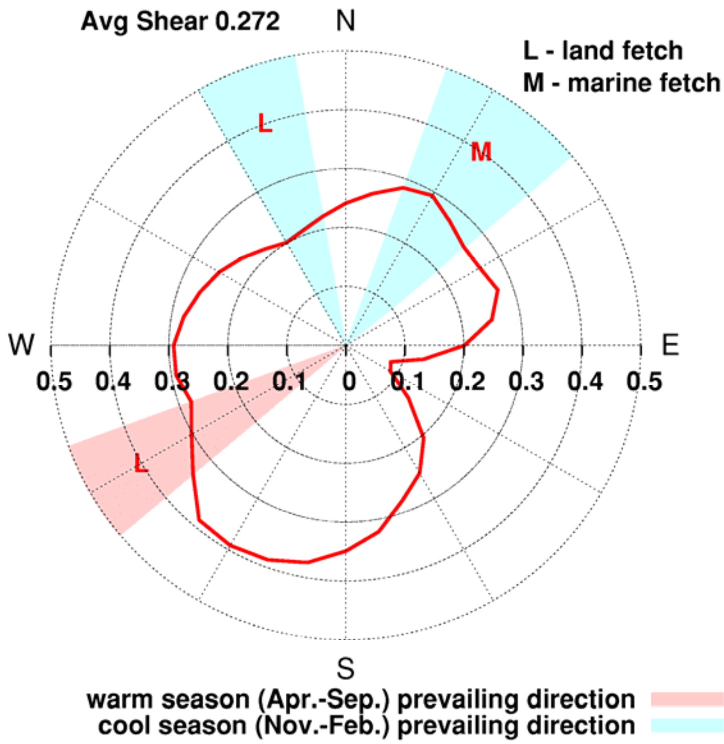

Figure 8. Wind shear rose for Stacy, NC.

An interesting feature of the shear by direction pattern during the warm season is the high shear of the southwest winds at the Cape Wind tower compared to the Buffalo tower even though the southwest winds at both locations have a marine fetch. In fact, the alpha value at Cape Wind is as large as those at stations where the warm-season southwest winds have a land fetch. The other interesting feature during the warm season is the low-shear winds from the southeast at Artificial Island. These winds travel up Delaware Bay and have a marine fetch. An analysis of the diurnal data indicates that these winds occur most frequently during the afternoon in spring and summer. These low-shear winds are likely related to the overall sea-breeze pattern along the New Jersey and Delaware coasts.

The cool season prevailing direction shear patterns also have some interesting features. All stations experience winds from the west to northwest during the cool time of year. Stations with a land fetch of winds from these directions (Artificial Island and Stacy) have alpha values around 0.20. Buffalo and Cape Wind have west winds with at least some marine fetch, and they experience lower shears. The Cape Wind data are somewhat remarkable in that the shears from 40-60 m are virtually zero. A hypothesis that explains the low shear is that cold air from the continent flows over the warmer water near Cape Wind. This leads to an unstable marine boundary layer with thorough mixing and uniform speeds. The cool season wind shear characteristics at the Stacy tower are also interesting. Winds from the northeast are common at this time of year. These winds travel over the ocean and Pamlico Sound before reaching Stacy. Nevertheless, the alpha values associated with these marine winds are quite high, between 0.25 and 0.30. In contrast, cool season winds that blow from the northwest at Stacy over land have shear exponents around 0.20.

The complex pattern of shear values by direction at the four stations, especially for winds having a marine fetch, indicates that the structure of the marine boundary layer in the vicinity of the stations has a major effect on the wind shear patterns. This effect is most apparent in the seasonal wind shear pattern. For instance, the spring and summer maximum at Cape Wind can be explained by the prevailing high-shear southwest winds during these seasons. Artificial Island's fall and winter shear maximum can be explained to a large extent by the appearance of the low-shear southeast sea breeze that occurs during spring and summer. The sea breeze reduces the average shear during the warm season, resulting in the fall and winter maximum observed at this tower.

Summary and Conclusions

A study of the wind characteristics at four tall towers in coastal and marine regions of the eastern United States, with an emphasis on wind shear exponent patterns, revealed some interesting wind characteristics at these sites. First, the overall wind shear patterns differed quite a bit among the tower sites, and the overall alpha values were not significantly different from those observed at inland tall-tower locations. Shear values similar to inland towers are not surprising at the three sites located adjacent to large land masses, but the alpha value of about 0.15 at the Cape Wind tower is greater than one might expect for a location 15 km from the U.S. mainland. An important mechanism for the relatively high shear value (many open ocean locations have alpha values estimated between 0.06 and 0.12) is the prevailing southwest winds in spring and early summer. These winds have a marine fetch but large wind shear values between 0.25 and 0.30. Measured data above 60 m are not available, so it is impossible to determine whether this shear continues up to 100 m above the surface. The Buffalo tower had a similar overall shear value but much less seasonal contrast than the Cape Wind site. These two sites help demonstrate that the structure of the marine boundary layer near a site has important effects on the shear pattern, especially on its seasonal distribution. Another conclusion is that wind directions with an overwater fetch are not easily correlated with either low or high wind shear values. Examples of this dichotomy are the Stacy tower, which was subject to a high-shear northeast flow from Pamlico Sound during winter, and the tower at Artificial Island, where the flow up Delaware Bay during the warm season is characterized by low wind shear.

The wind characteristics at coastal and marine locations need to be evaluated on a case-by-case basis. The variations in the structure of marine boundary layers are significant and require further detailed study. A key component of future studies is additional measurement data from 70 to 100 m above the surface. Thus, additional tall-tower measurements and data from remote sensing instrumentation will be crucial to increase the knowledge of marine boundary layer structure and its effect on the viability of wind energy projects in coastal and marine areas.

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