1.D5 OPEN TERRAIN GUST FACTORS IN LANDFALLING HURRICANES BASED ON MOBILE TOWER OBSERVATIONS

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1. INTRODUCTION

The past decade has seen the extensive deployment of mobile instrumented towers by teams from both Texas Tech University (TTU) and the Florida Coastal Monitoring Program (FCMP) in landfalling hurricanes in the US. These towers have been designed to withstand hurricane-force winds and make high-resolution measurements of wind speeds in the surface layer in an effort to improve our understanding of the hurricane boundary layer. One of the key parameters of interest in making these measurements is the gust factor, which is the ratio of the maximum short duration gust wind speed measured over some time period relative to the mean wind speed measured over the same time period.

Current theory for the prediction of gust factors states that the gust factor, *G*, is a function of a peak factor, *g*, that depends only on the gust averaging time, *t*, and the time *T* over which the mean wind speed is determined and the turbulence intensity I_u, the latter being a function of the underlying surface roughness. This allows the gust factor to be written as

$$G(t,T) = 1 + g(t,T)I_u. \quad (1)$$

Equation (1), if correct, implies that for a given combination of gust and mean wind speed averaging times the gust factors measured at different sites with the same turbulence intensity, or surface roughness, will be the same. This thinking has guided previously published analyses of the gust factors measured by both the TTU and FCMP mobile tower programs, where the gust factors have been analyzed by considering all tower sites simultaneously and classifying individual gust factor measurements by roughness length (see for example Edwards and Schroeder 2005, Yu and Gan Chowdhury 2009, or Schroeder et al. 2009) . The roughness length associated with each gust factor measurement is typically calculated using the measured turbulence intensity in combination with an assumption that the ratio of the standard deviation of the turbulent along-wind fluctuations, σ_u, to the friction velocity, u_*, is $\sigma_u/u_* = 2.5$, which through the use of the log-law then allows the roughness length to be estimated as

$$\ln(z_0) = \ln(z) - \frac{1}{I_u}, \quad (2)$$

where *z* is the height at which the turbulence intensity is measured. The gust factors are then grouped by roughness length and the results of the analysis presented on this basis.

The validity of the underlying analysis, however, depends on two key assumptions, one of which is explicit while the other is implicit is the way that previous analyses have been conducted. The first of these is that at all sites $\sigma_u/u_* = 2.5$, which allows the roughness length to be calculated using equation (2) in order to group the individual gust factor values by roughness length, irrespective of site. As can be seen, however, from Figure 1, which shows the variation of the mean value of σ_u/u_* with the corresponding mean along-wind turbulence intensity for the individual site/wind direction combinations considered in this paper, there is both considerable variation in this value from site to site, and that the value of $\sigma_u/u_* = 2.5$ that has been assumed in previous studies falls towards the lower end of the range of the observed values considered in this study. This must call into question the practice of using a constant value of 2.5 to determine the value of the roughness length, which will then affect the sorting of individual gust factor measurements into roughness length bins. The second key assumption that is never explicitly stated is that equation (1) is valid, and that the gust factors measured at multiple sites with the same turbulence intensity will, after allowing for sampling error, yield the same gust factor curve.

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In this study we take a different approach to that used in previous analyses and first consider the gust factors measured at individual FCMP tower sites over the period 1999-2008 by mean wind direction. In general, for most sites there are two primary wind directions associated with the passage of a hurricane which allows two sets of gust factors to be identified, one for each primary wind direction, along with the mean turbulence intensity associated with each wind direction. We then group the gust factors by wind direction and mean turbulence intensity to allow comparisons between sites for the same turbulence intensity. The reasoning behind choosing this method of analysis is that gust factors measured for a given wind direction should reflect the upstream terrain exposure in that direction. Classifying the gust factors by turbulence intensity also removes the need to make an a priori assumption about the relationship between the along-wind turbulent fluctuations and the friction velocity within the surface layer to calculate a roughness length using equation (2).

2. DATA

The dataset used in this study is the one described by Balderrama et al. (2012), which comprises of surface wind field data collected in 21 landfalling US hurricanes over the period 1999-2008 at a total of 72 individual tower sites. For detailed information on the processing of this dataset the reader is referred to the above paper, however a brief description is given here for information purposes. Although wind speed data is collected at heights of both 5 m and 10 m above ground using a custom array of three Gill propeller anemometers at each height, we only consider data obtained at a height of 10 m in this study. Following quality control of the data the remaining wind speed records were split into 10-minute segments and rotated into the 10-minute mean wind direction such that the mean across-wind (v) and vertical (w) velocities are equal to zero, while the mean along-wind (u) velocity was non-zero. Among the statistics calculated for each 10-minute segment are the mean along-wind velocity, the peak along-, across- and vertical wind velocities, the corresponding turbulence intensities in all three directions, and the friction velocity. Prior to determination of the peak along-, across- and vertical wind velocities the appropriate wind speed record was filtered using either an n-second moving average or n-second block average filter, where the filter interval was set to be 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 40, 50, 60, or 120 s. The final processed dataset consists of 62 individual tower sites with measurements from 19 individual named storms.

For each tower site a histogram of the 10-minute mean wind directions at 10^o intervals was used to identify the directions with the most 10-minute segments. In general this allows the identification of two primary wind directions for each site, although for several tower sites it proved possible to identify three or even four primary wind directions with sufficient measurements. For each identified primary wind direction a 30^o-wide arc, centred on the 10^o interval with the largest number of values, and extending to the adjacent 10^o intervals on either side of this interval was then defined. Figure 2 shows a typical mean wind direction histogram for tower site T2 in Hurricane Frances (2004) in which two primary wind directions at intervals of 20-30^o and 160-170^o can clearly be identified. After checking to ensure that the turbulence intensity values across the identified 30^o arcs were not showing an obvious variation across the arc with wind direction, and placing further restrictions on the 10-minute mean wind speed (values greater than 10 m/s), and the number of independent 10-minute segments (a minimum of 20) the mean along-wind turbulence intensity for the arc was calculated and then used to stratify the results by turbulence intensity. A minimum 10-minute mean wind speed of 10 m/s was used to try and ensure neutral or near-neutral stability conditions, while a minimum of 20 independent 10-minute segments was used to try and obtain statistically meaningful results.

Gust factors for the along-, across- and vertical wind components were then calculated for all averaging times and filters used by dividing the appropriate peak value by the corresponding mean along-wind velocity for each selected 10-minute segment. Since the mean across- and vertical velocities are zero, the peak values for these two components can take either positive or negative values, unlike the along-wind peak value which will always be positive. To obtain meaningful gust factors for these two components the absolute value of the peak value was first taken before calculating the across- and vertical wind gust factors. The final data set used for this study consisted of 65 individual tower/wind direction combinations.

3. RESULTS

In presenting the results of the study we first consider the impact of using either an n-second moving average or n-second block average filter on the resulting mean gust factor curves. The left-hand panel of Fig. 3 shows the mean along-wind gust factor curves derived using both moving and block average filters for a single tower/wind direction combination plotted against the nominal gust averaging time, which is simply taken to be the n-second value of the filter interval used. Although both curves are derived from the same underlying wind speed record, it is clear that the use of either moving or block averaging affects the resulting mean gust factor curves, and if we were not aware of the difference in how the gust values were filtered we might not unreasonably assume that the two curves were different. This is an issue in virtually all previous studies of gust factors in hurricanes where there has been a general failure to specify the method used to filter the underlying wind speed record, especially where the derived gust factor curves have been compared with that of Durst (1960), which is based on 5-second and higher block averages.

Since the two mean gust factor curves shown in the left-hand panel of Fig. 3 are both derived from the same underlying wind speed record, it is clear that there must be some way of collapsing the two curves onto a single universal curve that is valid for any averaging method and averaging interval. In fact, Miller (2007) shows that by defining an effective gust duration based on reciprocal of the half-power frequency of the effective filter function it is possible to collapse gust factor curves derived from the same wind speed record using different averaging filters onto a single, universal gust factor curve, as shown in the right-hand panel in Fig. 3. The use of an effective gust duration to remove differences in gust factor curves due to the choice of the averaging method used to determine the gust factors does however place an onus on authors to fully specify how the gust factors were calculated, and to not just refer to an n-second gust. In this study, all further results are presented in terms of an effective gust factor duration with both moving and block averaged curves combined into a single universal gust factor curve.

In classifying the results by the along-wind turbulence intensity we choose to define a range of intervals from 0.125 to 0.250, in steps of 0.025, similar to those used by Balderrama et al. (2012) in presenting some of their results. The values considered range from those associated with fairly open terrain to values that are tending towards those found in typical suburban terrain composed of single family dwellings. For each bin we plot the individual mean along-, across- and vertical gust factor curves for the individual tower/wind direction combinations where the mean along-wind turbulence intensity for the wind directions under consideration fall within the bin, the results for the mean along-, across- and vertical gust factors being plotted in Figs. 4, 5, and 6 respectively. An initial examination of the resulting curves shows that, as expected, the gust factor values for all three components tend to increase with increasing along-wind turbulence intensity. The curves for individual site/wind direction combinations within a given bin do, however, show some variability. This is particularly noticeable for the shorter duration gusts, and for the across- and vertical wind gust factors. A calculation of the corresponding mean peak factor curves to try and remove the influence of mean turbulence intensity variations for each tower/wind direction combination within each bin suggests that the variability visible in Figs. 4, 5, and 6 is also present in the mean peak factor curves. This suggests that simple variations in the mean turbulence intensity within each bin are not responsible for the observed behavior.

The question now becomes one of whether the observed variations are significant or not, and to a certain degree the answer will depend on the desired outcome. If we are simply interested in defining a generic mean gust factor curve then we might be justified in simply ignoring the variations between individual tower/wind direction combinations for a given bin, and then combining all values within that bin into a single generic curve. On the other hand, if we are interested in trying to predict the gust factors at individual sites that take into account the terrain at both the site and upwind of it for some distance then the variations seen in Figs. 4, 5, and 6 do become significant. Anecdotal evidence from recent landfalling US hurricanes suggests that insured losses from areas with similar roughness and mean wind speeds can be quite variable, and the observed variability seen in Figs. 4, 5, and 6 would go some way to explaining this, particularly if the gust wind speeds fall within the range where small changes in wind speed can lead to large differences in the predicted losses.

One way of trying to quantify the variability is to conduct some form of statistical testing to see whether the underlying observed gust factor distributions can be considered to be drawn from the same underlying parent distribution and the variation between individual curves attributed to simple experimental variability, or whether the observed variations are in fact statistically significant. Figure 7 shows the underlying along-, across-wind and vertical gust factor distributions for the 12 tower/wind direction combinations with mean along-wind turbulence intensities that fall within the range 0.200-0.225. Although there are clearly similarities between the distributions for a given gust component, there are also visible differences as well. To test whether we would consider pairs of gust factor distributions for a given gust component to be drawn from the same underlying parent distribution we perform a two-sample Kolmogorov-Smirnov test for all possible gust factor distribution combinations within each bin at a significance level of 0.05. The results show that while some gust factor distributions can clearly be paired with others for a given gust component, that not all distributions for a given gust component and along-wind turbulence intensity bin are drawn from the same underlying distribution.

One of the challenges in attempting to deal with real atmospheric boundary layers is that while we generally assume that we are dealing with equilibrium boundary layers, for many of the tower sites considered in this study non-equilibrium effects due to upstream changes of roughness are likely to be important when determining the gust factors at individual tower sites. Unfortunately there is very little in the published literature on the effects of changes of roughness on the turbulent structure of the atmospheric boundary layer. An attempt to try and correlate additional statistical indicators of the turbulent structure, such as σ_u/u_*, with the observed variations in the mean gust factor curves for a given along-wind turbulence intensity bin and gust averaging time was inconclusive with no clear trends being observed either within a bin, or across all bins for the indicators considered.

Further research is planned to examine other indicators of the turbulent structure and their correlation with the observed variations in the mean gust factor curves. One obvious avenue to explore is the variation in the associated spectral density functions and how these might relate to the observed mean gust factor curve variations, particularly since Yu et al. (2008) showed that there were differences in the observed spectral density functions at three of the tower sites considered in this study. Similar behavior was also noted by Panofsky (1972) when comparing along-wind spectral density functions measured at a number of different sites. In fact the dataset used in this study provides an ideal opportunity to act on the thoughts of Panofsky, who stated some 40 years ago that in his opinion a study was badly needed in which wind speed data measured in high wind conditions at multiple sites needed to be collected, before an attempt was made to associate the differences between the spectral density functions with upstream mesoscale terrain features.

4. CONCLUSIONS

In this study, rather than adopt the approach used in previous studies of gust factors in landfalling hurricane where gust factors measured at multiple tower sites are simply stratified by the associated roughness length without regard to the site itself, we first group the gust factors by wind direction at individual tower sites before stratifying the individual tower site/wind direction combinations by the associated mean along-wind turbulence intensity. The results show that there are variations in the resulting mean gust factor curves for the along-, across- and vertical wind components in a given along-wind turbulence intensity bin that cannot be explained by simple statistical variation. This suggests that a generic mean gust factor curve for a given terrain type cannot be defined, unless one is only interested in defining a generic curve and not a gust factor curve at an individual site that correctly takes into account the upstream terrain variations at that site and their impact on the resulting gust factors.

This also makes the comparison between gust factor curves measured at different sites somewhat problematical, particularly when comparing gust factors measured in hurricanes with those measured in extra-tropical cyclones, because the variations are not necessarily due to differences in the behavior of the atmospheric boundary layer in tropical and extra-tropical cyclones. The situation is further exacerbated by the fact that all previous studies fail to fully define the averaging method used to calculate the gust factors, and nor do they recognize that further differences arise because of the different filtering effects of the two most commonly used averaging methods, particularly when making comparisons with the gust factor curve of Durst (1960).

It is postulated that the observed differences in the mean gust factor curves for individual tower/wind direction combinations in a given along-wind turbulence intensity bin are due to the effects of upstream changes of surface roughness and their resulting impact on the measured gust factors at individual tower sites. Unfortunately it has not proven possible to correlate the observed variations with other statistical indicators of the turbulent structure, such as σ_u/u_*, although further work is planned to consider other parameters such as the associated spectral density functions.

5. REFERENCES

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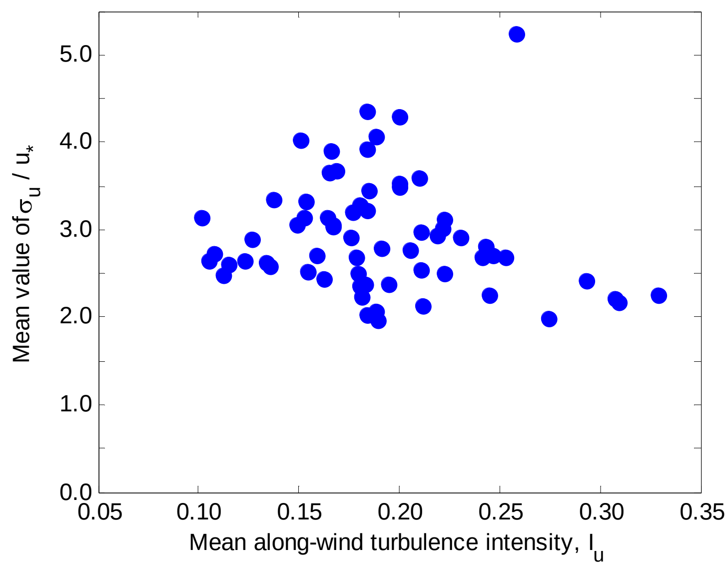

Figure 1: Variation of the mean value of σ_u/u_* with the mean along-wind turbulence intensity, I_u, for the tower/wind direction combinations considered in this study.

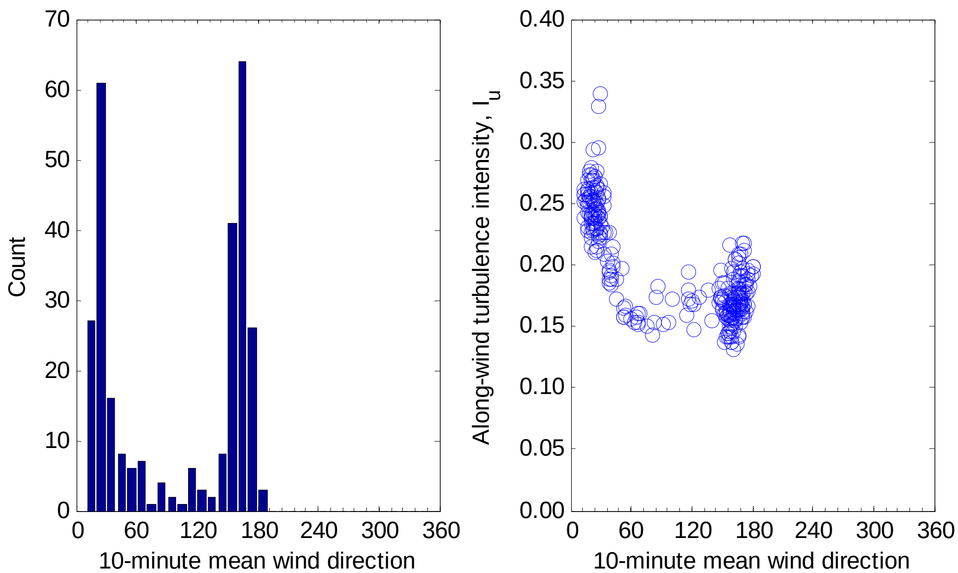

Figure 2: Typical 10-minute mean wind direction histogram (left) and the variation of the along-wind turbulence intensity, I_u, with wind direction (right) for tower T2 in Hurricane Frances (2004).

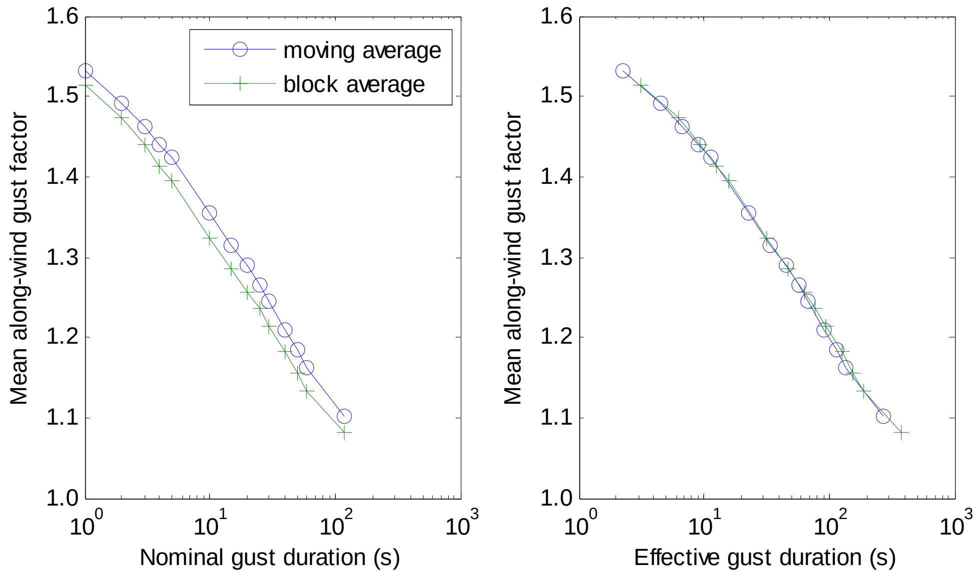

Figure 3: Impact of plotting the mean along-wind gust factor versus the nominal gust duration (left) and plotting the mean-along wind gust factor versus the effective gust duration (right).

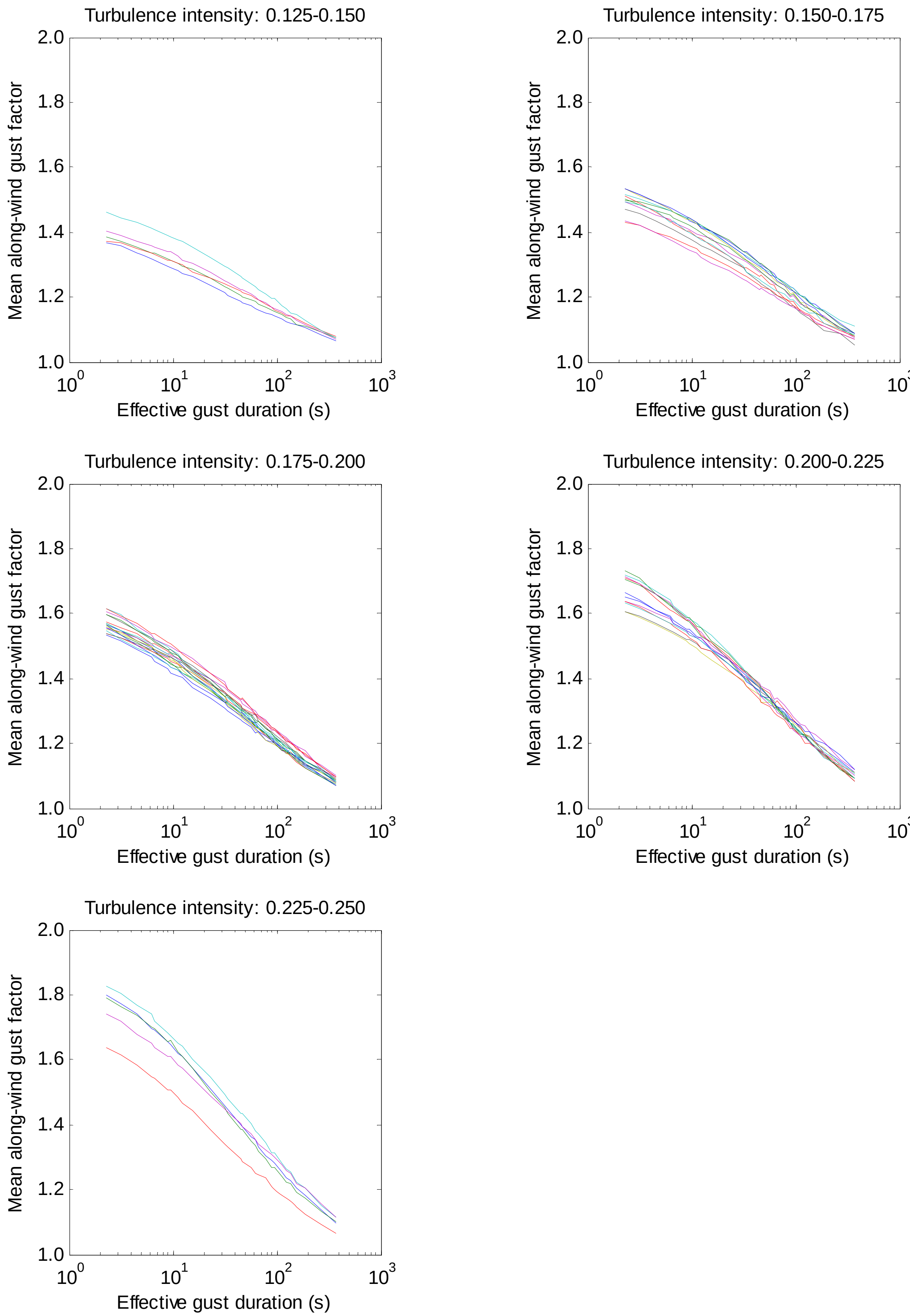

Figure 4: Mean along-wind gust factor versus effective gust duration for all tower/wind direction combinations falling within the indicated mean along-wind turbulence intensity ranges.

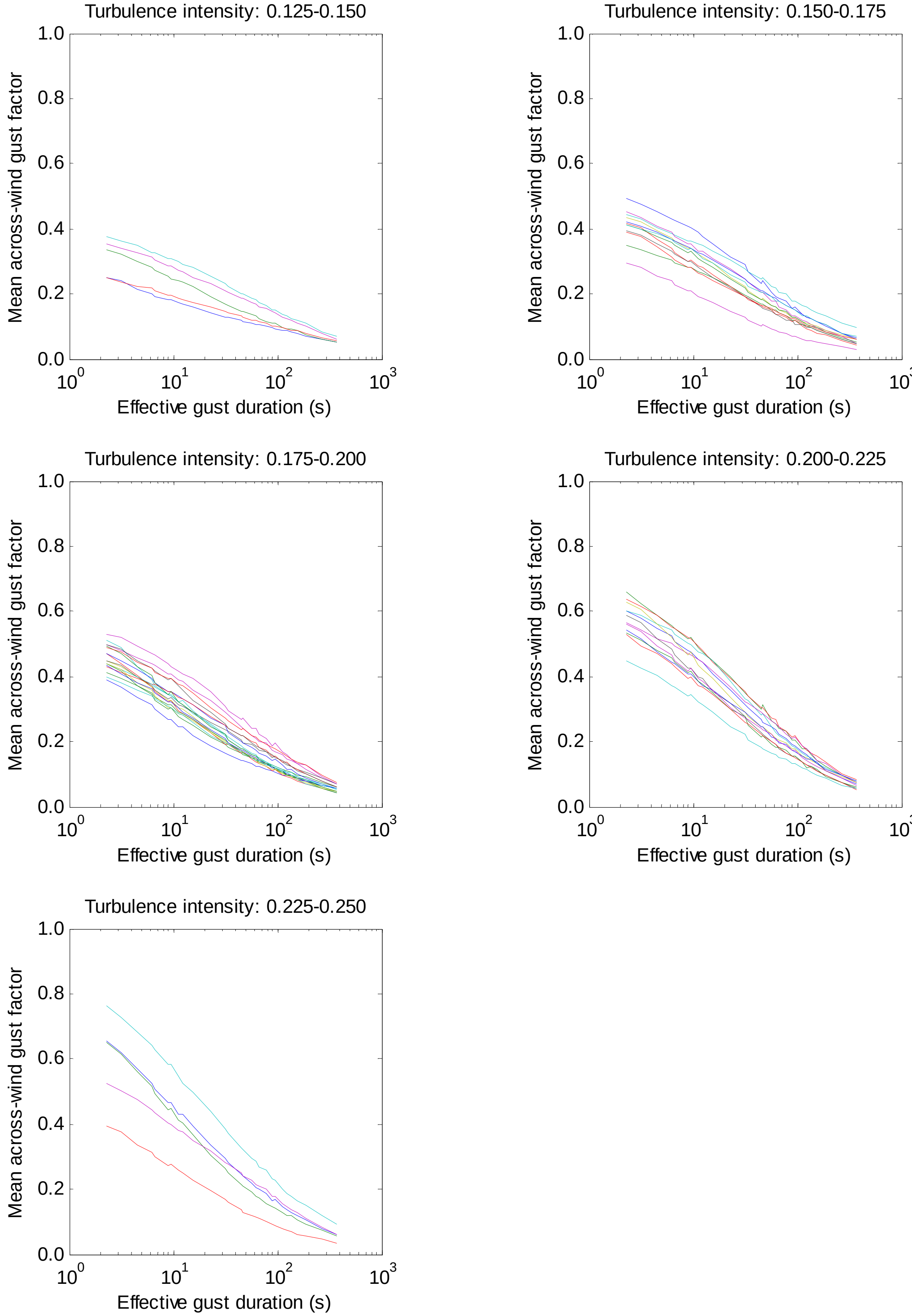

Figure 5: Mean across-wind gust factor versus effective gust duration for all tower/wind direction combinations falling within the indicated mean along-wind turbulence intensity ranges.

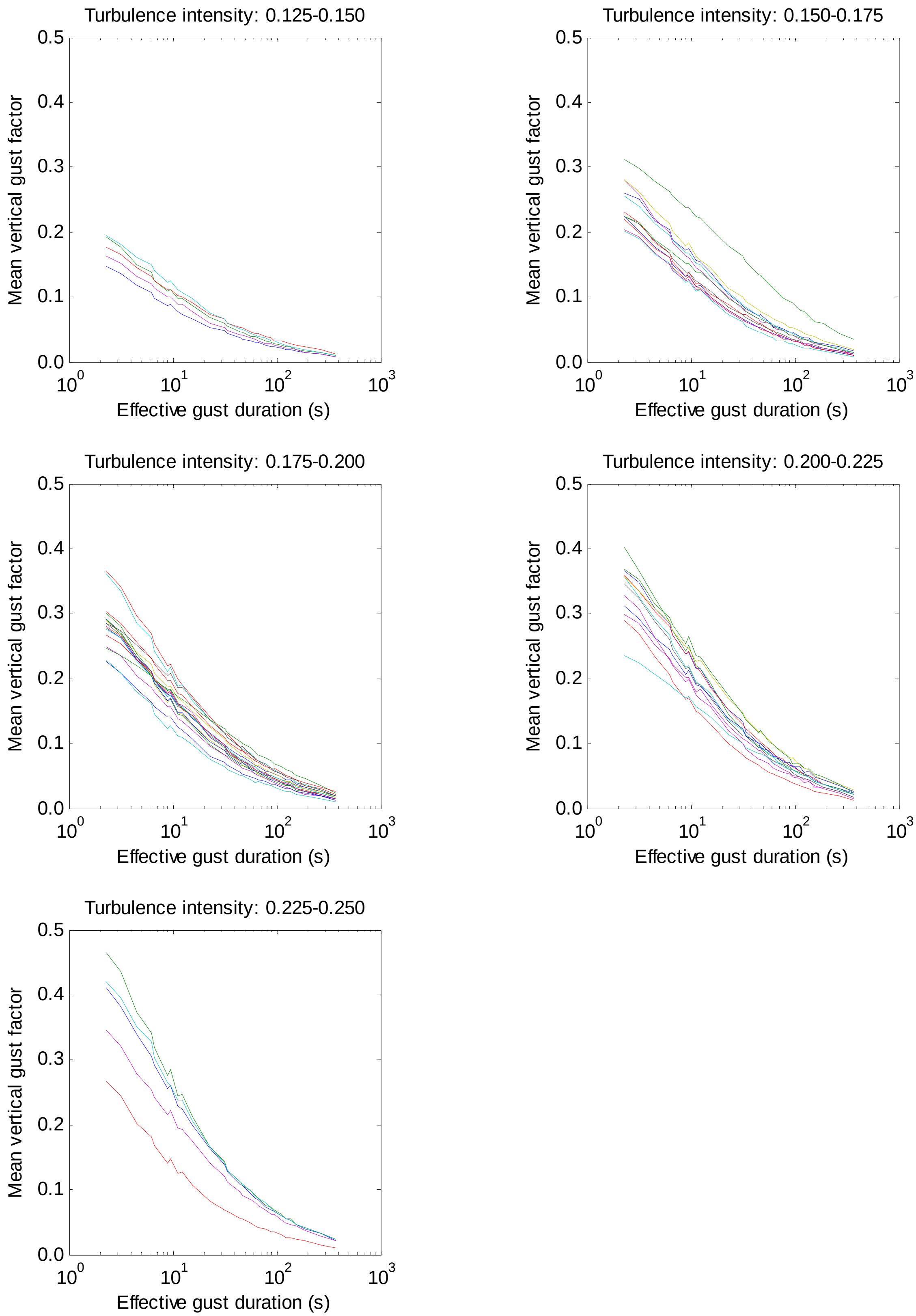

Figure 6: Mean vertical gust factor versus effective gust duration for all tower/wind direction combinations falling within the indicated mean along-wind turbulence intensity ranges.

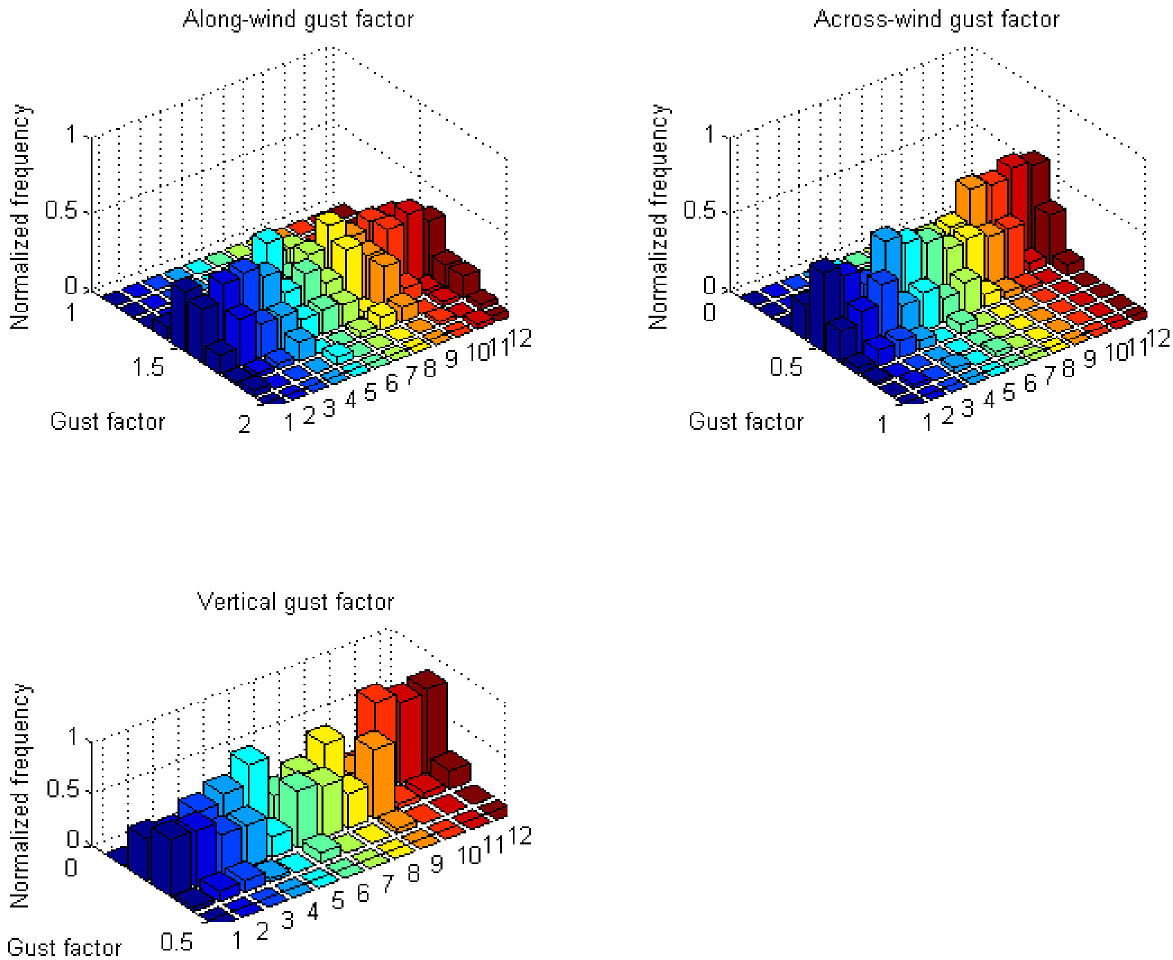

Figure 7: Gust factor distributions for all tower/wind direction combinations with a mean along-wind turbulence intensity falling within the range 0.200-0.225.