

Anonymous Referee #1

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The manuscript deals with gusts in a very complex terrain – the Perdiago experiment. It is a very comprehensive data evaluation of high quality measurements mainly from

9 meteorological towers, but also includes measurements from two vertically pointing wind lidars. The analysis is very comprehensive and interesting. It covers the description of gusts broadly and not only limited to “3 sec meteorological gusts” or the “Mexican Hat” gusts for wind energy. In this respect it was a pleasure to read the manuscript. I have a few comments for the authors to consider:

Thank you for your thorough and thoughtful response to this paper. Before addressing your specific suggestions,

it is important to note that, at the recommendation of a researcher who contacted us after reading our submitted paper online, we are now using an improved method of estimating wind speed coherences. Since the imaginary part of the complex-valued cross spectral density function will tend toward zero as the data length used in the estimation increases, and its presence tends to bias the coherence floor upward. We have elected to use co-coherence as unbiased estimate of coherence as in Eliassen and Obhrai (2016). This has lowered the coherence floor in our estimates to near zero, and improved the exponential fits to coherence decay. This change is noted and explained in the text (Page 11, lines 13 – 19).

1. Eq.(1). There seems to be a minus missing

Thank you for noticing this error. It has been corrected

2. Eqs. (6), (7) and (8) (9). Is it possible to provide references for the transfer functions?

A reference has been provided for the four probability distributions (page 7 line 36)

3. Although in the introduction the broad importance of gusts is described, on page 8 line 7 the thresholds that are applied in the data analysis here relates to wind turbines and wind energy. This limitation in the study should be mentioned more specifically and put up-front.

While the threshold magnitudes chosen in this study are related to wind energy, the application of gust thresholds is necessary to the study of gust behavior, since mean-wind-speed-normalized parameters (such as gust factor, peak factor, and turbulence intensity) have extremely high variance at the lowest wind speeds.

While the authors do not consider these thresholds to be a limitation, we now specifically describe the

threshold in the context of links to NWS (meteorological) protocols and the wind energy industry (Page 7, Lines 20 – 23)

4. Figure 5. It is difficult (impossible for me at least) to distinguish between the frame of the blue and black boxes.

The black boxes in Figure 5 (and the similar figures in supplementary materials) have been replaced with red, which should be easier for readers to distinguish from black.

5. Figure 10. The figure and its legend are very busy. I suggest having figure 10a as a separate figure.

Figure 10a and the color legend have been significantly increased in size (and panel b excluded). The color scheme has been changed to 10 categories rather than a continuous scale for increased clarity.

6. Page 19, line 10 to page 21, line 14, I find the idea to devise specific spectra for gusts periods and non-gusts periods as rather artificial and it does not contribute much to the overall discussion on gusts. The same goes for the discussion on the reverse height, which also does not adhere to the findings of the gusts characteristics.

Turbulence intensity (as a function of height) has been added to Figure 7, and a more explicit connection has been made between gust parameters (including TI) and reverse height (Page 17 lines 7-9) and (Page 26, lines 28-32)

Explanatory text has been added to elucidate the physical meaning of the gust and non-gust spectra and their relationship to gust phenomena (Page 25, lines 35 - 39)

Anonymous Referee #2

Received and published: 2 November 2018

General Comments

The manuscript entitled “Characterizing Wind Gusts in Complex Terrain” by Letson et al. addresses various aspects of wind gusts based on nine meteorological masts and two Doppler lidars within a region of about 3 km x 3 km in size, that is characterized by two topographic ridges separated by a valley, which are oriented in the northwest to southeast direction. Although it is not explicitly expressed in the manuscript, the study seems to be a follow-up of the work by the same authors (Hu et al., 2018), but here the attempt is to generalize the findings of Hu et al. (2018) by analyzing several mast measurements instead of one only. The present work focuses in understanding the statistical behavior of wind gusts as a function of height, in the horizontal plane, and as a function of atmospheric conditions (stability, wind direction, turbulence intensity). The paper presents in-depth analysis of various gust parameters using different types of statistical methods. However, due to this, in many parts the paper is laborious to read and to understand. Therefore, it is strongly recommended to restructure the manuscript by focusing more on the presentation of the key objectives of the work and addressing the results and conclusions accordingly. In other words, substantial revision is recommended.

Thank you for your thorough and thoughtful response to this paper. Before addressing your specific suggestions,

it is important to note that, at the recommendation of a researcher who contacted us after reading our submitted paper online, we are now using an improved method of estimating wind speed coherences. Since the imaginary part of the complex-valued cross spectral density function will tend toward zero as the data length used in the estimation increases, and its presence tends to bias the coherence floor upward. We have elected to use co-coherence as unbiased estimate of coherence as in Eliassen and Obhrai (2016). This has lowered the coherence floor in our estimates to near zero, and improved the exponential fits to coherence decay. This change is noted in the text (Page 11, lines 13 – 19).

Specific Comments

Introduction (page 1, lines 24-37): It is not clear what you mean by a wind gust. You refer to gusts generated by mesoscale convective systems and downdrafts and by mountain waves, but is the topographic channeling also

causing wind gusts? Recommendation: provide a clear definition for a wind gust already in the very beginning of the manuscript.

Wind gusts are now more clearly defined in the introduction as “coherent short-term wind speed maxima”

(Page 1 line 32).

The use of terminology is confusing in some parts of the work:

- Gust definitions are provided only on page 6, and before that you use terminology “descriptors of wind gusts” (p. 3, line 1), “wind gust characteristics” (p. 3, line 33) and “gust parameters” (p. 4, lines 19-20), without any explanations. Recommendation: define the gust already in the beginning (with a reference to Section 3.1) and use the terminology consistent within the whole manuscript.

The wording of references to wind gust parameters has been changed to be more consistent. The above phrases

have all been changed to ‘wind gust parameters’ since they refer to section 3.1

- Doppler lidar scanning technique: In the abstract and in different parts of the manuscript you write that the Doppler lidars are “vertically pointing”, “vertically-pointing conically scanning” and “vertically-scanning”, which is confusing. Moreover, in Section 2 (p. 5, lines 12-30) you indicate that the lidar is a scanning lidar with cone angle of +/-15°, but you don’t provide any information on, e.g., how many lines-of-sight the Doppler lidar has, etc.

Recommendation: provide detailed technical information of the Doppler lidars and the scanning techniques in Section 2. If the Doppler lidar was not applied in “stare mode” (i.e. measuring only in vertical direction) you can write “vertical profiles derived from Doppler lidar measurements” instead of “vertically pointing”.

A detailed description of ZephIR lidar operation has been added to address these questions (Page 5, line 10 –

Page 6, line 3)

- Objectives are expressed quite broadly in Section 1 (pages 3-5) and the conclusions in Section 5 do not include answers to all objectives. Recommendation: Provide a more concise list of objectives and check that you answer them in Section 5.

The conclusions section has been reorganized to include 5 bulleted paragraphs corresponding to the 5 bulleted paragraphs outlining the goals in the introduction (Page 2, line 6 to Page 4, line 5 and Page 24, line 13 to

Page 25, line 30)

Section 2: Reorganize the Section: start with the most important data set (met masts), then Doppler lidars, and in the end other supporting data (terrain elevation + canopy height). Adding subtitles would make the Section more organized. Figure 2c: percentages within each sector are difficult to read. Please, consider using bars instead of a line to indicate the histogram of wind directions.

Thank you for this recommendation. Sub-sections have been added to section 2 in the suggested fashion. Figure 2 has been amended to include bars for the wind direction histogram in the wind rose panel.

Section 3.1: Gust parameters were easier to understand after seeing the Figure 3a of Hu et al. (2018). Please, consider showing a similar picture also here. Furthermore, consider providing an equation for the gust length scale.

Rather than adding an additional figure, explanatory text has been added to more clearly describe the definitions of rise time, lapse time and length scale (Page 6, line 28 to Page 7, line 3) and an equation has been added for length scale (Eq. 1)

Section 3.1: Move the probability distributions (p. 6, line 34 – p. 8, line 5) into a separate subsection. Add the “gust period” (p. 8, lines 15-25) to the list of gust definitions on page 6. Consider also a new subsection for the gust parameterizations (p. 8, lines 6-14), or combine them to the list of gust parameters on page 6 (or consider leaving them out from the whole study).

A new sub-section has been added for probability distributions and joint distributions.

The definition of gust periods has been moved to the end of this section (page 7, lines 13-22).

Page 12, lines 10-11: comparison of 3-5 s averaging window and the gust rise time is unfair, as the gust rise time is defined based on 3 s moving averaged wind speed time series. Moreover, in Figure 4c, the 1% t_{rise} data are scattered around 4 s. Is this related to the presence of the lower limit for t_{rise} arising from its definition? Please, comment.

This comparison is now explained more clearly and the presence of a lower limit on rise and lapse times resulting from the 3 s averaging window is made explicit (Page 13, lines 19-23)

Page 12, line 18: At this point it was necessary to read the paper by Hu et al. (2018) in order to understand the work in this manuscript. Recommendation: mention already in the introduction, that this present paper is strongly

based on the work by Hu et al. (2018). You may even list their main findings in the introduction of this paper and then build the objectives of the present work on top of these findings, by addressing what else will be done here. This way, it will be probably easier to improve the structure of the present paper when everything is not presented as “new”.

We have added a more explicit statement that the current study is designed to mirror Hu et al., (2018) for ease of comparison to results from less complex terrain (Page 2, lines 12-14)

Figure 5 and Figures S1-S5: Could these results be shown as a Table? The images are not very informative. Without seeing aspect ratios, it is impossible to visually see the differences between the cases where the aspect ratio changes e.g. from 6.97 to 7.30 or from 1.18 to 1.32 or even to 1.60. Recommendation: show a couple of examples of these joint distributions in Section 3, where the methodology is described, to illustrate visually, how the aspect ratio is calculated. Then, in the results section, you could summarize all the results in a Table providing only the aspect ratios, maybe by grouping the results into high, medium and low values. This way, the main results from the Supplementary material could also be shown in the main manuscript, supporting the nice results on page 13 lines 20-25, which are relevant and a key part of this study.

Figure 5 and the similar supplementary figures communicate more information than could be included in a table in a similar amount of space, and may be quicker to interpret. We now explicitly refer to each figure in SI and present in more detail the results shown there in. (Page 14 lines 15-37)

The description of the method used to compute the joint distributions has also been made more explicit. (Page 8, line 34 – Page 9 line 13)

Figure 7 on page 16 is very difficult to interpret, because all the lines are close together and panels are very small. What is actually the added value of the upper panels (a1-f1) compared to the lower ones (a2-f2)? Moreover, the main results of Figure 7c2 are shown also in Figures 8b-c. Recommendation: remove all other panels except Figures 7e2 and 7f2, and modify the text accordingly. Only these panels provide something new compared to the other Figures.

Half of the panels (those representing all 10 minute periods, rather than gust periods alone) have been removed from Figure 7. This makes the remaining panels much larger and easier to read.

Page 16, lines 17-25, and p. 17, lines 1-4: you discuss the Doppler lidar volume averaging, but in Section 2 you don't describe in detail what is meant by the "volume" in case of the continuous wave ZephIR lidar (and how it differs from pulsed Doppler lidars). Please, provide explanations.

A parenthetical explanation of the volume has been added "(the volume of the annulus swept out by the lidar beam, in a cone 30° from vertical)" (Page 17, line 15). This volume averaging is now also described on Page 5 (lines 26 – 31)

Figure 9: Already Hu et al. (2018) showed that the peak factor is not a function of mean wind speed. Why do you show this picture? Please, consider removing it. Comparison to other parameterizations is not very relevant for this work, maybe you could remove the parameterization aspect from the whole paper, and leave it open for future studies. There is now enough material already for one paper, even without the parameterization.

The authors believe that Figure 9 represents an important link to the meteorological literature and have decided to continue to include it in the paper. Hu et al. (2018) does show a weak relationship between peak factor and mean wind speed. Which has been found in the current study to be stronger in complex terrain.

Section 4.3. and Figure 10:

- In the text, you introduce a new concept "mean marginal probability" without defining it. Please, explain.

Some explanatory text for mean marginal gust probability has been added (Page 19, line 6)

- Figure 10 is extremely difficult to interpret: color scale is continuous, but the results are presented as boxes. It is very difficult to interpret the color of each box; please, use categories in the color scale, for example at 0.1 intervals of probability.

Figure 10a and the color legend have been significantly increased in size (and panel b excluded). The color scheme has been changed to 10 categories rather than a continuous scale for increased clarity.

- Concerning panel (a), you conclude that the mean co-occurrence probability is 0.27 for 10 min data and 0.43 for 30 min data. This means, that in 73% and 57% cases the gusts do not occur simultaneously. Moreover, the Figure 10a illustrates the small differences in co-occurrence probabilities especially in the low range (blue colors). Is that really necessary? Recommendation: provide results only for probabilities > 0.5 (and with 0.1 intervals in color scale as suggested in the previous comment).

Since, for a significant fraction of tower pairs, the co-occurrence is below 50% (as you note), we have elected to include the values for co-occurrences below this level. We believe that the binning of co-occurrence data into 10% categories (as you suggested above) has made these values easier to for the eye to interpret.

- The color scale in panel (a) for 10 min data is different from the scale of 30 min data, because it is possible to distinguish the circles in the diagonal. Please, comment this.

With an adjustment to make the color scale more precise, this artifact disappeared. Thank you for noting it.

- What is causing the asymmetry across the diagonal in panels b-d? It is especially pronounced in panels (b) and (d). Overall, Figure 10 is extremely difficult to interpret. What are the parameters on each side of the Figure? Why do you give percentages only on the vertical axes?

The marginal probabilities of gust occurrence listed along the vertical axis would be identical to those along the horizontal axis, since they only reflect the probability of gusts at each individual sensor. The asymmetry is largely due to the differing marginal probability of gusts at different sensors. A specific example of this asymmetry is called out and interpreted on Page 19 (lines 12 – 16).

Why the results are not symmetric with respect to the diagonal? Have you calculated the average probabilities using data from the diagonals too? It is possible to find the answers to these questions based on the provided information but it takes a lot of time. Due to this complexity, it is foreseen that many readers will probably skip the Figure while reading the paper. Therefore, the value of the illustration is questionable. Consider removing the Figure, or simplify it substantially.

See previous response on asymmetry. The figure has been simplified in the specific ways that the reviewer has suggested (enlarging of panel a and the use of probability classes rather than a continuous scale)

Figure 11: Why do you show separately gusty conditions and all cases? Why not to show separately gusty and non-gusty cases (i.e. no overlap of underlying data)? The contribution of these spectra to the understanding of the characteristics of wind gusts is questionable, please, consider removing this Figure.

The spectra for all periods are included to allow for direct comparisons with spectra from terrain of varying complexity in the literature (e.g. Panofsky et al. 1982 QJRMS)

Figure 13 and text on p. 21, lines 17-29, and p. 22, lines 1-7: you have recognized a coherence floor, but still you perform exponential fits with respect to zero – why? What is the parameter “d” on the horizontal axes?

At the suggestion of helpful commenter, we are now using the co-coherence as a non-biased estimator of the wind speed coherences. The coherence floor is no longer a major factor (see text Page 11, line 13 – 19)

Section 5:

- Conclusions do not answer directly to the objectives of this study. Please, check and modify.

The conclusions section has been modified to have a structure parallel to the goals laid out in the introduction.

The third paragraph (p.23, lines 8-15) is too complicated. It is impossible to identify to which parts of the results section these conclusions refer to.

The concluding remarks have been substantially reorganized. There are now five bulleted paragraphs (Page 24, line 13 to Page 25, line 39) corresponding to the bulleted goals listed in the introduction. Thoughts synthesizing information from more than one of the goals have been moved to the end of the section

Technical Comments

p. 3, lines 1-3: long and complicated sentence, please simplify.

This sentence has been simplified by removing the references to specific gust parameters (Page 3, Line 6-7)

p. 4, line 1: Repetition: “characteristics”, “characterized”

Wording changed to avoid repetition (Page 4, Lines 1-2)

p. 4, lines 3-5: Complicated sentence: “Horizontal coherence.across the study domain.” Please, clarify.

This sentence was quite unclear. It has been re-written (Page 4, Lines 3 -5)

p. 5, lines 1-2: information in parentheses not necessary, please remove.

This information has been removed (Page 4, Lines 28-29)

p. 5 line 12: “Some analyses reported herein employ. . .” Quite arbitrary approach, please, be more specific.

This has been re-written to be more specific (Page 5, Line 11-15)

p. 10, line 19: Please provide the ZephIR lidar sampling rate here.

This has been added (Page 11, line 23)

p. 12, line 17: Add: “Figure 3f-g”.

Added. (Page 13, Line 22)

p. 12, line 18: Remove parentheses: “with (Hu et al., 2018); Table 2”, i.e., change to “with Hu et al. (2018); their Table 2”.

Done. (Page 14, Line 1)

p. 12, lines 18-20: Does this sentence summarize the results of the present study or those from the literature?
Please, clarify.

This has been reworded to indicate that it is a statement about the current study, which has been noted before in literature (Page 14, Lines 1-4)

p. 13, lines 3-7: Too complicated and long sentence. Please, simplify. Explain also what is meant by “all three time parameters”.

This sentences has been divided into 2 sentences to make it easier to parse. The ‘time parameters’ have been listed explicitly (Page 14, Lines 10-14)

p. 13, line 11: Please, define “gust intensity”.

Changed wording to “gust magnitude” which has been explicitly defined (Page 14, Line 15)

p. 13, line 14: Consider splitting the paragraph before “Joint distributions of gust...”

Done (Page 14 Line 23)

p. 15, line 18: Consider starting the sentence with “In Figure 7, data from all 10 minute periods within 64 days. . .”

This change has been made (Page 16 Line 18)

p. 16, line 25: Add to the end of the sentence: “. . .the fit vary between sampling location and instrument (Figure 8c).”

Reference added (Page 18, Line 6)

p. 18, line 9: Is the referred Figure 3g correct here? Figure 3g shows the distribution of lapse time, not gust length scale.

Thank you. This has been corrected to Figure 3i. (Page 19 Line 17)

p. 21, line 6: Should it read “Reversal height estimates”

Our preferred term in ‘reverse height’ the phrase ‘reversal height’ has been replaced throughout the paper for consistency.

p. 21, line 25: "Tower 29, Figure 13b) have C values between 8.4 and 10.6" - is this wrong? According to caption, Figure 13b shows the results for Tower 20, and in panel (b) the C values are smaller.

Thank you. The C values now changed due to the use of Co-coherence as a coherence estimator, mentioned above.

p. 21, lines 25-26: "sensors with vertical separation of 6 to 16.9 (Solari, 1987)" - this is not understood: what is the "vertical separation" here? Does it refer to the instruments here or in the study by Solari (1987)?

This has been re-worded for clarity (Page 23, lines 16-18)

p. 21, line 29: "Tower 25 exhibit C values of 4.6 to 6.7 (Figure 13c)" - these are probably also wrong. Please, check to be consistent with Figure 13.

Thank you. This has been corrected, and the values have changed somewhat due to the lower coherence floor associated with using co-coherence as an estimator.

p.23, lines 9-10: "Joint probability distributions of the gust properties indicate high aspect ratios for gust intensity metrics. . ." - What is the difference between the "gust properties" and "gust intensity metrics"? Please, explain.

These term have been replaced by 'gust parameters' and a specific example (U_{gust}), for consistency and clarity (Page 25, lines 1-2)

p. 23, lines 10-14: the sentence starting from "However, low aspect ratios. . ." and ending to "...by two parallel ridges (Figure 1)." is very difficult to understand. Please, simplify.

This has been separated into 2 sentences and simplified (Page 25, lines 2-4)

p. 23, line 19: Should it read "change in C"?

Yes, thank you. This has been corrected (Page 25 line 37)

p. 23, line 20: Should it be "Figure 13d"?

It absolutely should. This has been corrected (Page 25, line 37)

Characterizing Wind Gusts in Complex Terrain

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Abstract

Wind gusts are a key driver of aerodynamic loading, especially for tall structures such as bridges and wind turbines. However, gust characteristics in complex terrain are not well understood and common approximations used to describe wind gust behavior may not be appropriate at heights relevant to wind turbines and other structures. Data collected in the Perdigão experiment are analyzed herein to provide a foundation for improved wind gust characterization and process-level understanding of flow intermittency in complex terrain. High-resolution observations from sonic anemometers and vertically pointing Doppler lidars are used to conduct a detailed study of gust characteristics with a specific focus on the parent distributions of nine gust parameters (that describe velocity, time and length scales), their joint distributions, height variation and coherence in the vertical and horizontal planes. Best-fit distributional forms for varying gust properties show good agreement with those from previous experiments in moderately complex terrain but generate non-conservative estimates of the gust properties that are of key importance to structural loading. Probability distributions of gust magnitude derived from vertical pointing Doppler lidars exhibit good agreement with estimates from sonic anemometers despite differences arising from volumetric averaging and the terrain complexity. Wind speed coherence functions during gusty periods (which are important to structural wind loading) are similar to less complex sites for small vertical displacements (10 to 40 m), but do not exhibit an exponential form for larger horizontal displacements (800 to 1500 m).

1 Introduction and objectives

Topographic channeling or enhancement of the near-surface flow can lead to local increases in wind speed (Wagenbrenner et al., 2016) and hence enhance the wind resource (Clifton et al., 2014; Barthelmie et al., 2016; Jubayer and Hangan, 2018). Terrain inhomogeneity also induces complex flow conditions (Wood, 2000) particularly in the presence of vegetation (Suomi et al., 2013) that have implications for wind loading on structures, pollutant dispersion, wildfire propagation and wind turbine siting and operation (Sanz Rodrigo et al., 2017; Wagenbrenner et al., 2016; Butler et al., 2015). Key features of flow in complex terrain include: Thermo-topographic flows arising from differential heating (Rucker et al., 2008; Rotach and Zardi, 2007), and lee-side vortices that develop parallel to mountain ridges (Grubišić et al., 2008). Regions with complex topography and land cover heterogeneity also tend to experience more frequent and stronger wind gusts ([herein defined as](#) coherent short-term wind speed maxima) (Letson et al., 2018; Earl et al., 2017; Sheridan, 2011; Hasager et al., 2003) due in part to:

1. Terrain-induced alteration of the structure of mesoscale convective systems and thus the downdrafts and wind gusts generated therefrom (Markowski and Dotzek, 2011).
2. Generation of small amplitude mountain waves in stably stratified air that can cause strong and gusty downslope winds when the flow becomes supercritical and these waves ‘break’ (see detailed discussion in (Durrán, 1990) and (Hertenstein and Kuettner, 2005)).

Wind gusts represent an important source of structural engineering loads for tall buildings, towers, bridges and wind turbines (Solari, 1987;IEC, 2005;Cheynet et al., 2016), and are known to be of larger magnitude in complex terrain due in part to the factors listed above (Tieleman, 1992;Verheij et al., 1992). A number of numerical wind flow models have been developed for application at high spatial resolution over complex terrain, but model evaluation has been severely constrained by the lack of suitable observational data (Butler et al., 2015;Bechmann et al., 2011;Berg et al., 2011;Suomi and Vihma, 2018). Further, most past research on flow intermittency has focused on the intensity (i.e. magnitude) of wind gusts and has employed measurements from 10 m a.g.l. (e.g. (Vickery and Skerlj, 2005)). Thus, there is a need to advance understanding of the spatio-temporal coherence of wind gusts at heights above 10 m a.g.l., in complex terrain (Belu and Koracin, 2013;Mouzakis et al., 1999), and for better characterization of both (i) the height variation of gust properties (Suomi et al., 2013) and (ii) to characterize additional descriptors of wind gusts such as gust rise times and length scales since these properties also contribute to the wind-excited structural response (Solari, 2014;Frost and Turner, 1982) and fatigue loading on wind turbines (Chamorro et al., 2015;Hu et al., 2016). [The gust parameters and probability distributions used herein to describe the behavior of wind gusts in complex terrain are designed to mirror those used in \(Hu et al., 2018\), so that clear comparisons can be made between the results of the current study and those derived from measurements in less complex terrain.](#)

Herein we address these research needs using data collected during January – July 2017 at a site in eastern Portugal near Perdigão (Figure 1a). Two parallel ridges running from northwest to southeast and separated by 1.4 km dominate the local topography in the study area. These ridges stand 300 to 350 m above the surrounding terrain, and approximately 175 m above the valley located between them (Figure 1b). This location was the focus of a measurement campaign during which over 50 meteorological masts were deployed over an area of a few square km (Mann et al., 2017). The data collected in the Perdigão experiment and employed herein to characterize flow behavior at heights relevant to wind turbine selection, operation and micro-siting with a specific focus on wind gusts are: High-frequency (18 Hz) 3-D wind measurements from Gill WindMaster Pro sonic anemometers deployed on the nine tallest of the meteorological masts (that extended to heights (z) above 50 m a.g.l.) and horizontal wind speeds from two vertically-pointing conically scanning (ZephIR) Doppler lidars (locations of these instruments are shown in Figure 1b and Table 1, details of the measurement technologies are given in section 2).

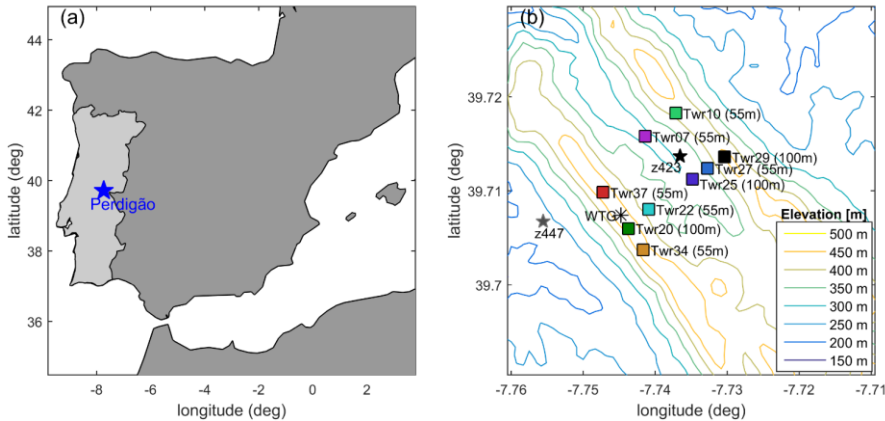


Figure 1: (a) Location of the Perdigão measurement site in Portugal. (b) Overview of the tower and ZephIR lidar locations and site topography (measured by the Shuttle Radar Topography Mission (Farr et al., 2007)). The height of each tower is shown in parentheses. The nine colors shown in this figure are used to distinguish the nine towers throughout the paper. A single wind turbine is located on the SW ridge (denoted by WTG *).

The objectives of the current study are as follows:

- Evaluate the degree to which the best-fit probability distributions to various [gust parameters](#) (e.g. intensity, temporal scale, and length scale) as advanced by (Hu et al., 2018), are generalizable across terrain types. The resulting parametric descriptions of gust properties are potentially of utility to the engineering community because they; permit estimation of extreme values (IEC, 2005;ASCE, 1998) (e.g. using Rice theory (Gomes and Vickery, 1977)), facilitate development of joint distributions of [gust parameters](#), allow characterization of gusts that contribute to structural fatigue, and are used with design standards (for example, extreme gusts are modeled in wind turbine design standards based on mean wind speeds and turbulence intensity (IEC, 2005)). They are potentially also of use within the meteorological community since they could afford a methodology for downscaling of wind gusts in either weather forecasting (Friederichs and Thorarinsdottir, 2012;Suomi and Vihma, 2018) or climate downscaling contexts (Cheng et al., 2014). Further, fluctuating wind loads on engineering structures requires estimates of multiple components of the flow, including characteristics that have previously received relatively little attention (e.g. the shape of wind gusts) (Mücke et al., 2011;Suomi et al., 2013). Various parametric distributions are evaluated in terms of their goodness-of-fit to the empirical data, and their accuracy at the distribution tails, and are used to develop joint probability distributions of different gust properties at a single location and of the same gust property across space (where the latter can be used to develop bivariate extreme value Copulas (Bonazzi et al., 2012)). Where possible the distributional forms for each gust parameter are compared with previous work in flat or moderately complex terrain (Morgan et al., 2011;Cheng and Bierbooms, 2001;Friederichs and Thorarinsdottir, 2012;Hu et al., 2018).
- Quantify the dependence of different descriptors of wind gusts on measurement height (z). Data from comparatively flat terrain show evidence that the characteristics of wind gusts, and particularly gust factors and gust durations, vary systematically with height (Román, 2017;Suomi et al., 2015;Suomi et al., 2013;Ashcroft, 1994). We seek to describe the magnitude and nature of this variability with height in complex terrain by conditionally sampling gust properties as derived from the sonic anemometers deployed on the meteorological masts and as determined from vertically pointing ZephIR lidars.
- Characterize power spectra of wind speeds from sonic anemometers and ZephIR lidars at different heights. These power spectra are used to determine how the presence of wind gusts affects their shape (Hu et al., 2018), and to derive first order estimates of the so-called reverse height (i.e. height above ground at which surface-driven processes cease to dominate scales of variability) using the amount of variance expressed at the diurnal timescale (Larsén et al., 2018;Troen and Lundtang Petersen, 1989). In the near-surface levels surface-driven processes produce the diurnal peak in the power spectrum of wind speeds, while aloft it is primarily the product of pressure perturbations deriving from the atmospheric tide (Larsén et al., 2018). At intermediate heights there is a relative minimum in the amount of variance expressed at periods ≈ 1 day. At these heights the first-order effect of the surface heat-flux modulations vanishes (Larsén et al., 2018), and thus it may provide an estimate of the height at which surface-driven processes cease to dominate scales of variability.
- Quantify the dependence of wind gust [parameters](#) on atmospheric conditions; specifically stability, wind direction and turbulence intensity (Barthelmie et al., 2016;Hu et al., 2018). Previous work has shown that gust factors are strongly and directly related to turbulence intensities (Ashcroft, 1994;Greenway, 1979;Hu et al., 2018), and that turbulent kinetic energy (and hence the potential for gusts) is enhanced downstream of obstacles (Jubayer and Hangan, 2018). Thus, wind gust properties at the nine towers are conditionally sampled by wind direction, stability class and by turbulence intensity.
- Quantify spatial coherence in flow properties particularly wind gusts. The physical scales of wind gusts are critically important to loading on structures (Solari, 1987;Hui et al., 2009;Bos et al., 2016), and the potential for gusts to remain coherent as they propagate through a wind farm has implications for power quality and grid management (Sørensen et al.,

Deleted: descriptors of wind gusts

Deleted: (gust factors, gust amplitude and peak factor)

Deleted: (rise and lapse time, and duration)

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2002;Viguera-Rodríguez et al., 2012). The frequency characteristics of longitudinal wind speed are investigated using spectral analysis of output from individual sonic anemometers and coherence functions between pairs of sonic anemometers during gusty periods. Horizontal coherence functions between sonic anemometers on different masts and thus displaced by distance of 100's of meters are used to describe the degree to which wind gust variations are coherent in the complex terrain of the study area, and comparisons are made to coherences from previous work.

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2 Data

2.1 Sonic anemometer observations

The primary data set analyzed herein comprises 18 Hz, 3-D wind components and sonic virtual temperature as measured by Gill WindMaster Pro sonic anemometers deployed on these meteorological masts (Table 1 and Figure 1) at heights above the surrounding vegetation. The three tallest towers have seven measurement heights (z) each extending from 10 to 100 m a.g.l. and the remaining six towers have five measurement heights each extending from 10 m to 55 m. The 18 Hz signals from each sonic anemometer are subject to coordinate rotation (including corrections for the boom alignment), and despiking using a five-sigma filter in each 10 minute period. In order to ensure that our characterization of spatial variations in wind gust parameters is not biased by differing measurement periods, the current analyses are restricted to days that have complete data records at all anemometers. Data analyzed here represent all 24 hour periods during which all of the 41 sonic anemometers had > 90% of all 18 Hz signals present in > 99% of 10 minute periods (143 out of 144, 10 minute periods in each day). Analyses of gust parameters based on data from the ZephIR Doppler lidar measurements are also for the same 64, 24 hour periods.

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Moved down [1]: High precision estimates of the terrain elevation and canopy height were derived from aerial laser scans performed by helicopter. The x, y and z positions of the maximum backscatter form a point cloud and are processed to derive terrain elevation and height of the canopy (Floors et al., 2018;Boudreault et al., 2015). Mean maximum canopy heights derived from these data for 50 m by 50 m grid cells centered on each of the nine meteorological masts and the ZephIR lidars are below 7 m (Table 1).

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Table 1: Locations and measurement heights of each meteorological mast (Tower) and each ZephIR lidar. Measurement heights referred to in this paper as '60 m' are shown in bold. Reference tower (Tower 29) is emphasized by italics and underlining. Tower base elevations are given in m above sea level (a.s.l.) and mean vegetation height is calculated from aerial laser scans in a 50 m square cell surrounding each tower/ZephIR lidar. Definitions used to conditionally sample the towers as valley or ridge are also shown along with a parenthetical statement of their location on the northeast (NE) or southwest (SW) ridge. Valley towers are those with elevations below 400 m a.s.l.

Tower #	Measurement heights [m a.g.l.]	Tower elevation [m a.s.l.]	Latitude [°N]	Longitude [°W]	Location	Mean canopy height [m]
7	10 20 30 40 55	290	39.7158	7.7414	valley	3.3
10	10 20 30 40 55	413	39.7183	7.7372	ridge (NE)	3.4
20	10 20 30 40 60 78 100	465	39.7060	7.7437	ridge (SW)	1.5
22	10 20 30 40 55	385	39.7080	7.7409	valley	3.8
25	10 20 30 40 60 80 100	309	39.7112	7.7348	valley	5.4
27	10 20 30 40 55	359	39.7124	7.7327	valley	6.7
<i><u>29</u></i>	<i><u>10 20 30 40 60 80 100</u></i>	<i><u>450</u></i>	<i><u>39.7136</u></i>	<i><u>7.7304</u></i>	<i><u>ridge (NE)</u></i>	<i><u>3.6</u></i>
34	10 20 30 40 55	468	39.7037	7.7417	ridge (SW)	2.9
37	10 20 30 40 55	474	39.7098	7.7473	ridge (SW)	1.9
ZephIR z423	20:20:200	310	39.7137	7.7366	valley	0.9
ZephIR z477	20:20:200	236	39.7067	7.7556	west of SW ridge	2.2

Tower 29, the 100 m tower on the northeast ridge (Figure 1), is used herein as a reference tower to represent pseudo free-stream flow and characterize the prevailing atmospheric stability because of the prevalence of northeasterly flow during the field experiment (Figure 2). Measurements from this meteorological mast indicate a high frequency of flow perpendicular to the ridges. Wind directions between 30° and 60° occurred during 20% of 10 minute periods while wind directions between 210° and 240° occurred during 14% of 10 minute periods (Figure 2c). At Tower 29, the mean 10 minute wind speed at 60 m is 5.0 ms⁻¹, and the mean turbulence intensity for mean wind speeds > 3 ms⁻¹ is 0.14 (Figure 2a,c). The greatest height represented at all nine

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meteorological masts is 55 or 60 m. Thus, this height is used to compare wind conditions across study domain and is referred to herein as the 60 m measurement height for brevity. In some of the following analyses the meteorological masts (towers) are classified as ‘ridge’ or ‘valley’ where the former group have base elevations above 400 m a.s.l., and the latter are at elevations below that level (see Table 1).

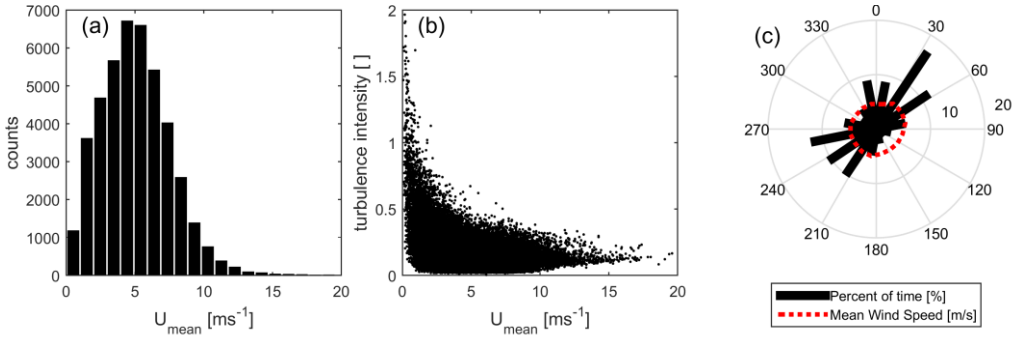
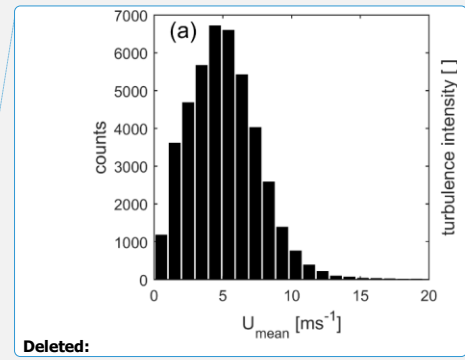


Figure 2: Overview of wind conditions at Perdigo. (a) 10 minute mean wind speed distribution at 60 m a.g.l. on Tower 29. (b) 10 minute turbulence intensities versus mean wind speed at 60 m a.g.l. on Tower 29. (c) Wind rose (black bars) and mean wind speed (red dotted line) from data collected at 60 m a.g.l. on Tower 29.

2.2 Doppler lidar observations

Lidars used in atmospheric applications can employ either light emitted in continuous wave or pulsed forms (Held and Mann, 2018; Vasiljević et al., 2017). Measurements from two ZephIR continuous wave Doppler lidars (referred to here as ‘lidars’ and by their unit numbers; z447 and z423) are used to extend the analysis of gust parameters to heights above 100 m a.g.l.. One ZephIR lidar was deployed in the central valley 311 m from meteorological mast 25, and one to the west of the SW ridge (Figure 1b; locations in Table 1). The ZephIR 300 series is a continuous wave coherent monostatic lidar that has a wavelength of 1.575 μm, and an operating frequency of 50 Hz (Smith et al., 2006). It is vertically-pointing (i.e. conducts velocity azimuth display scans) using a rotating prism to direct the laser over a scanning cone angle of 30°, and measures the Doppler shift for 50 data points every second across a full 360-degree scan (i.e. separation in the azimuth is approx. 7°). This variation of azimuth scan angle is necessary to convert from the Doppler shift derived from motion along the line-of-sight to the horizontal wind speed, and several hundreds of Doppler spectra are averaged in each azimuth sector. For all continuous wave lidars there is an ambiguity in the identification of the dominant frequency in the Doppler spectrum so a range of methods have been developed to derive that frequency and in the case of the ZephIR 300 it is identified from the centroid of the power spectral density above a noise threshold (Held and Mann, 2018). The Rayleigh length (a measure of the probe volume) scales with the square of the focus distance from the lidar. For the ZephIR 300 the probe length is 0.07 m at 10 m and 7.7 m at 100 m. These instruments were configured to measure horizontal wind speeds at 10 measurement heights (20 to 200 m a.g.l. at 20 m intervals), sampling at each height once every 17 s. Conically scanning Doppler lidars have been subject to extensive field validation (Gottschall et al., 2012). However, these Doppler lidars assume the flow to be homogeneous across the scanning volume in order to infer the horizontal wind speed. The radius (and circumference) of the annulus for the ZephIR 300 at a height of 100-m is thus 58 m (363 m) and at 200-m it is 115 m (726 m). Hence this assumption of homogeneity across the scanned annulus is not fulfilled in complex terrain leading to increased uncertainty and potentially error in retrieved horizontal wind speeds (Bingöl et al., 2009). Further, the volumetric averaging inherent in use of lidars means the wind speeds are not directly equivalent to those from in situ anemometry. Nevertheless, vertically pointing Doppler lidars offer the potential to quantify wind gusts at heights above those



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possible from sonic anemometers deployed on meteorological masts (Suomi et al., 2017), and are increasingly being adopted by the wind energy research and operations communities (IEA Wind Task-32 Lidar for Wind Energy Deployment) (Clifton et al., 2018). Herein, we evaluate the degree to which the probability distribution of gust amplitudes and GF derived from the maximum of the disjunct measurements sampled at each of 10 heights (effective duration of approximately 2 sec) in each 10 minute period correspond to those from the 18 Hz data from the sonic anemometers. We also use time series of 10 minute mean wind speeds from each height (up to 200 m a.g.l.) from the ZephIR lidars to investigate the reverse height (implied by the magnitude of the diurnal peak, estimated across the frequency range; 3×10^{-6} to 2×10^{-5} Hz) and to compute coherence functions. For this purpose, the longest continuous (any/all data gaps < 1 day in duration) data period from each ZephIR lidar is used (91 days of data at z423 and 142 days at z447).

2.3 Terrain and vegetation height

High precision estimates of the terrain elevation and canopy height were derived from aerial laser scans performed by helicopter. The x, y and z positions of the maximum backscatter from a point cloud and are processed to derive terrain elevation and height of the canopy (Floors et al., 2018; Boudreault et al., 2015). Mean maximum canopy heights derived from these data for 50 m by 50 m grid cells centered on each of the nine meteorological masts and the ZephIR lidars are below 7 m (Table 1).

3 Methods

Section 3.1 provides definitions used herein and outlines methods used in the conditional sampling, while section 3.2 briefly describes the methods used in the spectral and coherence analyses.

3.1 Wind gust parameters

The following definitions are used herein:

1. **U_{mean} [ms⁻¹]**: 10 minute mean longitudinal wind speed.
2. **Wind Direction [°]**: 10 minute mean wind direction.
3. **Gust magnitude (U_{gust}) [ms⁻¹]**: Maximum value of a 3 s moving average longitudinal wind speed (u_{3s}) during a 10 minute period.
4. **Gust amplitude (a_{gust}) [ms⁻¹]**: Deviation of the gust wind speed from the mean: $U_{gust} - U_{mean}$
5. **Peak Factor (k_{peak}) []**: 3 s gust amplitude (a_{gust}) normalized by the standard deviation (σ) of the 18 Hz longitudinal wind speed during the 10 minute period.
6. **Gust factor (GF) []**: Ratio between the 3 s gust magnitude and the 10 minute mean wind speed: U_{gust} / U_{mean}

The following four gust parameters (7 – 10) are all based on the relative timing of three distinct events in u_{3s}: t₁, the time of the last local minimum in u_{3s} before the gust which is below U_{mean}; t₂, the time of the maximum in u_{3s}; and t₃, the time of the first local minimum in u_{3s} after the gust which is below U_{mean}.

7. **Rise time (t_{rise}) [s]**: Time elapsed between the occurrence of the maximum 3 s wind speed (U_{gust}) and the immediately preceding local minimum in the 3 s moving average that is below U_{mean} (t₂ – t₁).
8. **Lapse time (t_{lapse}) [s]**: Time elapsed between the occurrence of U_{gust} and the next local minimum in the 3 s moving average that is below U_{mean} (t₃ – t₂).
9. **Gust duration, (t_{gust}) [s]**: t_{gust} = t_{rise} + t_{lapse} (or t₃ – t₁).

Deleted: easurements from two ZephIR Doppler lidars (z447 and z423). One was deployed in the central valley 311 m from meteorological mast 25, and one to the west of the SW ridge (Figure 1b; locations in Table 1). The ZephIR series 300 units use a wavelength of 1.575 μm, an operating frequency of 50 Hz, and have a probe length of 0.07 m at 10 m and 7.7 m at 100 m. They were configured to measure horizontal wind speeds at 10 measurement heights (20 to 200 m a.g.l. at 20 m intervals), sampling at each height once every 17 s. Conically scanning Doppler lidars (such as the ZephIR 300 continuous wave lidars (Smith et al., 2006) used herein) can be used to retrieve relatively high frequency (and time averaged) horizontal wind speeds at multiple heights (in the case of the ZephIR 300 instruments to a height of 200 m) above the instrument, and have been subject to extensive field validation (Gottschall et al., 2012). However, these Doppler lidars assume the flow to be homogeneous across the scanning volume (the ZephIR use a scanning cone angle of ±15°) in order to infer the horizontal wind speed. This assumption is not fulfilled in complex terrain due leading to increased uncertainty and potentially error in retrieved horizontal wind speeds (Bingöl et al., 2009). Further, the volumetric averaging inherent in use of lidars means the wind speeds are not directly equivalent to those from in situ anemometry. Nevertheless, vertically pointing Doppler lidars offer the potential to quantify wind gusts at heights above those possible from sonic anemometers deployed on meteorological masts (Suomi et al., 2017), and are increasingly being adopted by the wind energy research and operations communities (IEA Wind Task-32 Lidar for Wind Energy Deployment) (Clifton et al., 2018).

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10. Gust length scale (L_{gust}) [m]: An estimate of the physical extent of a wind gust, defined as the integral of the 3 s moving average of longitudinal wind speed during the duration of the gust

$$L_{gust} = \int_{t_1}^{t_3} u_{3s} dt \quad (1)$$

11. Turbulence intensity (TI) []: Standard deviation (σ) of the 18 Hz longitudinal wind speeds during the 10 minute period divided by the 10 minute mean wind speed, σ/U_{mean}

12. Stability class: Five classes denoting atmospheric stability based on Monin-Obukhov length (L):

$$L = \frac{-u_*^3}{\kappa \left(\frac{g}{\rho}\right) w' \theta'} \quad (2)$$

Where κ is the von Karman constant, u_* is the friction velocity, g is the acceleration due to gravity, and w' and θ' are the fluctuating components of vertical velocity and sonic virtual temperature respectively. It is acknowledged that the surface similarity theory that underpins use of L as a stability parameter derives from measurements in flat terrain and within the surface layer (Monin and Obukhov, 1954). Thus, L as computed based on measurements at 60 m on the reference tower (29) is used to conditionally sample the gust properties based on broad stability classes from (Barthelmie, 1999) wherein; $0 < L < 200$ m indicates very stable conditions, $200 < L < 1000$ m is stable, $|L| > 1000$ m is neutral, $-1000 < L < -200$ m is unstable and $-100 < L < 0$ m is used to indicate very unstable conditions.

Herein, the 10 minute periods which make up the measurement campaign are divided into 2 groups: *gust periods* and *non-gust periods*. We classify any 10 minute period that meets two wind intensity criteria: $U_{mean} > 3 \text{ ms}^{-1}$ and gust amplitude (a_{gust}) $> 4 \text{ ms}^{-1}$ as being a 'gust period' and denote all other 10 minute periods as non-gust periods. These thresholds are applied to exclude periods with high GF that occur solely because of low U_{mean} , and to ensure the wind gusts represent periods during which typical wind turbines would be operating. The threshold of $a_{gust} > 4 \text{ ms}^{-1}$ is a simple approximation of the gust criteria used in the National Weather Service's Automated Surface Observation System (ASOS) (NOAA, 2004; Nadolski, 1998), which also results in minimum gust magnitudes of just over 7 ms^{-1} . A threshold of $U_{mean} > 3 \text{ ms}^{-1}$ is also motivated in part by applications to the energy industry, since many commercial wind turbines commence operation at a wind speed near 3 ms^{-1} . In numerical weather prediction (NWP) models, wind gusts are generally sub-grid scale and thus are estimated using parameterizations. In the simplest case, the peak factor (k_{peak}) is assumed to be a constant factor of 1.7 (Woetmann Nielsen and Petersen, 2001). An approximation, derived using measurements between 8 and 80 m a.g.l. near a lake and within a city (Wieringa, 1973), that describes k_{peak} (as measured over an averaging period of t) as:

$$k_{peak} = 1 + \frac{1.42 + 0.3013 \ln\left(\frac{990}{U_{mean} t^{-4}}\right)}{\ln\left(\frac{z}{z_0}\right)} \quad (3)$$

Where z_0 is the surface roughness length (a value of 0.5 m is used here). The value of 990 m in the numerator is the wavelength below which an effective majority of the locally-derived turbulent fluctuations are expressed within a 10 minute period, while longer wavelengths derive from mesoscale features (Wieringa, 1973). Estimates from these two approximations are compared to k_{peak} derived from measurements at 60 m height at all 9 towers to establish whether they are conservative in complex terrain.

3.2 Wind gust parameter probability distributions

Following (Hu et al., 2018) four 2-parameter probability distribution types are fitted to the gust parameters (1 and 3-10, above) as derived from time series from sonic anemometers on all meteorological masts, for all 10 minute periods when $U_{mean} > 3 \text{ ms}^{-1}$. These four distribution types and their probability density functions are as follows (Morgan et al., 2011):

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1. Weibull

$$f(x|a, b) = \frac{b}{a} \left(\frac{x}{a}\right)^{b-1} \exp\left[-\left(\frac{x}{a}\right)^b\right]$$

(4)

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2. Log-logistic

$$f(x|a, b) = \frac{\exp\left[\frac{\ln(x)-a}{b}\right]}{bx\left\{1+\exp\left[\frac{\ln(x)-a}{b}\right]\right\}^2}$$

(5)

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5 3. Lognormal

$$f(x|a, b) = \frac{1}{xb\sqrt{2\pi}} \exp\left[\frac{-(\ln x - a)^2}{2b}\right]$$

(6)

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4. Gamma

$$f(x|a, b) = \frac{1}{b^a \Gamma(a)} x^{a-1} \exp\left(-\frac{x}{b}\right)$$

(7)

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Where Γ is the gamma function, x is the random variable being described, and a and b are the distribution parameters.

10 Distributions are fitted to each gust parameter using maximum likelihood estimation (MLE), and best fit distribution types are determined using negative-log-likelihood (NLL) values (Hogg et al., 2005). Since two or more distributional forms may exhibit relatively good fits to the empirical distributions we also note results wherein a second distribution type exhibits equivalent NLL values (i.e. those within 0.1% of the 'best fit'). The tails of probability distributions are typically of greatest importance to wind loading (e.g. turbine design and control systems (IEC, 2005)) and are not always well described by distributional forms that best represent the body of the distributions (Friederichs and Thorarinsdottir, 2012). Thus, the effectiveness of each distribution type in

15 representing the 99th percentile gust magnitude and gust amplitude, and the 1st percentile rise time is evaluated by comparing the parametric estimate derived from the fitted distribution to the empirically derived percentile value.

[Once distributional forms for individual gust properties have been derived they are used to construct joint mass distributions of gust parameters using a general method that converts gust parameters following any type of distribution to the standard Gaussian domain and generates the joint distribution of the transformed gust parameters.](#) For gust parameters following Weibull distribution with the probability density function (PDF, Eq (2)) the transformation to a Gaussian form is realized using the following explicit equation:

20

$$U = -\Phi^{-1}\left[\exp\left(-\left(\frac{X}{a}\right)^b\right)\right]$$

(8)

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where a and b are the two PDF parameters (scale parameter and shape parameter, respectively) calculated using the MLE method. X and U represent the original random variable following Weibull distribution and the transformed random variable following standard Gaussian distribution, respectively. For gust parameters following a lognormal distribution (Eq (4)), the explicit transformation equation is expressed as

25

$$U = \frac{\ln(X) - a}{b}$$

(9)

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For gust parameters that follow a Gamma distribution (e.g., gust length scale at tower 29), there is no explicit transformation equation. Thus, the gust parameters are empirically transformed to standard Gaussian variables using:

30

$$U = \Phi^{-1}[F(X)]$$

(10)

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where $F(X)$ is the empirical cumulative distribution function (CDF) of random variable X and Φ^{-1} is the inverse CDF of standard Gaussian random variable.

[After the gust parameters are transformed to standard normal variables, 2-D elliptical contours are computed that enclose a specified percent of transformed data using the fact that the sum of squared Gaussian random variables follows a Chi-Square](#)

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distribution. The orientation angle ϕ , major axis L_1 , and minor axis L_2 of an ellipse are calculated from the specified percentage, and two eigenvalues and the largest eigenvector of the covariance matrix of each pair of transformed gust parameters (Wilks, 2011),

$$\phi = \arctan\left(\frac{\mathbf{v}_1(2)}{\mathbf{v}_1(1)}\right) \quad (11)$$

$$L_1 = 2\sqrt{F_{\chi^2(2)}^{-1}(P)\lambda_1} \quad (12)$$

$$L_2 = 2\sqrt{F_{\chi^2(2)}^{-1}(P)\lambda_2} \quad (13)$$

where $\mathbf{v}_1(1)$ and $\mathbf{v}_1(2)$ are the two elements in the largest eigenvector \mathbf{v}_1 ; P is the specified percentage; $F_{\chi^2(2)}^{-1}$ is the inverse cumulative distribution function of a chi-square distribution with 2 degrees of freedom; λ_1 and λ_2 are the largest eigenvalue and the smallest eigenvalue, respectively. The aspect ratio between the lengths of the major axis and the minor axis of the ellipse (i.e., L_1/L_2) represents the degree to which the data are clustered around the primary axis, thus indicating the correlation between the gust parameters. An average aspect ratio of 99 ellipses ($P = 0.01 - 0.99$) is calculated (added in the bottom-right corner of each subplot). Herein we report joint distributions of a single gust parameter at two heights from the same tower and joint distributions of two different gust parameters at the same height from two towers.

Conditional sampling is used to explore the functional dependencies of gust properties. Gust periods (as defined by the gust criteria in section 3.1) are treated separately in several of the analyses below. The presence or absence of wind gusts is always determined locally (at a given sonic anemometer). The samples of U_{mean} and gust properties from the different towers and heights do not conform to Gaussian distributions (see examples in Figure 3) thus the central tendency is uniformly described herein using the median. The co-occurrence of wind gusts at pairs of sonic anemometers (sensor 1 and sensor 2) is given as the conditional probability of a gust occurrence at sensor 2 when a gust occurs at sensor 1 during a given 10 minute period.

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$$k_{\text{peak}} = 1 + \frac{1.42 + 0.3013 \ln\left(\frac{990}{U_{\text{mean}} t}\right)}{\ln\left(\frac{z}{z_0}\right)} \quad (9)$$

Where z_0 is the surface roughness length (a value of 0.5 m is used here). The value of 990 m in the numerator is the wavelength below which an effective majority of the locally-derived turbulent fluctuations are expressed within a 10 minute period, while longer wavelengths derive from mesoscale features (Wieringa, 1973). Estimates from these two approximations are compared to k_{peak} derived from measurements at 60 m height at all 9 towers to establish whether they are conservative in complex terrain.

Moved up [2]: In these analyses we classify any 10 minute period that meets two wind intensity criteria: $U_{\text{mean}} > 3 \text{ ms}^{-1}$ and gust amplitude (a_{gust}) $> 4 \text{ ms}^{-1}$ as being a 'gust period' and denote all other 10 minute periods as non-gust periods. These thresholds are applied to exclude periods with high GF that occur solely because of low U_{mean} , and to ensure the wind gusts represent periods during which typical wind turbines would be operating. The threshold of $a_{\text{gust}} > 4 \text{ ms}^{-1}$ is a simple approximation of the gust criteria used in the National Weather Service's Automated Surface Observation System (ASOS) (NOAA, 2004; Nadolski, 1998), which also results in minimum gust magnitudes of just over 7 ms^{-1} .

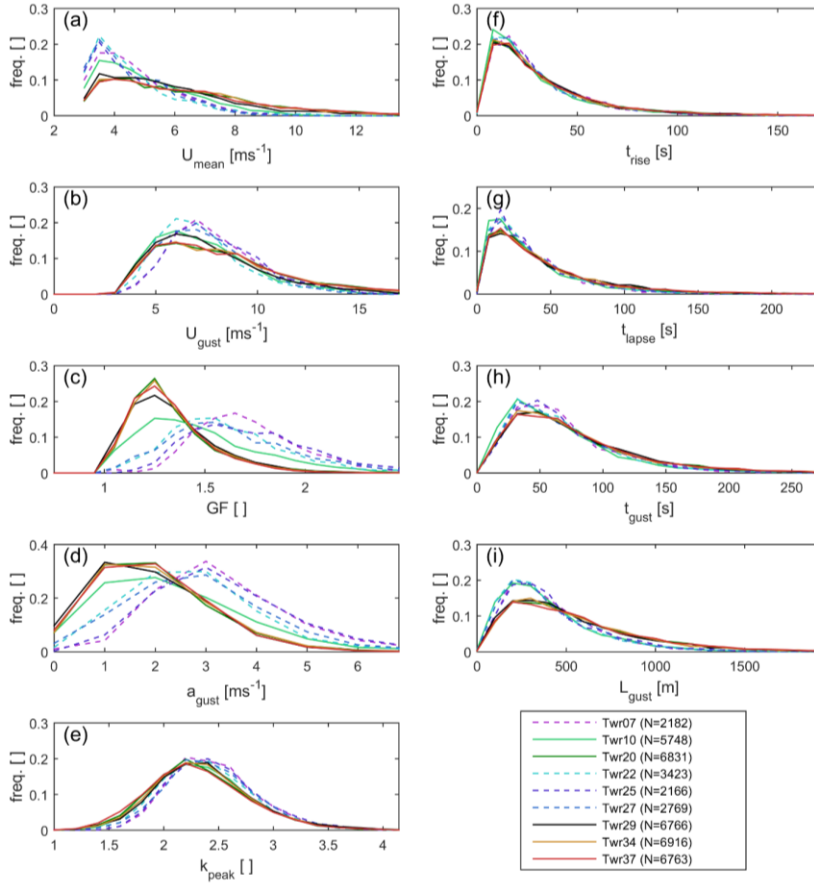


Figure 3: Distributions of gust parameters at each of the 9 towers (using data collected at 60 m a.g.l) for 10 minute periods with $U_{\text{mean}} > 3 \text{ ms}^{-1}$. Valley towers are shown with dashed lines and ridge towers with solid lines. The frames show the (a) 10 minute mean wind speed (U_{mean}), (b) gust magnitude (U_{gust}), (c) gust factor (GF), (d) gust amplitude (a_{gust}), (e) peak factor (k_{peak}) (f) rise time (t_{rise}) (g) lapse time (t_{lapse}), (h) gust duration (t_{gust}) and (i) gust length scale (L_{gust}). The legend reports the sample size (N) for 10 minute periods used to construct the empirical distributions for each tower. The towers are denoted by the color scheme introduced in Figure 1.

3.3 Spectra and Coherences

Power spectral densities (PSD) of wind speeds from the sonic anemometers and the ZephIR lidars are calculated using Welch's method (Welch, 1967). For the sonic anemometer data this method is applied to two hour time series of 18 Hz longitudinal wind speed measurements that meet the gust criteria and (separately) those that do not. Spectra are plotted in non-dimensionalized form wherein the power at each frequency is multiplied by the frequency and divided by the variance computed from the 18 Hz time series, and the frequency is multiple by a measurement height (z) of 60 m and the mean wind speed during that 2 hour period. Mean PSD computed for sonic anemometers deployed on all ridge and valley towers are presented for data conditionally sampled by atmospheric stability, turbulence intensity and wind direction.

Spatial relationships of longitudinal wind speeds from the sonic anemometers (and ZephIR lidars) are characterized in the frequency domain using coherence functions, C_{xy} , given by the cross-spectral properties:

$$C_{xy}(f) = \frac{|P_{xy}(f)|}{\sqrt{P_{xx}(f)P_{yy}(f)}} \quad (14)$$

where f is frequency, $P_{xy}(f)$ is the cross-spectral density of x and y , and P_{xx} and P_{yy} are the auto spectral densities of x and y respectively (Bendat and Piersol, 2011). The normalization means that if two time series are perfectly correlated at a given frequency $C_{xy}(f) = 1$. Wind speed coherence functions are often characterized using a single-parameter exponential decay function, $C_{fit,xy}$ (Solari, 1987):

$$C_{fit,xy}(f) = \exp\left(-C \frac{f \cdot d}{U_{mean}}\right) \quad (15)$$

where C is the decay coefficient and d is the distance between sensors. A non-dimensional reduced frequency $\left(\frac{f \cdot d}{U_{mean}}\right)$ is used herein to facilitate comparison of the coherence functions between sonic anemometers deployed on different towers and with previous research (Solari, 1987; Mehrens et al., 2016). Empirical estimates of a coherence function are influenced (and their accuracy limited) by the number of sub-series used in the cross-spectral density calculation. Hence estimates of $C_{xy}(f)$ do not decay to zero but to a coherence floor (Mann, 1994). [This upward bias of the coherence estimate is the result of the imaginary contribution to the numerator in Eq. 14, which will tend toward zero as the data length increases. This bias can be excluded from the coherence estimate by including only the real part of \$P_{xy}\(f\)\$, in the estimation \(Eliassen and Obhrai, 2016\). This estimator is also called the co-coherence \(\$CC_{xy}\$ \). Eq. 16 is used to estimate coherence functions in the current study.](#)

$$C_{xy}(f) \approx CC_{xy}(f) = \frac{\text{Real}(P_{xy}(f))}{P_{xx}(f)P_{yy}(f)} \quad (16)$$

Thus herein, C values are determined by least squares fitting of Eq. (15) to the coherence function values, [as approximated by the co-coherence](#). Previous research has indicated large C values are most frequently observed in unstable conditions and that coherence decays quickly with reduced frequency (Kristensen and Jensen, 1979). For 10 minute mean wind speeds over water an average value of $C = 4.3$ has been proposed for horizontal separations of < 5 km (Viguera-Rodríguez et al., 2012), and the correlation between two measured time series displaced horizontally asymptotes to a constant value (i.e. the coherence floor) at a normalized frequency ≈ 0.36 (Mehrens et al., 2016). Due to the relatively low sampling rate of the ZephIR lidars (~ 17 seconds), coherences of horizontal wind speeds from the ZephIR lidars are calculated over a 72 hour period with an FFT window length of 256 (2^8), while the coherence functions calculated from the sonic anemometer observations are based on 2 hour periods of 18 Hz longitudinal wind speed data, transformed into the frequency domain using an FFT window length of 16384 (2^{14}).

Characterization of the height at which the surface characteristics cease to dominate scales of flow in the atmosphere has applications to microscale model verification and validation and is accomplished herein through investigation of the height dependence of the spectral peak associated with the diurnal time scale ($f = 1 \text{ day}^{-1}$) (Larsén et al., 2018). The magnitude of the diurnal peak, S_p , is calculated as a function of height from the PSDs of wind speeds from all ten ZephIR lidar measurement heights and sonic anemometer data from the three tallest towers (20, 25 and 29) as follows (Larsén et al., 2018):

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1. Calculate the PSD using Welch's and the longest complete data period
2. Perform log-smoothing (35 points per decade) of these PSDs by piecewise cubic interpolation
3. Fit a linear function to each PSD ($\log S(f)$ Vs $\log(f)$), to the data in the range $3 \cdot 10^{-6} < f < 2 \cdot 10^{-5}$ Hz, excluding the value at F_d (frequency = 1 day⁻¹)
4. Calculate three parameters:

$S_{reg}(F_d)$: Value of the linear fit at the daily peak frequency, F_d

$S(F_d)$: Value of the PSD at F_d

S_p : Height of the daily peak above the linear background ($S(F_d) - S_{reg}(F_d)$)

The reverse height is the height of the minimum value of S_p from each independent measurement and, as described above, is interpreted as the height at which surface-driven processes no longer dominate flow variability.

4 Results

4.1 Wind Gust Properties and Parameter Distributions

Mean sustained (10 minute) wind speeds (U_{mean}) are higher at ridge towers than at towers in the valley. The median values are 5.70 ms⁻¹ and 4.26 ms⁻¹, respectively (Figure 3a). Tower 10 is an exception to this general pattern because although it is located on the northeast ridge it is sheltered by an area of higher elevation to the north (Figure 1) and thus experiences flow conditions that are, overall, more like the valley towers. Although the full sample of U_{mean} values at all towers is best fit by a Weibull distribution (Figure 2, as at flat sites and offshore (Morgan et al., 2011; Pryor et al., 2004)), when a threshold of 3 ms⁻¹ is applied, the resulting samples of U_{mean} values are log-normally distributed at all towers (Table 2).

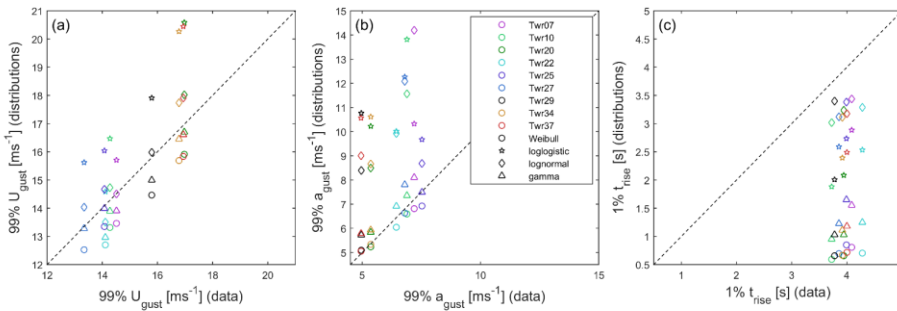
In accord with a priori expectations, gust amplitudes ($a_{gust} = U_{gust} - U_{mean}$) are higher in the valley than along the ridges (Figure 3d) while U_{gust} (the maximum 3 s moving average in a 10 minute period) exhibits similar values at ridge and valley towers (7.36 ms⁻¹ and 7.57 ms⁻¹, respectively), with valley towers showing a more peaked distribution and ridge towers exhibiting a longer tail (Figure 3b). The total sample of U_{gust} estimates is best represented by either a Weibull distribution, as commonly used in wind turbine modeling (Cheng and Bierbooms, 2001), or a gamma distribution, which has been used in previous work describe gusts below a canopy (Shaw et al., 1979) (Table 2). Consistent with measurements from moderately complex terrain (Hu et al., 2018), when U_{gust} is conditionally sampled for $U_{mean} > 3$ ms⁻¹, it is best fit by a lognormal distribution. Extreme values of U_{gust} (i.e. 99th percentile (p_{99}) which ranges from 13.2 to 17.1 ms⁻¹ across the towers) are most accurately predicted by the gamma distribution. Parametric estimates of p_{99} are conservative when derived from the log-normal fit, but are biased low from both gamma and Weibull distribution fits to data from sonic anemometers deployed at/close to 60-m a.g.l. on all towers (Figure 4a). Consistent with measurements from moderately complex terrain (Hu et al., 2018), a_{gust} (i.e. the deviation of the maximum 3 s moving average from the 10 minute mean) are best described by a Weibull distribution (Table 2), but 99th percentile values of a_{gust} (5 to 7.8 ms⁻¹) estimated from the Weibull parametric fit are also non-conservative. While all other distribution types tend to over-predict the 99th percentile gust amplitude value (Figure 4b), the gamma distribution appears to generate the most representative (but conservative) estimates. Thus, if the upper percentiles of wind gust intensity are of particular interest (e.g. in engineering for wind loading) it may be preferable to use a log-normal distribution to represent U_{gust} and a gamma distribution for gust amplitude ($a_{gust} = U_{gust} - U_{mean}$).

Although gust magnitude and amplitude are useful for determining the loading force exerted by wind gusts, gust factors (GF, i.e. the ratio of the 3-5 s gust magnitude to the sustained wind speed) are frequently used in the meteorological community as a non-dimensional intensity index (Krayner and Marshall, 1992) and are sometimes used for assessment of wind hazards (Deaves,

1993). GF are generally higher in the valley than on the ridge (median GF at valley towers is 27% higher than those from the ridge towers; Figure 3c), consistent with the lower U_{mean} in the valley. GF samples from the 60 m measurement level are best described by the log-logistic distribution (as in a site in moderate terrain complexity (Hu et al., 2018)) or lognormal distributions (as in a sample of sites distributed across the eastern United States (Pryor et al., 2014)) (Table 2).

5 **Table 2: Best fit distribution types for each gust property (in each 10 minute period when $U_{\text{mean}} > 3 \text{ ms}^{-1}$) for a measurement height of 60 m a.g.l. at each tower. Also shown are results from moderately complex terrain (Hu et al., 2018). The distribution types are referred to as 1-4 where 1: Weibull, 2: log-logistic, 3: log-normal, 4: gamma. Distributions types shown in parenthesis represent an equivalently good fit (i.e. those with negative log likelihood of less than 0.1% lower than the best fit distribution).**

	Tower									Hu et al, 2018
	7	10	20	22	25	27	29	34	37	
U_{mean}	3	3	3	3	3	3	3	3	3	-
U_{gust}	3	3	3	3	3	3(4)	3	3	3	3
GF	2	3	2	3	3	3	3	2	2	2
a_{gust}	1	1	1	1	4	1	1	1	1	1
k_{peak}	2	2	2	2	3	2	2	2	2	2
t_{rise}	3	3	3	3	3	3	3	3	3	3
t_{lapse}	3	3	3	3	3	3	3	3	3	3
t_{gust}	3(4)	3	3	3	3	3	3(4)	3	4	3
L_{gust}	3(4)	3	4(3)	3	3	3(4)	4	4(3)	4	3



10 **Figure 4: (a) 99th percentile wind gust magnitude (U_{gust}), (b) 99th percentile amplitude (a_{gust}) and (c) 1st percentile rise time (t_{rise}) as derived directly from the observations at 60 m a.g.l. and estimated from the parametric distributional fits (shown by the different symbols). The towers are denoted by the color scheme introduced in Figure 1. The dashed line indicates 1:1 correspondence.**

15 Gust rise time values are similar at ridge and valley towers, median(t_{rise}) = 24.3 and 23.0 s, respectively (Figure 3e) and greatly exceed the minimum 3 s averaging window used in the gust time-scale calculations performed herein, and the 3-5 s averaging period employed by the World Meteorological Organization and National Weather Service. Again consistent with previous research, t_{rise} is best fit by a log-normal distribution (Table 2) (Hu et al., 2018). Short gust rise times are of particular interest in the wind energy industry, since gusts may ramp up faster than turbine pitch control systems, which may take several seconds to respond, can mitigate the induced loads (Burton et al., 2011; Kanev and van Engelen, 2010). The 1st percentile rise times are uniformly near 4 s. This is because the definition used herein sets $t \geq 3 \text{ s}$ for the observational estimates, although the distributional fits permit $t < 3 \text{ s}$ (Figure 4c). The rise time is most accurately estimated using a lognormal distribution fit to the complete sample (Figure 3f-g), and all distribution types produce conservative predictions of the 1st percentile (i.e. over-estimate the rapidity of the rise, Figure 4c). Gust lapse times tend to be longer than rise times (by 30 to 40%; Figure 3f), and also

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conform to a log-normal distribution, consistent with Hu et al. (2018); their Table 2. The asymmetry in the temporal evolution of wind gusts implied by these rise and lapse times indicates that the Mexican-hat form often assumed in the wind energy industry is not realized (Hu et al., 2018) which has relevance to power control from wind turbines under high wind gust magnitudes (Gottschall and Peinke, 2007). Gust length scales tend to be higher for the ridge towers (with modal values of 200 m (which is similar to the height of the ridges above in the intervening valley), and values of up to 1200-1400 m; Figure 3g) than in data from the valley towers, and to conform to log-normal or gamma distributions with only a small difference in goodness-of-fit (NLL) between these two distribution types (Table 2).

The results from analyses of data collected in the complex terrain of Perdigão are thus internally consistent across towers in terms of the distributional form that best describes the gust samples and are also generally consistent with analyses of sonic anemometer data at 65 m a.g.l. collected in moderate complexity terrain (Hu et al., 2018). To the extent distribution types are uniform across the site, and consistent with previous work (as they are for U_{gust} , a_{gust} , k_{peak} , t_{rise} , t_{lapse} and L_{gust}), it is reasonable to conclude that the best-fit distributions identified herein are effective for describing wind gusts in complex and moderately complex terrain. As noted above, these best fit distributions can be non-conservative when estimating values in the distribution tail, as is the case with U_{gust} and the Weibull distribution.

Joint distributions of U_{gust} at different heights on the same meteorological mast (upper-left off-diagonal panels with green boxes in Figure 5, see other joint distributions of other parameters in Supplementary Information) indicate large ratios of major to minor axes and thus a strong association of gust magnitude across heights of 10-100 m a.g.l. The aspect ratio (ratio of major to minor axis) of the joint probabilities of U_{gust} at different heights also exhibits a clear influence from vegetation at the lowest measurement height. For example, in joint distributions of U_{gust} on Tower 29 the aspect ratio declines from 3.08 (between measurements at 20 m and 10 m a.g.l.) to 1.99 (between 100 m and 10 m a.g.l.), but above 10-m a.g.l. ranges from 9.66 (between 30 m and 20 m a.g.l.) to 3.79 (between 100 m and 20 m a.g.l.).

Joint distributions of gust length scale at different heights (L_{gust} , bottom-right off-diagonal panels in Figure 5) conversely indicate very low ratios of axes length and hence weaker coherence. Joint probabilities of wind gust magnitude (U_{gust}) and length scale (L_{gust}) at the same height (i.e. the diagonal in Figure 5) indicate moderate aspect ratios (1.6 to 1.8) and thus coherence (consistent with previous research (Doran and Powell, 1982)), but there is little systematic variation with height. Thus, while gust length scales do not exhibit similarity across heights, there is strong vertical coherence in the magnitude of wind gusts across the layer from 20-100 m a.g.l..

Joint distributions of gust magnitudes (U_{gust}) at 60 m a.g.l. at towers 20, 22, 34 and 37 (Supplementary Information, Figure S1) indicate very high aspect ratios for values from the three towers (20, 34 and 37) on the southwest ridge (7.6-9.9), but considerably lower values with data from tower 20 (within the valley, of approx. 3). This again reemphasizes that although the occurrence of individual wind gusts at towers along the ridge is not simultaneous (see conditional probabilities discussed below), the probability distributions of their magnitudes are similar. Conversely, consistent with results shown in Figure 5, joint distributions of gust length scales and time scales across all towers indicate lower consistency and in some cases near independence (as manifest in small aspect ratios of ~ 1.07-1.55) (see Supplementary Information, Figures S2 and S3). A further uniform feature of the joint probability plots is that they exhibit evidence of closer correspondence in peak factor values than GF both between towers and between heights on a single tower. As shown in Supplementary Information, Figures S4 and S5, aspect ratios for peak factor at 60 m a.g.l. between the ridge-top towers vary between 2.8 and 3.6, while those for GF are 1.8 to 2.1.

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Joint distributions of gust magnitudes at 60 m a.g.l. at towers 20, 22, 34 and 37 (Supplementary Information) indicate very high aspect ratios for values from the three towers on the southwest ridge (7.8-8.4), but considerably lower values with data from tower 20 (within the valley, of approx. 3). This again reemphasizes that although the occurrence of individual wind gusts at towers along the ridge is not simultaneous (see conditional probabilities discussed below), the probability distributions of their magnitudes are similar. Conversely, consistent with results shown in Figure 5, joint distributions of gust length scales and time scales across all towers indicate lower consistency (as manifest in smaller aspect ratios) (see Supplementary Information).

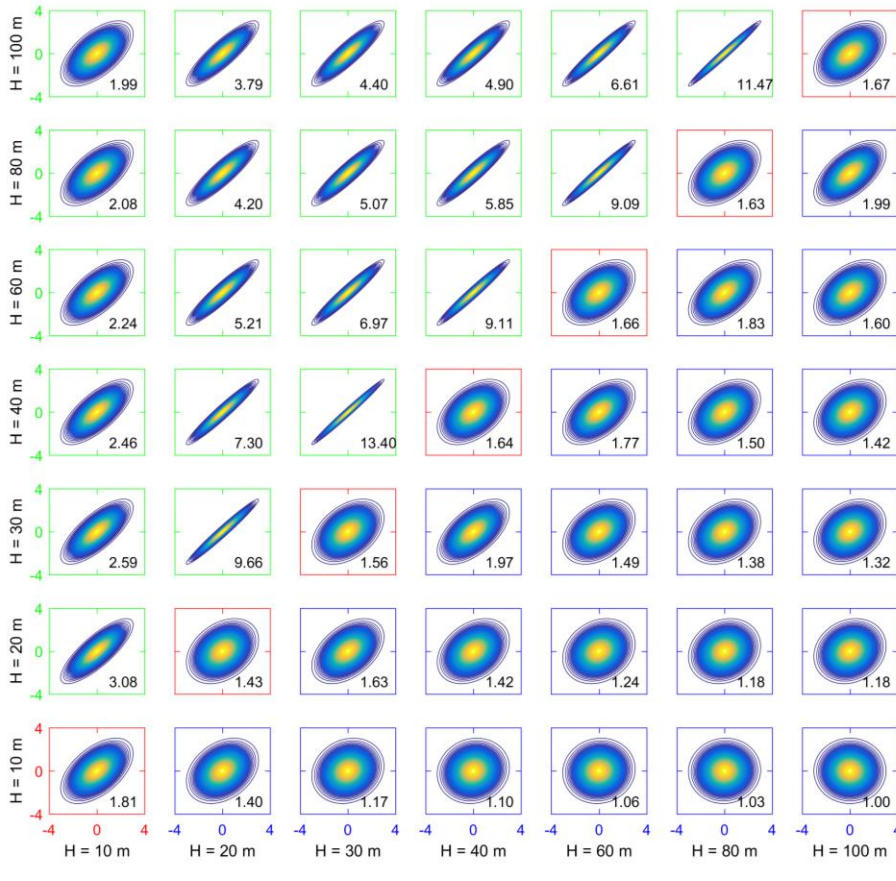
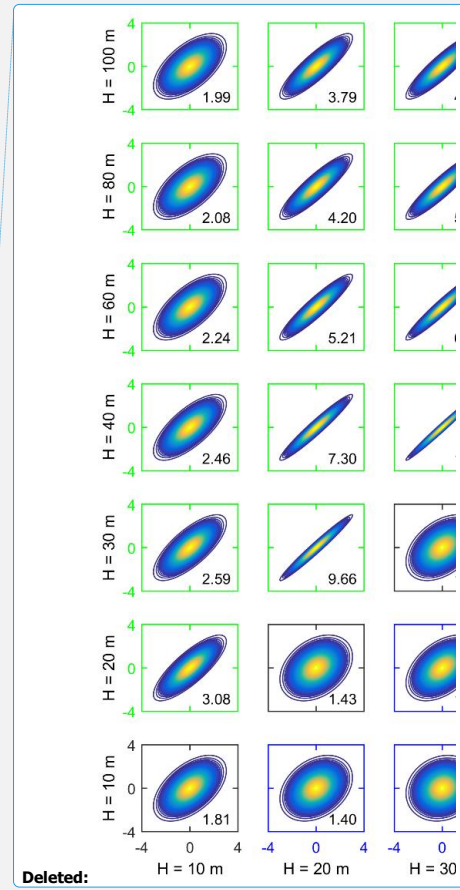


Figure 5: Joint distributions of U_{gust} and L_{gust} at different heights (H) from Tower 29. Upper-left off-diagonal panels with green boxes show the joint distributions of U_{gust} at each pair of heights. Diagonal panels with red boxes show the joint distributions of U_{gust} and L_{gust} at the same height. Bottom-right off-diagonal panels with blue boxes show the joint distributions of L_{gust} at each pair of heights. The number at the bottom-right corner of each panel is the average ratio between the major axis and minor axis of ellipses. There are 99 ellipses corresponding to the confidence levels from 1% (the innermost ellipse with the warmest color) to 99% (the outermost ellipse with the coldest color).

4.2 Conditional sampling of wind gust properties

Consistent with previous research, the probability of a wind gust varies systematically with dynamic stability and is higher under near-neutral and unstable conditions (Hart and Forbes, 1999), although gust probability at the valley towers is most similar to the ridge towers during times of very high (> 0.25) and very low (< 0.1) turbulence intensity (TI) (Figure 6, column 3). Large values of U_{gust} tend to occur during stable and near-neutral conditions, especially at the ridge-top towers (Figure 6, column 1) (stable conditions are also found to be associated with higher U_{mean}). Consistent with previous research GF exhibit only a weak dependence on prevailing stability (Agustsson and Olafsson, 2004), but both GF and gust length scales scale with TI (Ashcroft, 1994; Greenway, 1979; Hu et al., 2018). Gust length scales are largest under the most unstable conditions particularly at the ridge towers (Figure 6), while gust amplitude shows large inter-tower variability particularly during very stable conditions potentially



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reflecting the role of orographic wave breaking in inducing high magnitude gusts (Durrán, 1990; Hertenstein and Kuettner, 2005). This is consistent with the finding that U_{gust} at the ridge towers decrease with increasing TI (from 15 ms^{-1} at low TI to 10 ms^{-1} at $TI > 0.3$) since low TI is likely to occur under stable stratification when orographic forcing of standing waves is most likely to occur. Gust probability also shows a consistent dependence on wind direction and is highest for valley towers during perpendicular flow (Figure 6, column 2), while under flow parallel to the ridges the empirical distributions of wind gust magnitudes, amplitudes and GF are rather similar for valley and ridge towers. This indicates that terrain-induced heterogeneity in wind gust parameters is associated with perpendicular flow and that higher spatial resolution may be required to characterize wind gusts at sites with a high frequency of cross-ridge flow.

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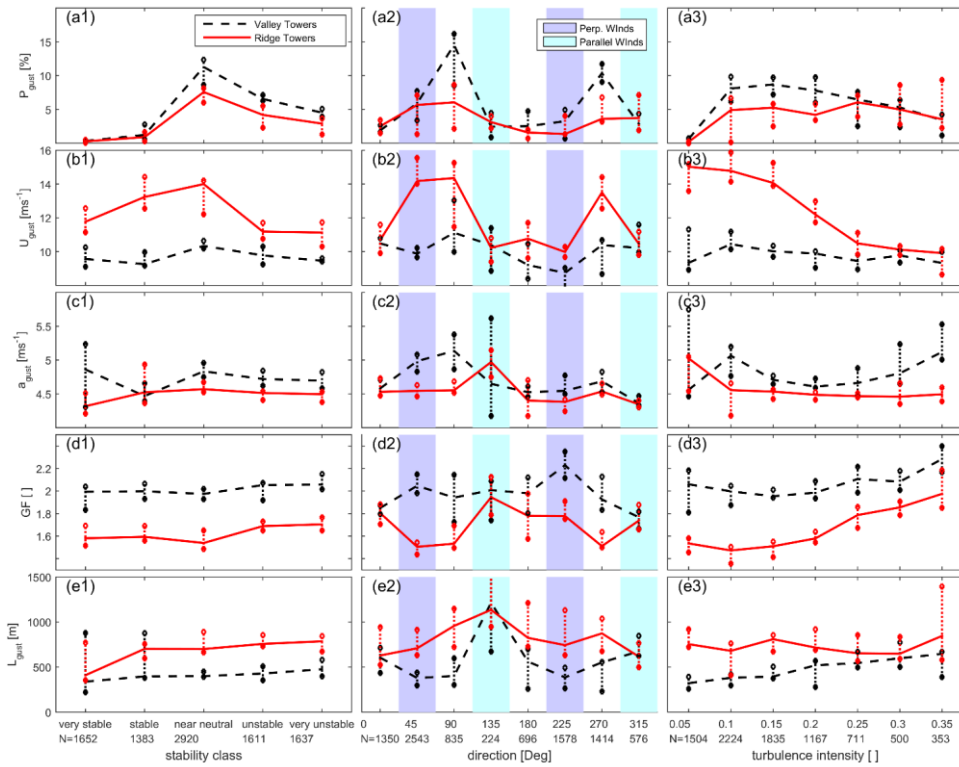


Figure 6: Median gust parameters during gusty conditions ($U_{mean} > 3 \text{ ms}^{-1}$, $a_{gust} > 4 \text{ ms}^{-1}$) at 60 m a.g.l. from ridge (solid red) and valley (dashed black) towers. The data sampled are conditionally sampled by stability classes based on Monin-Obukhov length (column 1), wind direction (column 2) and turbulence intensity (column 3) as measured at Tower 29 (60 m a.g.l.). Vertical whiskers at each data point denote the range of median parameter values for all towers in each class. N values in the second row of x-axis labels are the number of 10 minute periods in each sample. One gust parameter is shown per row: (a) Probability of a gust (i.e. percentage of 10 minute periods that meet the gust criteria), (b) Gust magnitude (U_{gust}), (c) gust amplitude (a_{gust}), (d) gust factor GF, (e) gust length scale (L_{gust}).

In Figure 7, data are conditionally sampled to select only periods when wind gusts occurred (i.e. $U_{mean} > 3 \text{ ms}^{-1}$ and gust amplitude $> 4 \text{ ms}^{-1}$), median gust length scale, time scale and magnitude all increase with height at both ridge and valley towers (Figure 7). Median gust duration also at the ridge towers increases modestly with height from 58 s at 30 m to 72 s at 100 m a.g.l..

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This equates to an increase of 14 s duration over a 70 m height interval (i.e. 0.2 sm⁻¹) which is approximately two-thirds of the value (0.35 sm⁻¹) found for flat terrain (Román, 2017). The increase of gust duration with height 0.20 sm⁻¹ (Figure 7e). Median GF and gust amplitudes decrease modestly with height. The median GF decreases from 1.55 at 30 m to 1.5 at 100 m. The change of GF with height is thus smaller than over a flat, homogeneous grassland where GF decreased by 0.2 over a 90 m layer (Suomi et al., 2015; Shu et al., 2016). In contrast to the data from the other meteorological masts, gust amplitudes from Tower 25 tend to increase with height consistent with its location in the lee of a ridge which causes a pronounced reduction in U_{mean}, but has a lesser impact on U_{gust}. Turbulence intensities decrease with height and, at the ridge-top towers, reach their minimum value by 80 m a.g.l., indicating that the influence of the ground on this parameter (as well as U_{mean}, U_{gust} and GF) is substantially decreased at elevations more than 80 m above the ridge tops.

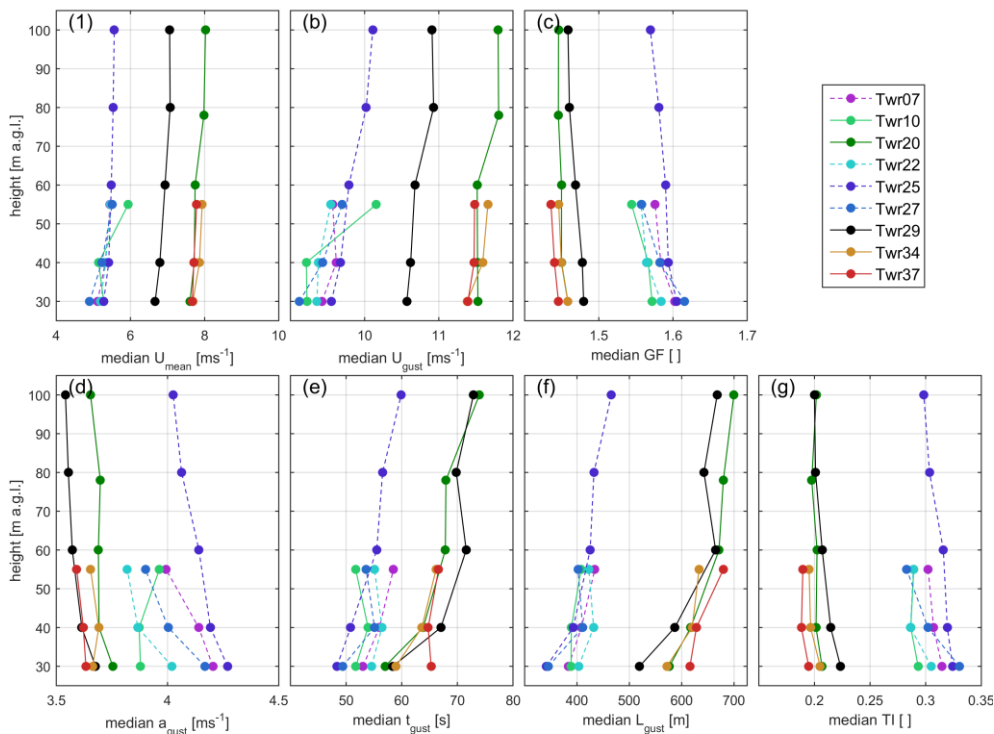
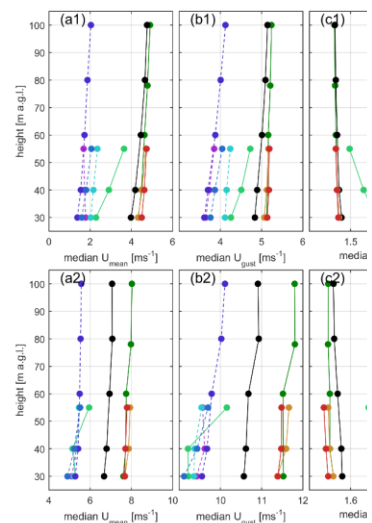


Figure 7: Median values of the gust parameters, by height, at each of the nine towers for 10 minute periods which meet the gust criteria: $U_{mean} > 3 \text{ ms}^{-1}$ and $a_{gust} > 4 \text{ ms}^{-1}$. (a) 10 minute mean wind speed (U_{mean}), (b) 3 s maximum wind speed (U_{gust}), (c) gust amplitude (a_{gust}), (d) gust factor (GF), (e) gust duration (t_{gust}), (f) gust length scale (L_{gust}) (g) turbulence intensity (TI)

Although the ZephIR lidar measurements are disjunct (at approx. 2 s) for each height and are subject to volumetric averaging (over the volume of the annulus swept out by the lidar beam, in a cone 30° from vertical), the probability distribution of U_{gust} at 100 m a.g.l. derived from measurements with the ZephIR lidar (z423) located close to Tower 25 exhibits accord with that derived from the sonic anemometer deployed on this Tower (Figure 8a). The U_{gust} distribution for 100 m a.g.l. from ZephIR z447

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- Deleted: irrespective of whether the data meet the criteria $U_{mean} > 3 \text{ ms}^{-1}$ and $a_{gust} > 4 \text{ ms}^{-1}$ (i.e. a strong gust) or not. In the total data sample median GF decreases from 1.4 at 30 m to 1.3 at 100 m at Towers 20 and 29, while for samples restricted to gust events t
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(which is at 74 m lower altitude and west of the SW ridge) indicates a much higher frequency of $U_{\text{gust}} < 3 \text{ ms}^{-1}$ than at any of the 100 m towers or ZephIR z423 (Figure 8a) partly due to sheltering by the SW ridge under northeasterly flow. Vertical profiles of wind gust magnitudes and mean wind speeds follow a power law form under some circumstances (Brook and Spillane, 1970; Stull, 2012). Median gust factors ($GF = U_{\text{gust}}/U_{\text{mean}}$) from both the ZephIR lidars and sonic anemometers on the towers also conform to a power law with height (z), although the power law coefficients and quality of the fit vary between sampling location and instrument (Figure 8c). As shown in Figure 8b, the GF profiles are more linear below the elevation of the ridge tops and data from the ZephIR lidars indicate a higher power law coefficient consistent with suppression of gust maxima from increased volumetric averaging with height (Suomi et al., 2017). The power law coefficients for the GF dependence on height are approx. -0.04 to -0.05 in data from the sonic anemometers deployed on the ridge-top towers, but is double that for the tower in the valley (25) and are -0.13 and -0.17 in data from the ZephIR lidars (Figure 8c). For comparison, data from flat surfaces indicate lower GF values and smaller power law coefficients derived from GF profiles (-0.034 to -0.051, with larger magnitude values under more stable conditions) (Suomi et al., 2015) than those observed in the current study (Figure 8c).

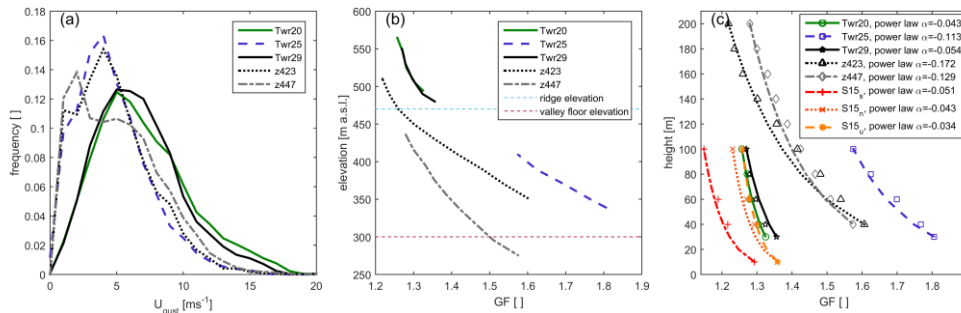


Figure 8: (a) Probability distributions of gust magnitude (U_{gust}) at 100 m a.g.l. as derived from sonic anemometers deployed on the three 100 m towers and from the ZephIR lidars. (b) Median GF versus height above sea level (a.s.l.) for all 10 minute periods with $U_{\text{mean}} > 3 \text{ ms}^{-1}$ from sonic anemometers and ZephIR lidars. The ridge and valley floor elevations above sea level are shown by the horizontal dashed lines. (c) Power law fits to median GF as a function of height a.g.l. for 10-minute periods with $U_{\text{mean}} > 3 \text{ ms}^{-1}$. Also shown are results from measurements over flat terrain (Suomi et al., 2015), under stable (S15_s) near-neutral (S15_n) and unstable (S15_u) conditions

Gust peak factor (k_{peak}) derived from sonic anemometer measurements at 60 m a.g.l. greatly exceed 1.7 (Woetmann Nielsen and Petersen, 2001) and results from the empirical expression in Eq (9) (Wieringa, 1973). Increasing the pre-factor in Eq. (3) from 1 to 2.4 (shown as Wieringa* in Figure 9) leads to a more conservative approximation, which exceeds 90% of observed k_{peak} values for a given sustained wind speed, but the ratio of the 3 s gust amplitude to the standard deviation of the longitudinal wind speed is substantially enhanced in complex terrain and is not well described by either approximation.

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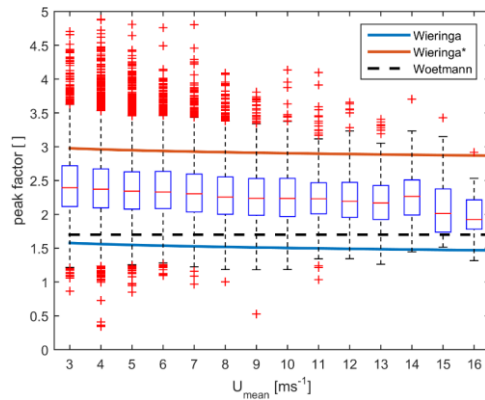


Figure 9: Box plot of gust peak factor (k_{peak}) estimates at 60 m a.g.l. from all nine towers as a function of U_{mean} . Also shown are estimates from Eq. (3) (Wieringa, 1973) and a revised empirical function in which the leading term in Eq. (3) is increased from 1.0 to 2.4 (Wieringa*) and a constant value of 1.7 value (Woetmann Nielsen and Petersen, 2001).

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5 4.3 Spatial co-occurrence of wind gusts

The mean marginal gust probability (the average of unconditional gust probability at all sensors) at 60 m a.g.l. across all nine towers is 2.7% (range of 1.8% to 5.1%, Figure 10a). Thus, on average in any 10 minute period at any tower there is a 2.7% chance that $U_{\text{mean}} > 3 \text{ ms}^{-1}$ and $a_{\text{gust}} > 4 \text{ ms}^{-1}$. The mean wind gust co-occurrence probability at 60 m between towers has a mean value of 0.27 indicating that if a wind gust is detected at one given tower in a 10 minute period there is a 27% chance that there will be a gust detected at another given tower in the same 10 minute period. When adjacent 10 minute periods are included the mean co-occurrence across towers rises to 0.42 (Figure 10a). The asymmetry in the conditional probabilities shown in Figure 10 reflects the fact that marginal probability of gusts varies across the study area. For example, the relatively low co-occurrence probabilities seen in Figure 10c, near the upper-left corner of the panel indicate that, at Tower 29, given the occurrence of a gust at 20 m, there is a ~30% chance of observing a gust at 60 m in the same 10 minute period (as compared to a 2% marginal gust probability at 80 m). This is distinct from the probability of observing a gust at 20 m, given a gust at 80 m (70%), shown in the lower-right corner of the same panel. The towers are separated by distances of 221 to 1666 m (mean separation of 912 m), thus although the length scale analysis shown in Figure 3(j) indicates that individual wind gusts may not have a sufficient spatial scale to ‘engulf’ two towers, the flow in which these features are embedded is likely to spawn multiple of these coherent transient features across the site. Towers 10 and 20 have largest overall conditional probability of gust co-occurrence with all other towers (Figure 10a) in part due to their high marginal wind gust probabilities (4.3 and 5.1%, respectively). Conversely, wind gusts at Towers 34 and 37 are not strongly associated with gusts at other towers especially those located within the valley (Figure 10a). Towers 20, 34 and 37 are all on the southwest ridge, and their heterogeneity in marginal (1.8 to 5.1%) and conditional probabilities (10 to 40%) of wind gust occurrence indicate significant spatial variability in flow conditions and the presence of these intermittent coherent structures along the ridge. Indeed the mean gust co-occurrence among these three southwest ridge towers is lower than the site-wide mean. These wind gust co-occurrence probabilities are thus greatly distorted by terrain-flow interactions and are substantially smaller than those reported for flat terrain (of up to 90% for locations separated by 200 m (Branlard, 2009)).

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At Towers 25 and 29 (two 100 m towers representing valley and ridge conditions, respectively), the mean intra-tower gust co-occurrence probabilities (computed across heights on the same tower) are 60 and 55%, respectively. It is noteworthy that the two ridge-top towers have higher gust probabilities (both conditional and marginal) at their lowest measurement heights; 10 and 20 m, and these probabilities decrease strongly with height (Figure 10c). Conversely, marginal wind gust probabilities are highest at 80 and 100 m in data from Tower 25 (in the valley) and there is some evidence of a decoupling of data from this tower between heights above and below 80 m as manifest in high joint probabilities of gusts in data from 80 and 100 m, and between sonic anemometers at 30, 40 and 60 m a.g.l., but low conditional probabilities between data collected at 80 m and, for example, 40 m.

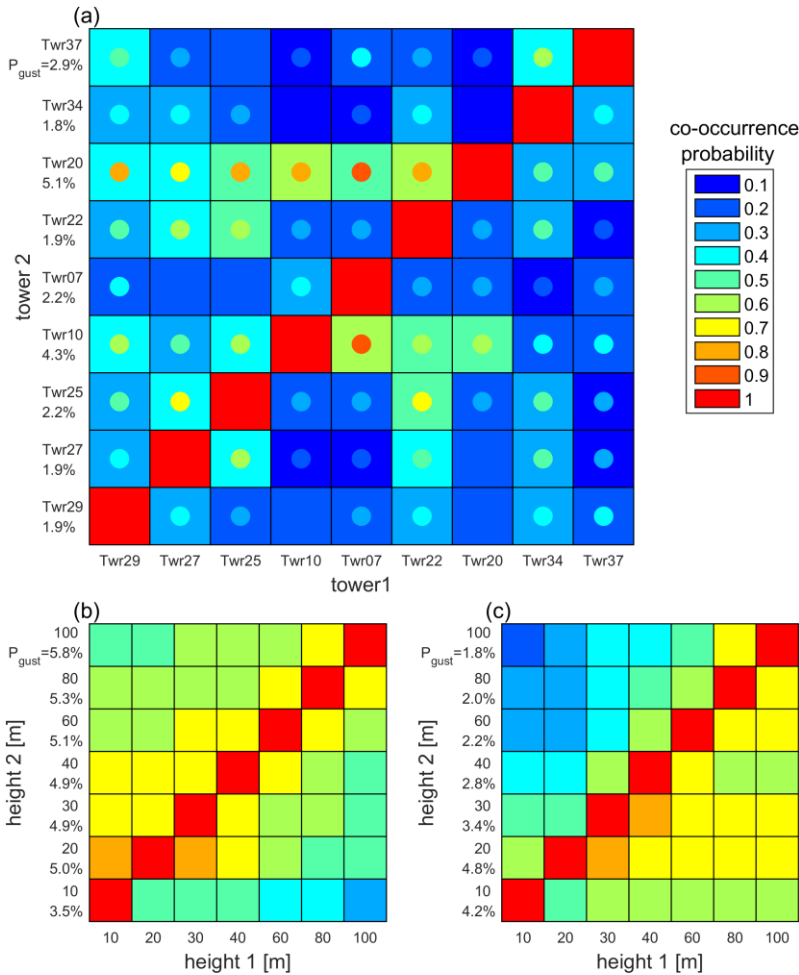
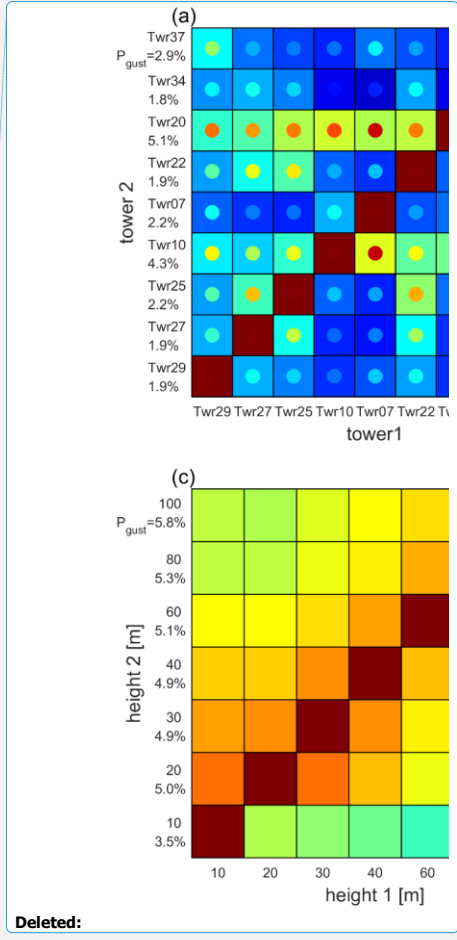


Figure 10: Co-occurrence of wind gusts in individual 10 minute periods between sonic anemometers deployed on different towers (frame a) or at different heights on the same meteorological mast (frame b-c). The colors in each of the four panels indicate probability (in 10 probability classes) of a wind gust at anemometer 2 (on the vertical axis) during any 10 minute period that also has a gust at anemometer 1 (on the horizontal axis). The marginal probability of a wind gusts is also shown along the y axis. (a) Co-occurrence probabilities for gusts at 60 m a.g.l. across all 9 towers. Towers are sorted by their distance from Tower 29, colored dots in each square

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show the probability of co-occurrence when the time window is extended to 30 minutes. Also shown is the co-occurrence of wind gusts at different heights on (b) Tower 25 and (c) Tower 29.

4.4 Spectra and Coherences

5 Normalized power spectra of longitudinal wind speeds from the sonic anemometers during gust periods differ in three primary ways from the mean spectra derived as the composite of all two hour non-gust periods. Firstly, during gusty periods the spectral peak is shifted to the left (to lower normalized frequencies), second, the spectral peak is more distinct and lastly, the spectra exhibit lower variance at higher frequencies (normalized frequency > 1) (Figure 11). [This is consistent with the lower-frequency effects \(such as terrain forcing and mountain waves\) which are associated with gust production, being more pronounced during these gusty periods.](#) The relative magnitude of spectral peak at normalized frequencies of 0.07 to 0.17 is greater during gusty periods in data from the valley towers than the ridge towers (Figure 11a) and is in the same frequency range (i.e. period \approx 120 s) as in less complex terrain (Hu et al., 2018). At the three tall towers, the proportion of wind speed variance associated with normalized frequencies > 1 decreases monotonically with height, while the share of variance expressed at low frequency increases (Figure 11b-d). (Kaimal and Finnigan, 1994) Composite spectra during stable and unstable conditions (Figure 11e) indicate that during stable conditions, the variance at both ridge and valley towers is shifted toward lower normalized frequencies in contrast to previous research in rolling terrain that indicated a shift of variance towards higher normalized frequency during stable conditions (Panofsky et al., 1982). Composite spectra conditionally sampled by wind direction indicate that when the flow is parallel to the ridges (within $\pm 15^\circ$ of NW or SE), consistent with results shown in Figure 6, the power spectra of longitudinal winds from the ridge and valley towers are very similar (Figure 11f), while during periods of perpendicular flow the variance at the valley towers is shifted to higher normalized frequencies (consistent with the energy cascade induced by topographic forcing and previous work at lower measurements height (1.6 m) downstream of a smaller obstruction (11.6 m) (Panofsky et al., 1982)).

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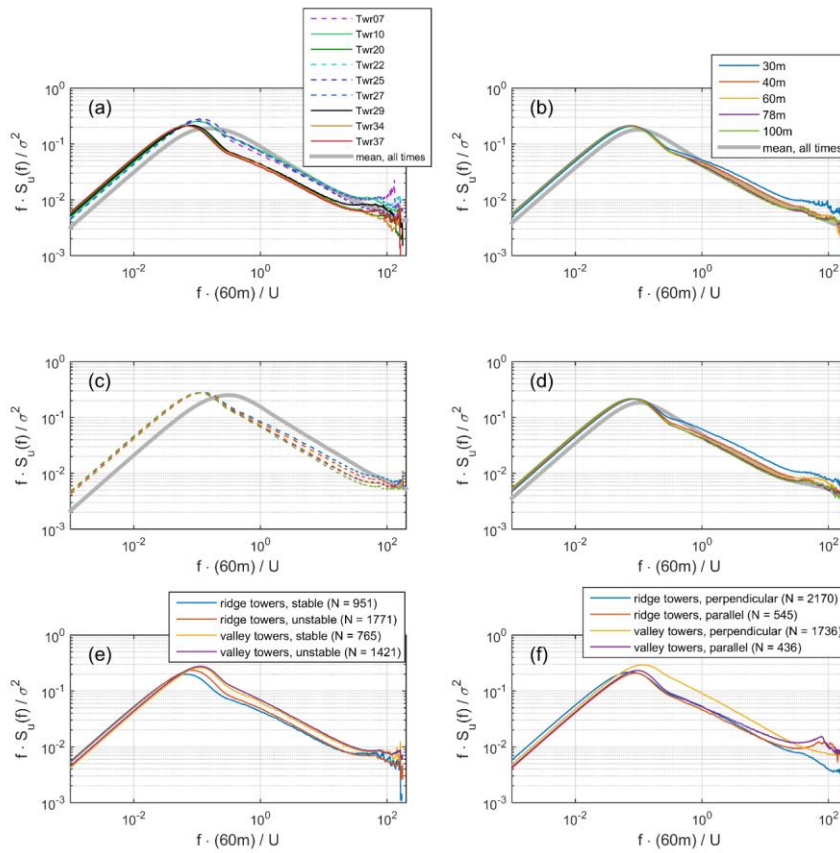


Figure 11: Power spectra of wind speeds during gusty conditions ($U_{\text{mean}} > 3 \text{ ms}^{-1}$ and $u_{\text{gust}} > 4 \text{ ms}^{-1}$) (a) Spectra of wind speeds at 60 m a.g.l. on the 9 towers. Frames (b-d) show the normalized composite spectra from b) Tower 20, c) Tower 25 and d) Tower 29 from multiple heights. (a-d) also show the mean normalized spectra for all measurement periods (including non-gust periods). (e) Mean normalized spectra at ridge and valley towers, conditionally sampled by stability class: stable (including very stable) and unstable (including very unstable) conditions and (f) mean normalized spectra at ridge and valley towers, conditionally sampled by wind direction: parallel ($\pm 15^\circ$ of NW or SE) and perpendicular ($\pm 15^\circ$ of NE or SW) to the ridges.

Power spectra of horizontal wind speed computed for all ten ZephIR lidar measurement heights and from sonic anemometers deployed on the 100 m meteorological masts indicate relatively wide variability in the magnitude of the diurnal peak, S_p , from 0.6×10^4 to $2.6 \times 10^5 \text{ m}^2\text{s}^{-1}$ due to variations in surface forcing across the site and instrumentation differences. Preliminary estimates for the reverse height (i.e. the height of minimum variance at a frequency equal to 1 day^{-1}) derived from the ZephIR lidars (z423 in the central valley and z447 that was deployed outside the ridge-valley system), are approximately 180 m a.g.l. (Figure 12) which is higher than reported for coastal sites (approx. 120 m a.g.l. (Larsén et al., 2018)). Reverse height estimates from sonic anemometers on the ridges (tower 20 and 29) and ZephIR lidar z423 are approximately 40-80 m above the ridge top (Figure 12).

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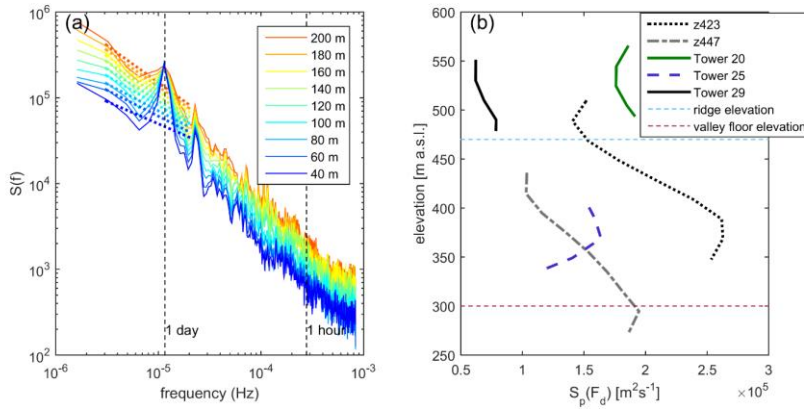


Figure 12: (a) Power spectra of horizontal wind speeds at ten heights from ZephIR lidar z447 and linear fits defining the trend in each near the frequency 1 day^{-1} . (b) Vertical profiles of the magnitude of the diurnal peak in wind speed variance S_p from each ZephIR lidar and the sonic anemometers deployed on each 100 m tower. Measurement heights are shown by their elevation above sea level (a.s.l.). The towers and lidars are denoted by the color scheme introduced in Figure 1. Ridge and valley floor elevations are also shown.

Coherence functions of longitudinal wind speed from horizontally-separated sonic anemometer pairs do not conform to an exponential form, and instead exhibit a marked concave-down section at reduced frequencies below 0.7 (Figure 13a). Nevertheless, functional values are substantially higher for ridge towers (excluding 10) than for valley towers, indicating greater coherence across the top of the valley than within the valley. Fitted C values (from Eq. 15) range from 1.5 at some ridge top towers up to 9.7 at tower 27 (one of the most sheltered towers). These C values, computed for horizontal separation, are toward the low end of C values reported in previous research that indicate C estimates between 5 and 15, and that for sensor separation distance to height ratios > 2 (which is the case for inter-tower coherences in the current study), the mean decay rate was greater than 19 (Solari, 1987; Larsén et al., 2016). It is possible that the discrepancy in C values with previous research is due to poor fit to an exponential form in coherence functions (Figure 13a), although it may also reflect faster decoupling of flow regimes in complex terrain. Intra-tower coherences derived using data from different heights relative to data from 60 m a.g.l., are well described by Eq. (15). Coherence functions for the 100 m ridge towers (represented by Tower 29, Figure 13c) have C values between 9.6 and 14.0, which lie in the middle of the range (C = 6 to 16.9) observed in previous work for pairs of sensors separated by a vertical distance (Solari, 1987). These values are higher overall than those measured for longitudinal separation, which is consistent with Taylor's Hypothesis: that turbulent structures evolve slowly, as they are advected by the mean flow (Larsén et al., 2016). Though Tower 25 had among the highest decay rate of coherence with the reference tower, the intra-tower coherences for Tower 25 exhibit C values of 7.6 to 11.8 (Figure 13b). Consistent with expectations, the sensors closest to 60 m a.g.l. at each tower have the highest coherence with measurements at 60 m a.g.l., while the measurements at 30 m a.g.l. sensor (the lowest height included in this analysis) have the lowest coherence values (and highest decay rate). The vertical coherence functions from Perdigo towers decay to their minimum value at a reduced frequency of ~ 0.3 , which similar to the value of 0.36 calculated for wind over water (Mehrens et al., 2016). Coherence functions derived using wind speeds from ZephIR lidar z423 show slightly larger C values that are derived from sonic anemometer data from the nearby Tower 25, and exhibit high C values between measurements at 60 m a.g.l. and those above 100 m a.g.l. indicating a reduction in the degree to which flow at these heights is coupled (Figure 13d).

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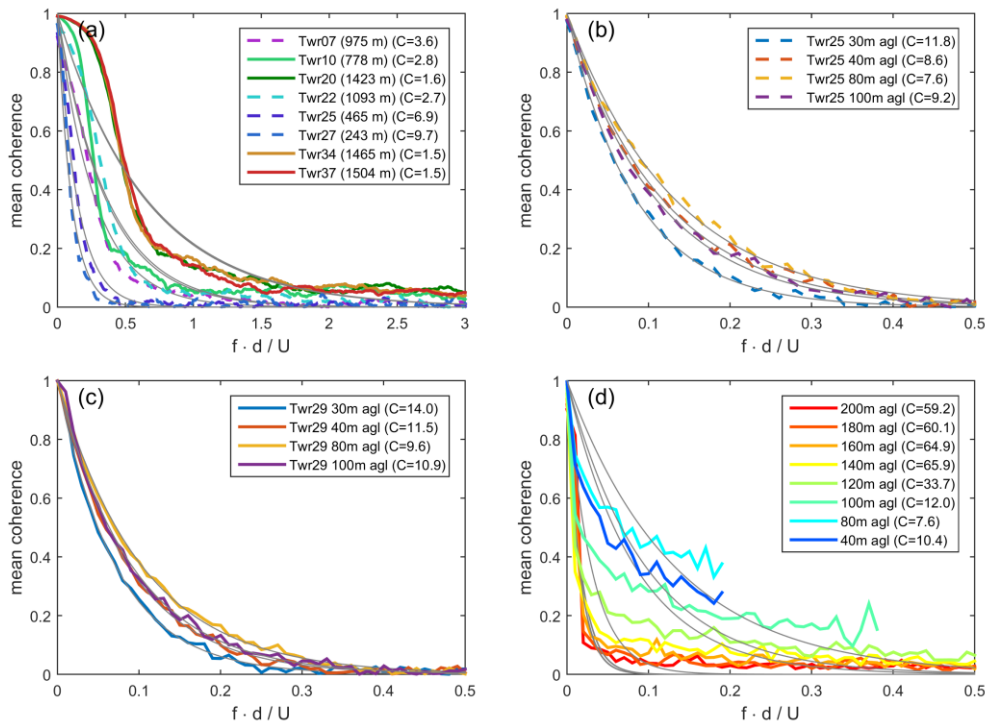


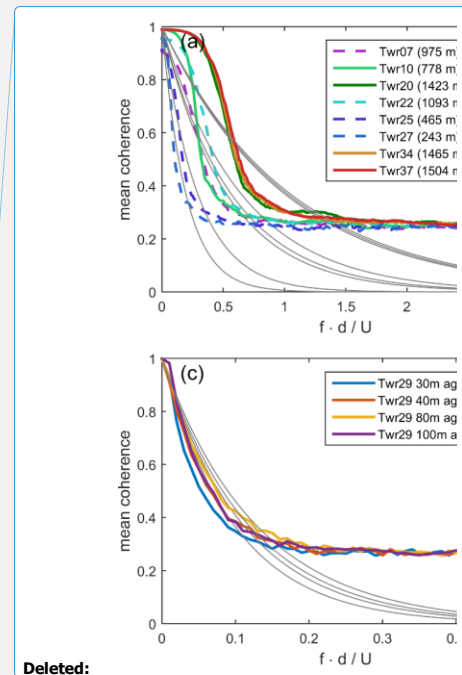
Figure 13: Mean coherence in longitudinal wind speeds as measured by sonic anemometers based on 2 hour time series. (a) Mean coherences between Tower 29 and each other tower, for a 60 m measurement height, and exponential fits there to. (b) Coherences between each height and the 60 m reference height at Tower 20. (c) Coherences between each height and the 60 m reference height at Tower 25. (d) Coherence in horizontal wind speed at each height and the 60 m reference height measured by ZephIR lidar z423.

5 Concluding Remarks

The experiment conducted at Perdigo provides an unprecedented data set for studying flow characteristics in complex terrain. Herein we focus on wind gust characteristics as described using six months of data recorded at 18 Hz from 51 3-D sonic anemometers deployed on nine tall meteorological masts at heights of 10 to 100 m and two vertically pointing Doppler lidars.

Consistent with previous research, analyses presented herein illustrate substantial spatial heterogeneity in the magnitude, scale and occurrence of wind gusts over an area of approximately 3 by 3 km (Figure 1) and reemphasize the complex effects of terrain forcing on near-surface flow.

- Nine properties of wind gusts (intensity measures; magnitude, amplitude, peak factor and gust factor, and scale metrics; rise and lapse time, duration and length scales) exhibit similar parent probability distributions to those derived from measurements in moderately complex terrain (Hu et al., 2018), indicating that these distributional forms may be generalizable. However, the best-fit distributional forms (selected using negative log-likelihood) underestimate the magnitude and amplitude of intense gusts (i.e. the 99th percentile values). Although the wind gust parameters (including probability of gust occurrence) exhibit similar distributional forms across the site, they differ greatly in terms of the shape and scale parameters of the distributions as applied to data from locations in the valley compared to the ridge



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tops. Joint probability distributions of the gust parameters indicate high aspect ratios for gust intensity (e.g. gust magnitude; U_{gust}) across different measurement heights and locations. However, low aspect ratios are evident for gust length scale (L_{gust}) computed from sonic anemometers deployed at two heights on the same meteorological mast and/or deployed on meteorological masts separated by horizontal distances of 200 to 1600 m (Figure 5).

- Gust factors measured at Perdigo are larger than those measured in less complex terrain (Figure 8c; Suomi, 2015), but decrease with height (z) at a rate similar to measurements over flat grassland (Figure 7c; Shu et al., 2016). While the majority of gust parameters exhibit a decreasing rate of change with z as z increases t_{gust} and L_{gust} show a marked increase between 80 and 100 m. this is consistent with the idea that the spatial and time scale of gusts may be more affected by the presence of complex terrain than gust intensity (as measured by U_{gust} , GF or a_{gust}). The rate of decrease in t_{gust} with height is roughly two thirds that measured in flat terrain (Román, 2017).
- Wind speed spectra during gusty periods (when $U_{mean} > 3 \text{ ms}^{-1}$ and gust magnitude (U_{gust}) $> 4 \text{ ms}^{-1}$) exhibit a shift toward higher variance at lower frequencies, and a more pronounced peak near a reduced frequency (fz/U) of 0.1, indicating that, while individual gusts may not be sufficient to affect 10 minute spectra, gusty conditions are associated with a significant change in spectra. The amount of variance in wind speeds associated with the diurnal cycle varies depending on measurement system and location within the study site. Nevertheless, there is evidence that the reverse height (where the first order effects of heat exchange at the land surface is minimized) is ~ 60 m above the ridges that enclose the valley.
- Gust parameters, and their spatial heterogeneity are found to vary with atmospheric conditions including wind direction, stability and turbulence intensity. Differences in observed gust parameters between ridge and valley towers are less pronounced when the flow is parallel to the ridge orientation. Unstable and very unstable conditions (as well as high turbulence intensity) are associated with less ridge-valley differentiation in U_{gust} magnitudes suggesting that increased vertical mixing leads to decreased orographic sheltering of the valley towers.
- Gust co-occurrences and coherence statistics indicate the presence large-scale gust phenomena that are simultaneously manifest at the ridge towers but not the valley towers. Gust occurrence across the Perdigo site is significantly influenced by the terrain resulting in much lower average gust co-occurrence probability (of 27%) across towers than those observed in flat terrain (Branlard, 2009). The decay of coherence functions for vertical displacements is in the range found in flat terrain (Solari, 1987; Viguera-Rodríguez et al., 2012). However, coherences for the large horizontal displacements ($> 700\text{m}$) between towers do not fully conform to an exponential fit (as with those presented in (Mehrens et al., 2016)) and are characterized by smaller decay coefficients than have been found in research conducted in less complex terrain.

There are clear commonalities in gust properties across the site and between estimates derived using data from sonic anemometers and vertically-scanning Doppler lidar. Additionally, co-occurrence probabilities of wind gusts across the site illustrate the very high complexity of flow over what is superficially a simple two-dimensional valley enclosed by two parallel ridges (Figure 1). These results further indicate that terrain features (and the vegetation canopy) may have a more profound impact on the dimensions of wind gusts than their magnitude. The reverse height (approximately 60 m above the ridge tops) is consistent with a decoupling of flow derived from the coherence functions estimated from the vertically scanning Doppler lidars (as indicated by the step change in C values, Figure 13d). This is similar to the height at which some gust properties exhibit diminishing dependence on local surface characteristics (U_{gust} , a_{gust} and TI; Figure 7 b,g,d), supporting the hypothesis that reverse height is linked to the influence of the ground on wind speed fluctuations on the time scale of gusts. Gust length scales on the

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ridge tops are frequently similar to the height of the ridge above intervening valley (which is approx. 175 m deep), and the modal gust length scale measured in the valley is 200 m.

Data collected during the Perdigão experiment and analyses presented herein provide a foundation for improved wind gust characterization in complex terrain. These data also provide an unprecedented opportunity for detailed validation and verification of numerical wind flow models (Butler et al., 2015;Suomi and Vihma, 2018).

Data availability

All data analyzed herein are available for download from the New European Wind Atlas data portal (2018) hosted by the University of Porto and accessible at; <http://perdigao.fe.up.pt>.

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Field Code Changed

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Characterizing Wind Gusts in Complex Terrain.

Supplementary Information

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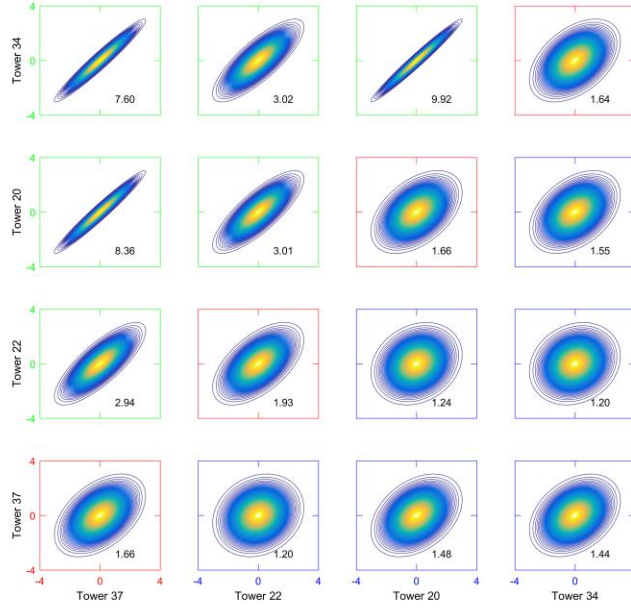
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10 As described in the main text, (Section 3.1) best fit distribution types are chosen based on minimum negative-log-likelihood (NLL), though the minimum NLL is frequently similar to the next-best choice. In order to expand on the information given in Table 2 of the main text, Table S1 shows the best and second-best fit distribution types and their associated NLL values.

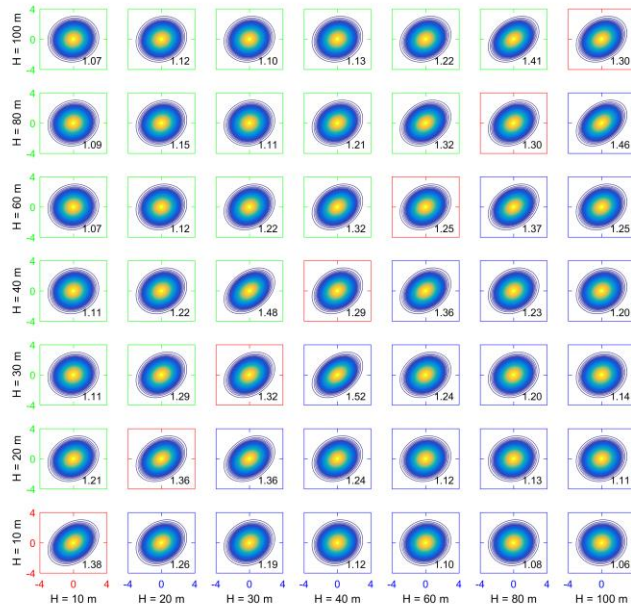
15 Figures S1 to S5 show joint distributions of pairs of gust parameters which have been transformed to be normally distributed as described in Section 3.1. These parameters joint probability distributions describe the correlation of gusts parameters between towers and between measurements heights at Tower 29.

Table S1 – Best and second-best fit distribution types for each gust properties (in each 10 minute period when $U_{\text{mean}} > 3\text{ms}^{-1}$) for a measurement height of 60 m a.g.l. at each tower. The distribution types are referred to as 1-4 where 1: Weibull, 2: log-logistic, 3: log-normal, 4: gamma. Negative-log-likelihood values for each distribution type (best and second-best) are also shown.

		Tower								
		7	10	20	22	25	27	29	34	37
Best fit distributions	U_{mean}	3	3	3	3	3	3	3	3	3
	U_{gust}	3	3	3	3	3	3	3	3	3
	GF	2	3	2	3	3	3	3	2	2
	a_{gust}	1	1	1	1	4	1	1	1	1
	k_{peak}	2	2	2	2	3	2	2	2	2
	t_{rise}	3	3	3	3	3	3	3	3	3
	t_{iapse}	3	3	3	3	3	3	3	3	3
	t_{gust}	3	3	3	3	3	3	3	3	4
	L_{gust}	3	3	4	3	3	3	4	4	4
Best fit NLL	U_{mean}	3447	10129	15010	5572	3527	4332	13835	14954	14879
	U_{gust}	4711	12790	16767	7188	4714	5962	15716	16858	16558
	GF	201	771	-1691	532	475	686	-1352	-1735	-1878
	a_{gust}	3792	9677	10027	5569	3695	4801	9733	10257	9756
	k_{peak}	4303	6889	-16140	4374	1097	4077	-10870	-16874	10026
	t_{rise}	7786	19802	23128	12302	7983	9904	22580	23292	22608
	t_{iapse}	9000	23589	28551	14216	9183	11552	28329	28945	28292
	t_{gust}	9001	23098	26872	14238	9174	11495	26347	27216	26318
	L_{gust}	13543	35204	42949	21266	13845	17136	42128	43278	42450
Second-best fit distributions	U_{mean}	4	4	4	2	4	4	2	4	4
	U_{gust}	4	4	4	2	4	4	4	4	4
	GF	3	2	3	2	4	2	2	3	3
	a_{gust}	2	4	4	4	2	4	4	4	4
	k_{peak}	3	3	3	3	4	3	3	3	3
	t_{rise}	2	2	2	2	2	2	2	2	2
	t_{iapse}	2	2	2	2	2	4	4	2	2
	t_{gust}	4	2	4	2	4	4	4	4	3
	L_{gust}	4	4	3	2	4	4	3	3	3
Second-best fit NLL	U_{mean}	3497	10246	15159	5588	3577	4403	14000	15084	15037
	U_{gust}	4737	12865	16860	7226	4727	5967	15836	16953	16654
	GF	227	862	-1599	538	501	712	-1325	-1686	-1817
	a_{gust}	3888	9730	10076	5656	3716	4913	9807	10303	9898
	k_{peak}	7103	14773	16307	9151	1109	7907	15713	17693	19044
	t_{rise}	7820	19900	23234	12364	8019	9948	22679	23402	22719
	t_{iapse}	9029	23682	28662	14277	9222	11597	28438	29051	28397
	t_{gust}	9009	23172	26907	14283	9189	11517	26364	27271	26320
	L_{gust}	13550	35251	42975	21312	13865	17139	42175	43307	42499



5 **Figure S1 – Joint distributions of gust magnitude (U_{gust}) at different towers and joint distribution of gust length scale (L_{gust}) at different towers. Wind data from Towers 20, 22, 34, and 37 at 60 m (See Figure 1 and Table 1 in the main text for locations). Upper-left off-diagonal panels (green boxes): U_{gust} vs. U_{gust} at each pair of towers; Diagonal panels (red boxes): U_{gust} vs. L_{gust} at the same tower; Bottom-right off-diagonal panels (blue boxes): L_{gust} vs. L_{gust} at each pair of towers. There are 99 ellipses corresponding to the confidence levels from 1% (the innermost ellipse with the warmest color) to 99% (the outermost with the coldest color).**



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Figure S2 – Joint distributions of gust lapse time (t_{lapse}) and gust rise time (t_{rise}) at different heights from Tower 29. Upper-left off-diagonal panels with green boxes show the joint distributions of t_{lapse} at each pair of heights. Diagonal panels with red boxes show the joint distributions of t_{lapse} and t_{rise} at the same height. Bottom-right off-diagonal panels with blue boxes show the joint distributions of t_{rise} at each pair of heights. The number at the bottom-right corner of each panel is the average ratio between the major axis and minor

axis of ellipses. There are 99 ellipses corresponding to the confidence levels from 1% (the most inner ellipse with the warmest color) to 99% (the most outer ellipse with the coldest color).

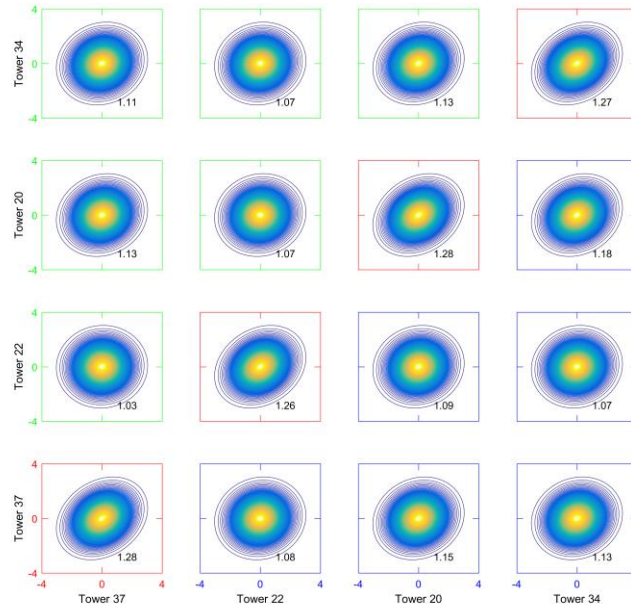


Figure S3 – Joint distributions of lapse time (t_{lapse}) at different towers and joint distribution of gust rise time (t_{rise}) at different towers. Wind data are from Towers 20, 22, 34, and 37 at 60 m (See Figure 1 and Table 1 in the main text for locations). Upper-left off-diagonal panels (green boxes): t_{lapse} vs. t_{lapse} at each pair of towers; Diagonal panels (red boxes): t_{lapse} vs. t_{rise} at the same tower; Bottom-right off-diagonal panels (blue boxes): t_{rise} vs. t_{rise} at each pair of towers. Wind data are from Towers 20, 22, 34, and 37 at 60 m (See Figure 1 and Table 1 in the main text for locations). There are 99 ellipses corresponding to the confidence levels from 1% (the innermost ellipse with the warmest color) to 99% (the outermost with the coldest color).

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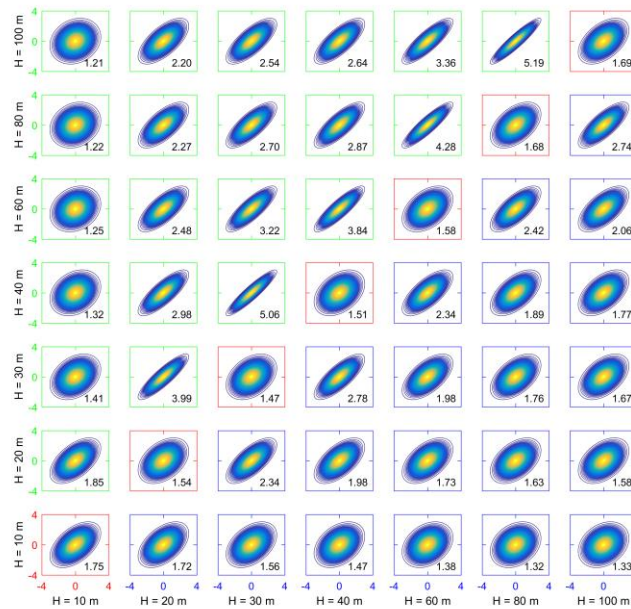
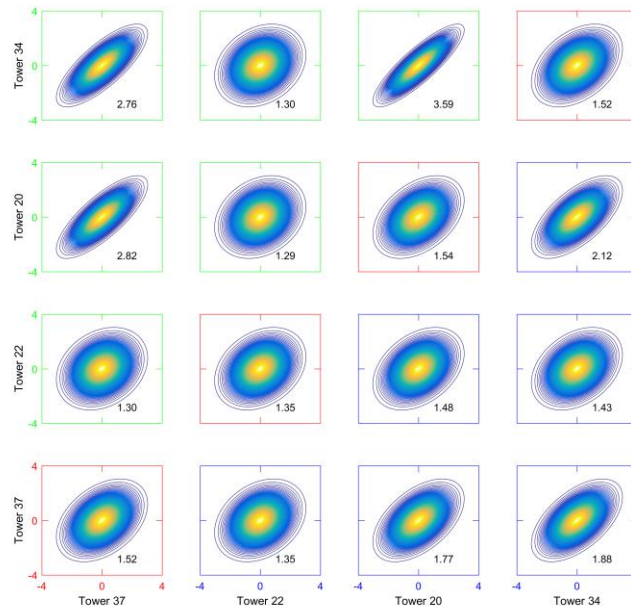


Figure S4 – Joint distributions of gust peak factor (k_{peak}) and gust factor (GF) at different heights from Tower 29. Upper-left off-diagonal panels with green boxes show the joint distributions of k_{peak} at each pair of heights. Diagonal panels with red boxes show the joint distributions of k_{peak} and GF at the same height. Bottom-right off-diagonal panels with blue boxes show the joint distributions of GF at each pair of heights. The number at the bottom-right corner of each panel is the average ratio between the major axis and minor

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axis of ellipses. There are 99 ellipses corresponding to the confidence levels from 1% (the most inner ellipse with the warmest color) to 99% (the most outer ellipse with the coldest color).



5 Figure S5 – Joint distributions of gust peak factor (k_{peak}) at different towers and joint distribution of gust factor (GF) at different towers. Wind data from Towers 20, 22, 34, and 37 at 60 m (See Figure 1 and Table 1 in the main text for locations). Upper-left off-diagonal panels (green boxes): k_{peak} vs. k_{peak} at each pair of towers; Diagonal panels (red boxes): k_{peak} vs. GF at the same tower; Bottom-right off-diagonal panels (blue boxes): GF vs. GF at each pair of towers. There are 99 ellipses corresponding to the confidence levels from 1% (the innermost ellipse with the warmest color) to 99% (the outermost with the coldest color).