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Surface-Layer Turbulence in Landfalling Tropical Cyclones: Integral Length Scales And Spectra

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Abstract

In this study we examine the behaviour of the integral length scales and associated spectra for all three turbulence components using measurements made by mobile weather stations in the surface layer of landfalling tropical cyclones. While the vertical wind results show little variation with surface roughness, both the along- and across-wind integral length scales and spectra depend heavily on the underlying surface roughness. For the integral length scale it is found that this decreases significantly as the surface roughness increases. For the spectra, both the spectral shape and the position of the spectral peak depend on the surface roughness, with the spectral shape flattening and the spectral peak shifting to the right as the surface roughness increases. It is suggested that the increase in energy at low frequencies observed in previous studies of spectra in landfalling tropical cyclones arises as a result of the fact that the measurements on which the spectra have been based have inevitably been made at the coast in a low roughness marine boundary layer.

Introduction

Traditionally within the wind engineering community it has been assumed that there is a single universal form for the along-wind spectra, that is invariant from site to site, and independent of the underlying surface roughness. This is in spite of the fact that within the boundary layer meteorology community there has been a considerable body of evidence published since the early 1970's that suggests that the shape of the along- and across-wind spectra in particular are heavily dependent on the upstream terrain conditions at a particular site. The vertical wind spectra tend to be less affected as the limitation on the size of the associated turbulent eddies is set more by the height that the measurements are being made at, rather than the upstream terrain conditions. More recently, published measurements of spectra in landfalling tropical cyclones, such as those of [1] or [2] have noted that the observed spectra contain more energy at lower frequencies, with the spectral peak shifted to the left, when compared to what are considered to be standard over-land spectra, such as that of [3].

In this paper we consider the behaviour of both the integral length scale and the associated spectra for all three turbulence components using measurements made in the surface layer of landfalling tropical cyclones by mobile weather stations situated in a wide range of terrain conditions. We then attempt to explore some of the factors that may be affecting both the integral length scale and the associated spectra to answer the question of whether these parameters are truly independent of the underlying surface roughness and invariant from site to site, or whether our approach to defining these parameters needs to be rethought, particularly when dealing with structures located within the surface layer, or the underlying roughness sublayer..

Data

As in [4] this study uses the dataset described by [5], and subsequently used by [6] in their study of gust factors in landfalling tropical cyclones, which consists of surface wind-speed data collected in 21 tropical cyclones making landfall along the Gulf and Atlantic coasts of the United States of America over the period 1999-2008 at a total of 72 individual station sites. For a brief summary of the processing of this dataset as used in this paper, the reader is referred to [4], with detailed information to be found in [5, 6]. The salient features of the processing of this dataset as it relates specifically to this paper are that the selected 10-minute wind-speed data records for each station site/wind direction combination are first transformed in such a way that the velocity components are aligned in such a way that the mean non-zero along-wind component (u) is directed along the corresponding 10-minute mean wind direction, with the associated mean cross-wind (v) and vertical (w) velocity components being equal to zero. Any linear trend that was present in the individual time histories of each velocity component was then removed prior to any further processing.

Spectral estimates for each station site/wind direction combination were first calculated for each individual 10-minute data record using a Hanning window with no overlap. The individual spectral estimates, one for each 10-minute data record, were then averaged using the frequency smoothing method of [7], with 10 non-overlapping bands per decade. In fitting curves to the resulting spectra care has to be taken with the roll-off at higher frequencies due to the filtering effect of the response of the anemometers used to make the measurements. In this study we use the wind speeds measured at a height of 10 m above ground using a custom array of three RM Young model number 27106R Gill propeller anemometers, which have a stated distance constant of 2.7 m. In terms of the non-dimension frequency n, which is calculated as $fz/\overline{u}$ where f is the frequency in Hz, z is the height above ground, and $\overline{u}$ is the 10-minute mean wind speed, it can be shown that the half-power frequency of the equivalent first-order filter is equal to 0.38. For this reason when fitting curves to the measured spectra we use only those data-points where the non-dimensional frequency n is less than 0.38 to ensure that the high-frequency part of the curve is not unduly influenced by the effect of the anemometer response on the measured wind speeds.

The corresponding integral length scales were determined by first calculating the autocorrelation coefficient, and then integrating the area under the resulting curve to the point at which the curve first become zero to calculate the integral time scale for each 10-minute data record. The corresponding integral length scale was then calculated using Taylor's frozen turbulence hypothesis, before the individual estimates were averaged to determine the mean integral length scale for a particular station site/wind direction combination.

Results

Integral Length Scales

The integral length scale is a measure of the average size of a turbulent eddy for the specified turbulence component. Figure 1 shows the variation of the calculated along-wind integral length scales versus various flow parameters for the two groups of station site/wind direction combinations identified in [4]. Although we have split the sites into two groups it is clear that there is no real distinction between the behaviour of the two groups from the point of view of the integral length scale, and that there is a continuous spectrum of behaviour across the range of integral length scales considered. The along-wind integral length scales vary significantly with both the along-wind turbulence intensity, I_u, and the normalized friction velocity, $u_*/\bar{U}_{10\ min}$, with the value of the integral length scale decreasing as the value of these two parameters increases. Although the integral length scale varies significantly with both I_u and $u_*/\bar{U}_{10\ min}$, the variation of the integral length scale with the ratio of these two parameters, σ_u/u_*, is less clear cut with much larger variability for a given value of σ_u/u_*.

Both I_u and $u_*/\bar{U}_{10\ min}$ can be considered to be indicators of the underlying surface roughness, with larger values indicating increasingly rougher surfaces. Although previous studies have suggested that the integral length scale in the surface layer is weakly dependent on the surface roughness, the variation in the current study is much larger than has been previously suggested. The across-wind integral length scales show a similar pattern of behaviour to that shown for the along-wind integral length scale in figure 1, with a significant reduction in the length scale values with increasing surface roughness. The vertical wind integral length scales, on the other hand, show much less variation, and could be considered to be independent of the underlying surface roughness for all practical purposes. This result is not surprising since the vertical wind motions are constrained by the height above the surface at which the measurements are being made which then puts a limit on the size of the associated turbulent eddies. The same is not true of the along- and across-wind motions, which explains why the integral length scales for these two components show the variation that they do with increasing surface roughness.

Spectra

In fitting a spectral model to observed spectra it is usual to consider one of two forms, given by

$$\frac{fS_i(n)}{\sigma_i^2} = \frac{an}{(1+bn)^{5/3}} \quad (1)$$

or

$$\frac{fS_i(n)}{\sigma_i^2} = \frac{an}{(1+bn^{5/3})} \quad (2)$$

where i is one of u, v, or w, f is the frequency, and n is the non-dimensional frequency. Traditionally the spectral model described by equation (1) is used for the along- and across-wind spectra, while the model described by equation (2), which produces a more peaked spectrum, is used for the vertical wind spectra. The fit coefficients a and b control the total energy under the spectral curve and the energy distribution in the high frequency range of the spectrum respectively. From a theoretical viewpoint we can also note that for model (1) the relationship between coefficients a and b should be such that $a/b = 2/3$ in order for the area under the spectral curve to integrate to 1.

For each station site/wind direction combination both spectral models were fit to the observed spectra for all three turbulence components using non-linear least squares methods. Overall, it was found that while both models provided adequate fits to the observed spectra for a particular turbulence component, from the point of view of the resulting correlation coefficients over all the sites considered in this study, model (1) gave a slightly better fit to the observed along- and across-wind spectra, while model(2) gave a better fit to the vertical spectra. Any further discussion of the fit coefficients in this paper will assume that the fit coefficients for the along- and across-wind spectra being discussed are those for model (1), while those for the vertical wind spectrum are for model (2).

Figure 2 shows the relationship between the fit coefficients for each turbulence component for all of the station site/wind direction combination considered in this study. As for the integral length scales presented in the previous section, although we have split the sites into two groups following [4], there is a continuous spectrum of behaviour with no distinction between the two groups of sites. It can also be seen that the relationship between the fit coefficients for the along- and across wind spectra closely follow the expected two-thirds relationship, which is indicated by the dashed line in figures 2 a) and b). The fit coefficients for the vertical wind spectra also show a clear relationship between their respective values. Although there is a clear relationship between the fit coefficients for all three components, we would also note that the values of the coefficients are in many cases significantly larger than those reported in previous studies. The reasons for this are still not entirely clear, but we would note that the current study is the first study to consider spectra measured at a wide range of sites, many of which are located in non-homogeneous terrain conditions, but which have been processed in a consistent manner across all sites considered.

In considering how the fit coefficients vary with other statistical flow field descriptors, such as the turbulence intensity, the normalized friction velocity, or the ratio of the standard deviation of the appropriate turbulence component to the friction velocity, we find that, as for the integral length scales, the most appropriate descriptors are the turbulence intensity and the nor-

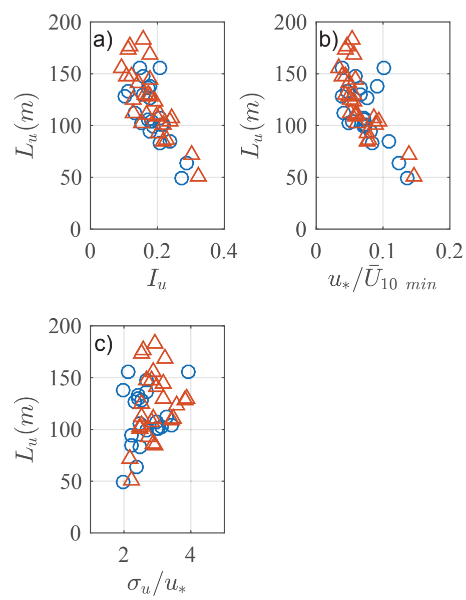

Figure 1: Along-wind integral length scale versus a) I_u, b) $u_*/\bar{U}_{10\ min}$, and c) σ_u/u_* for Group 1 (circle) and Group 2 (triangle) sites combined

malized friction velocity, both of which can be viewed as being representative of the underlying surface roughness conditions. Figure 3 shows the variation of the fit coefficients a and b for model (1) for the along-wind spectra for both of these parameters. Although there is considerable variability in the results, it is clear that there is both no distinction between the two groups of sites considered, and that there is a tendency for both fit coefficients to reduce with increasing surface roughness. In an attempt to see whether the distance from each site to the coast affected the results, the sites were grouped into bands by distance to the coast and replotted, but this only showed that there was a tendency for the surface roughness to increase with distance from the coast which would be consistent with the transition of the boundary layer from a relatively smooth over-water surface to much rougher over-land surface. No discernible distance to coast effect was found in terms of the impact on the fit coefficients for a particular value of either surface roughness or normalized friction velocity. Similar behaviour was found for the across-wind spectra, the overall conclusion being that the surface roughness is the main factor controlling the spectral shape for both the along- and across-wind spectra.

Figure 4 shows the corresponding results for the vertical wind spectra. In this case the impact of the underlying surface roughness is much harder to quantify. Once again, with the exception of a small number of isolated sites, one might conclude that the vertical wind spectra are relatively insensitive to the underlying surface roughness, and can be described by a single universal spectral model which is independent of surface roughness, and controlled more by the height above ground which places limitations on the size of the eddies associated with vertical motion in the surface layer.

In terms of determining the non-dimensional frequency at which the peak in the spectral curve will occur, it can be shown that for model (1) this is related to the value of the spectral fit coefficient b by the following expression

$$\hat{n}_i = \frac{2}{3b}. \qquad (3)$$

The non-dimensional frequency at which the spectral peak occurs is then inversely proportional to the value of b which implies for both the along- and across-wind spectra as b decreases

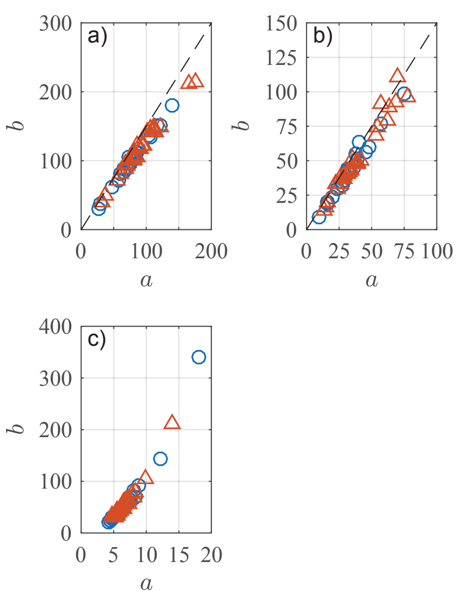

Figure 2: Spectral fit coefficients for a) along-wind, b) across-wind, and c) vertical wind components for Group 1 (circle) and Group 2 (triangle) sites combined. Dashed line in a) and b) shows the theoretical 2/3 slope for the spectral model considered.

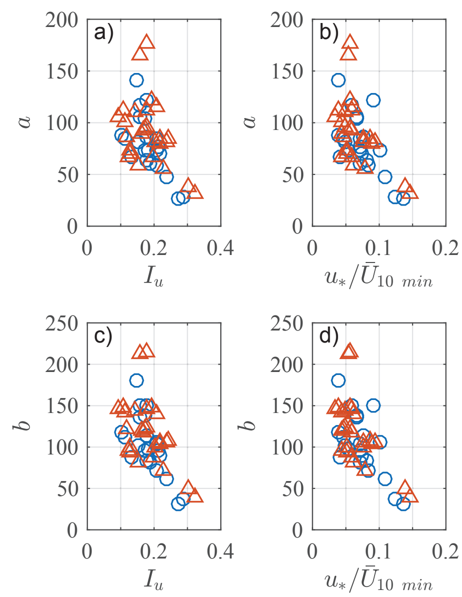

Figure 3: Variation of the spectral fit coefficients for the along-wind spectra for a) a versus I_u, b) a versus $u_*/\bar{U}_{10\ min}$, c) b versus I_u, and d) b versus $u_*/\bar{U}_{10\ min}$ for Group 1 (circle) and Group 2 (triangle) sites combined

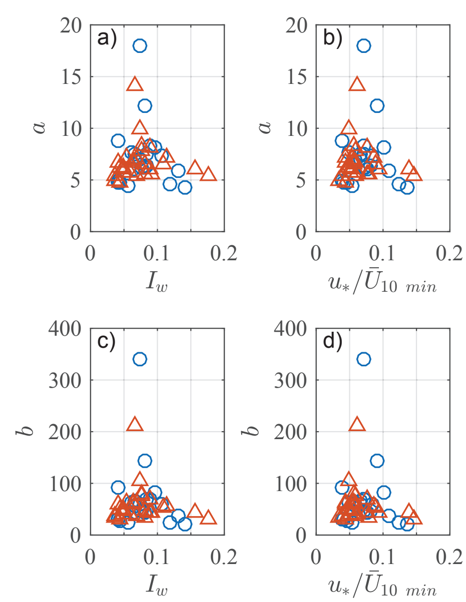

Figure 4: Variation of the spectral fit coefficients for the vertical wind spectra for a) a versus I_w, b) a versus $u_*/\bar{U}_{10\ min}$, c) b versus I_w, and d) b versus $u_*/\bar{U}_{10\ min}$ for Group 1 (circle) and Group 2 (triangle) sites combined

with increasing surface roughness, the peak in the corresponding spectral curve shifts to the right. Figure 5 shows a plot of the variation of the corresponding integral length scale with the non-dimensional frequency at which the spectral peak occurs for both the along- and across-wind spectra, from which it can clearly be seen that the two are related. As surface roughness increases and the spectral peak shifts to the right, the integral length scale reduces, which should not come as a surprise since the integral length scale and the corresponding spectral curve are related to each other by the area under the associated autocorrelation function, which is simply the inverse Fourier transform of the spectral curve.

Discussion

One of the implications of the current study is that the shape of the along- and across-wind spectral curves is not universal, rather it is a function of the underlying surface roughness. As the surface roughness increases the spectra tend to flatten out, and the spectral peak shifts to the right. Previous studies in landfalling tropical cyclones have noted that the peaks of the spectral curves, where measured, have tended to lie to the left of the peak in the spectra observed by [3], with more energy at lower frequencies. This apparent increase in energy at lower frequencies has been ascribed to the fact that the measurements were made in tropical cyclones, as opposed to previous measurements which have been made in non-tropical cyclone conditions. We would suggest that the apparent increase in energy at lower frequencies is not due to the fact that the measurements were made in tropical cyclones, but that they were inevitably made at the coastline in a low roughness marine boundary layer. As the boundary layer transitions to increasingly rougher terrain inland, there is a shift in the spectral peak to the right which then leads to a reduction in the energy at lower frequencies. If we consider the turbulent kinetic energy, we can note that as the surface roughness increases there must be a corresponding increase in the turbulent kinetic energy. If this is the case, then [9] note that in order for the spectral shape to remain universal there must be a shift in the spectral peak towards higher frequencies, an observation that is consistent with the results of this study.

Conclusions

In examining the behaviour of both the integral length scale and the associated spectra for all three turbulence components in the surface layer of landfalling tropical cyclones, it is found that while the vertical wind results show very little variation with surface roughness, the same cannot be said for the along- and across-wind results, where it is found that both the integral length scale and the spectra depend heavily on the underlying surface roughness. For the integral length scale it is found that this decreases significantly as the surface roughness increases. The spectral fit coefficients for the spectral models considered also show a strong dependency on the underlying surface roughness, and suggest that both the spectral shape and the position of the spectral peak change as a function of the surface roughness. As the surface roughness increases the spectral shape tends to flatten out, while the spectral peak shifts to the right. It is suggested that the increase in energy at low frequencies observed in previous studies of spectra in landfalling tropical cyclones arises not as a result of the fact that the measurements are being made in tropical cyclones, but that the measurements on which the spectra have been based have inevitably been made at the coast in a low roughness marine boundary layer.

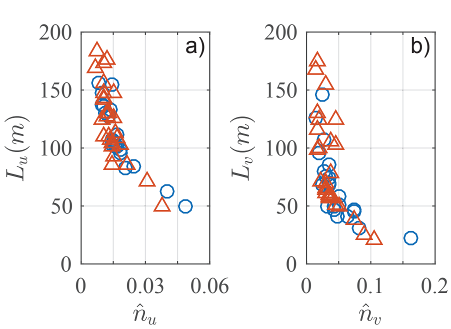

Figure 5: Variation of the integral length scale with the non-dimensional frequency at which the spectral peak occurs for the a) along- and b) across-wind turbulence components for Group 1 (circle) and Group 2 (triangle) sites combined

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