EGU General Assembly 2020
Vienna | Austria | 3–8 May 2020

CL5.6 - Climate Data Compilations, Homogenisation and Analysis of Variability, Trends and Extremes

POSTER # EGU2020-12298

Effects of Sensor Response and Gust Duration on Maximum Wind Gust Measurements and Data Homogenisation

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ABSTRACT

Wind speed data recorded using different signal-processing procedures can introduce errors in the wind speed measurements. This study aims to assess the effects of a set of various moving average filter durations and turbulence intensities on the recorded maximum gust wind speeds. For this purpose, a series of wind-tunnel experiments was carried out on the widely-used Vaisala WAA151 cup anemometer. The variations of gust factor as a function of the gust duration and turbulence intensity are presented. The wind-tunnel results are compared with values computed from a theoretical approach, namely random process and linear system theory, and the results were also validated against values reported in the literature where possible. The results show that the maximum gust wind speeds measured using large averaging durations (e.g. 3 s or 5 s) lead to up to 25% – 30% negative biases compared to high frequency measurements (e.g. 4 Hz unfiltered gust measurements). This result can strongly impact subsequent meteorological, climatological and wind engineering studies, as different gust definitions have been adopted by National Weather Services and institutions around the world. Lastly, a set of correction factors (i.e. gust factor ratios) have been proposed that allows measurements at a specific gust duration to be converted to equivalent measurements at specified particular gust durations of interest.

INTRODUCTION

Issue:

- Historical wind data have been recorded using different instruments and gust durations (e.g. Fig. 2). Particularly after the implementation of Automatic Weather Stations (AWS) and 3-s gust definition in the 1990s.
- These changes have resulted in breakpoints and discontinuities in wind time series (e.g. Fig. 1).

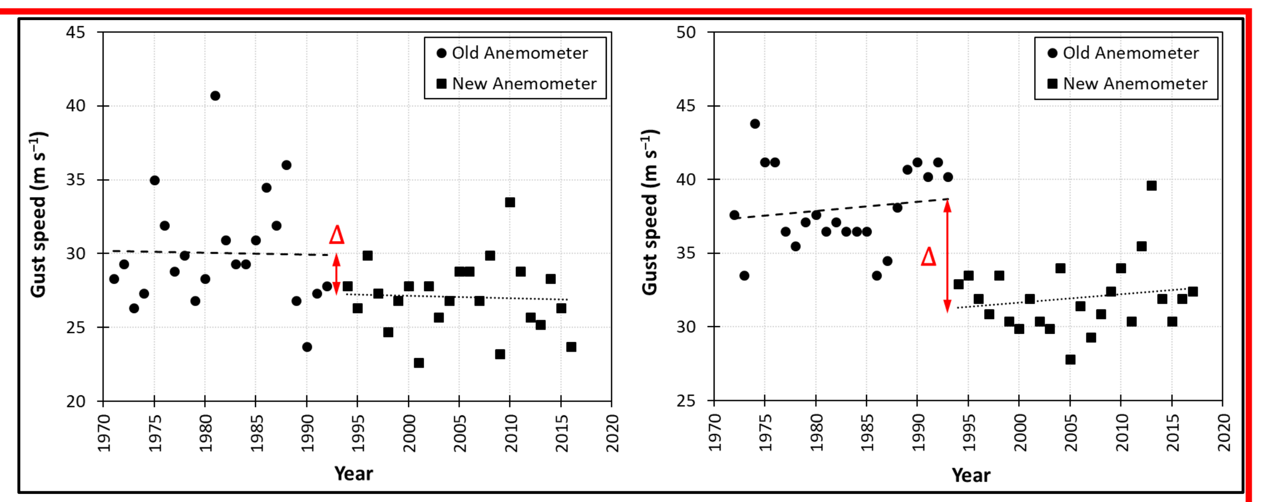

Figure 1. Annual maximum gust wind speeds recorded at: (a) Auckland; (b) Wellington

Objectives of Study:

- Quantitatively assess the effects of gust duration on gust wind speed measurements.
- Propose correction factors (i.e. Gust Factor (GF) ratios Eq. 2) that can be used for the homogenisation of wind speed time series and for converting measurements with a certain gust duration to equivalent gust measurements with different gust durations.

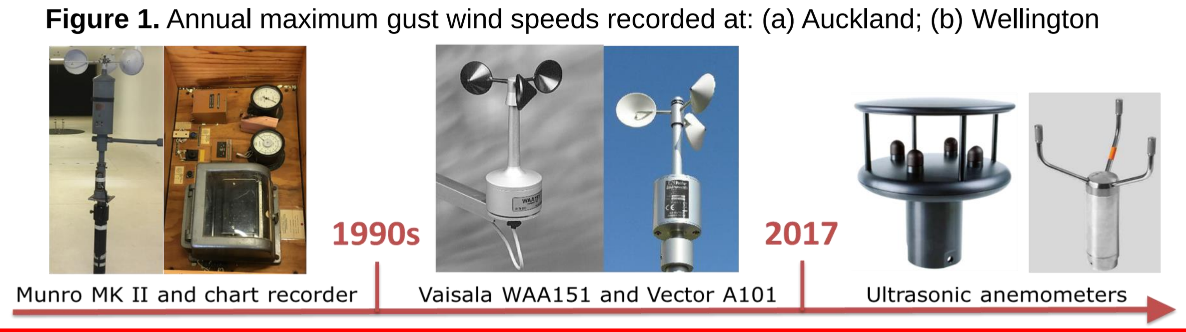

Figure 2. Anemometers used in New Zealand

METHODOLOGY

Wind-tunnel (WT) experiments were carried out to consider the real response characteristics of the anemometer and recording system. For comparison and validation purposes, the WT results have been compared with theoretical results, using the properties of the full-scale (FS) wind flow, and also with values reported in the literature [4,5].

Wind Tunnel Experiments

- Vaisala WAA151 cup anemometer was used for the present tests.
- Tests were carried out in the boundary-layer WT at the University of Auckland, New Zealand, which has a max speed of 20 m/s, and cross-section of 3.6 m × 2.5 m (width × height).
- Turbulence-inducing elements (Fig. 3) were used in the WT to replicate the random fluctuations of wind in nature. Turbulence intensities of the flow in WT are shown in Fig. 4.

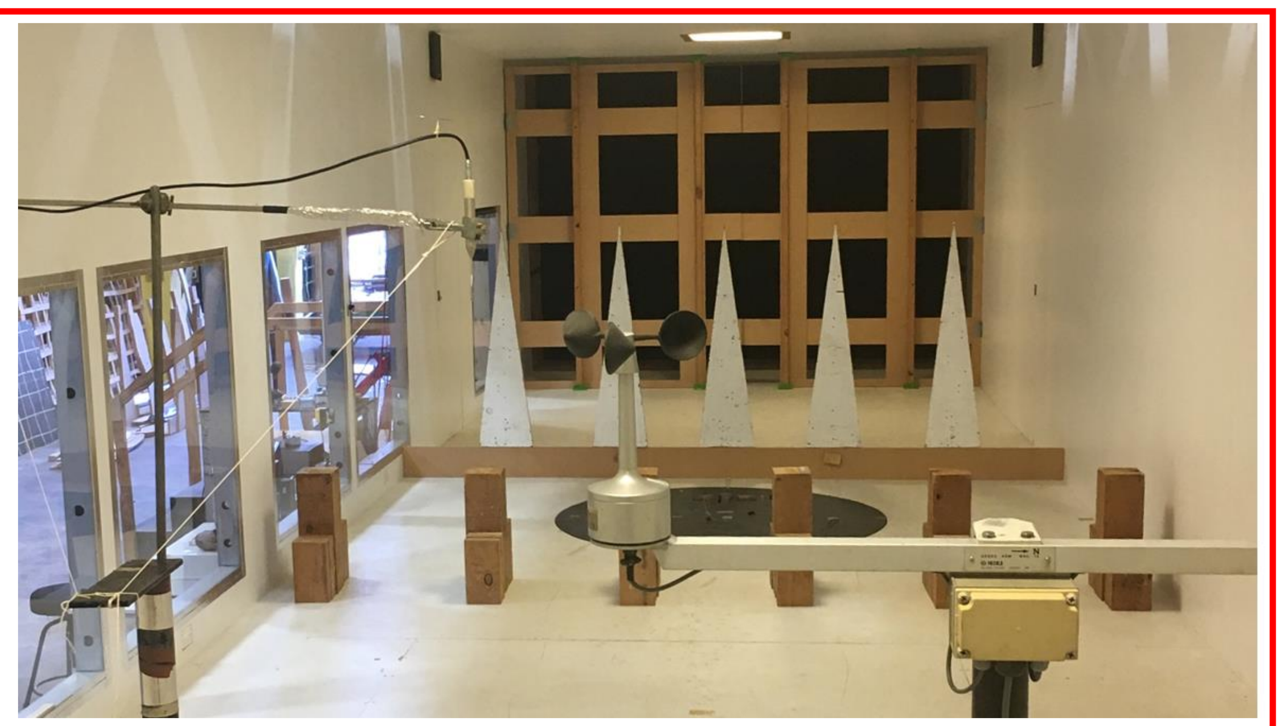

Figure 3. Example of wind tunnel setup for generating turbulence

Theoretical Approach: Random process and linear system theory

Due to the smaller turbulence integral length scales (λ) inside the WT compared to FS, a theoretical approach, i.e. random process and linear system theory [4, 5], was employed, where the corresponding FS λ were used, to compute GF and to compare them with the WT results.

Parameters for Comparison

Two parameters were defined to quantify the difference between parameters φ (e.g. GF) at various gust durations (i.e. d1 and d2).

$$\varepsilon = \frac{\varphi_{d1} - \varphi_{d2}}{\varphi_{d1}} \times 100 \quad \text{(Eq. 1)}$$

$$R = \frac{GF_{d1}}{GF_{d2}} \quad \text{(Eq. 2)}$$

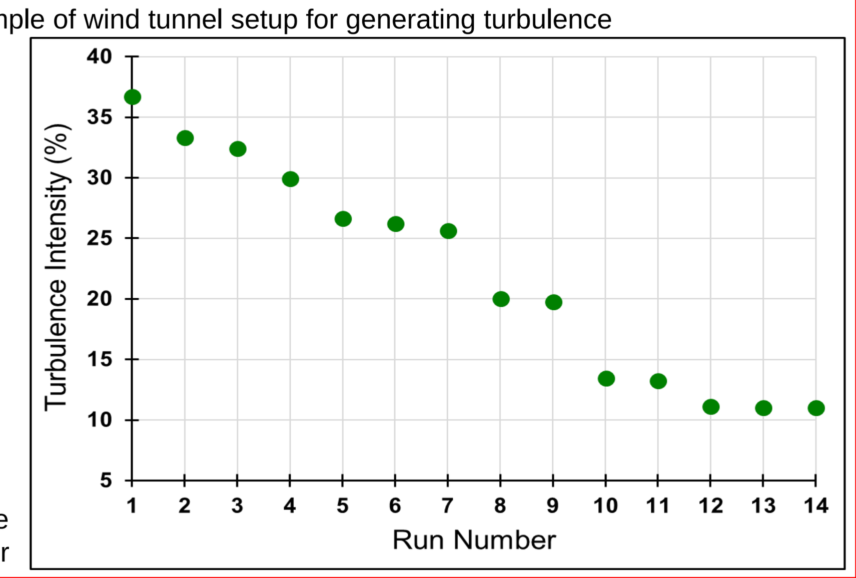

Figure 4. Turbulence intensities of wind produced in the wind tunnel measured by the reference Cobra sensor

RESULTS

- Applying a moving average filter reduces the area under the wind spectrum (Fig. 5a), and smoothens the wind fluctuations Fig. 5b, which consequently affect the gust factor.
- Fig. 6 shows GF ratios (Eq. 2) obtained from WT tests, theoretical method, and literature [4,5]. Results agreed well with less than 1.5% and 3.5% differences for low and high turbulence cases, respectively.
- GF ratios (Eq. 2) and errors (Eq. 1) for two sets of gust durations are shown in Fig. 7 as a function of turbulence intensity. In high turbulence conditions, GF ratios in the order of 1.25-1.30 (Fig. 7a) and 1.03-1.05 (Fig. 7b) are required to convert 3-s gusts to raw 4Hz and 2-s gusts, respectively.
- Complete sets of correction factors for various gust durations will be reported in a full paper.

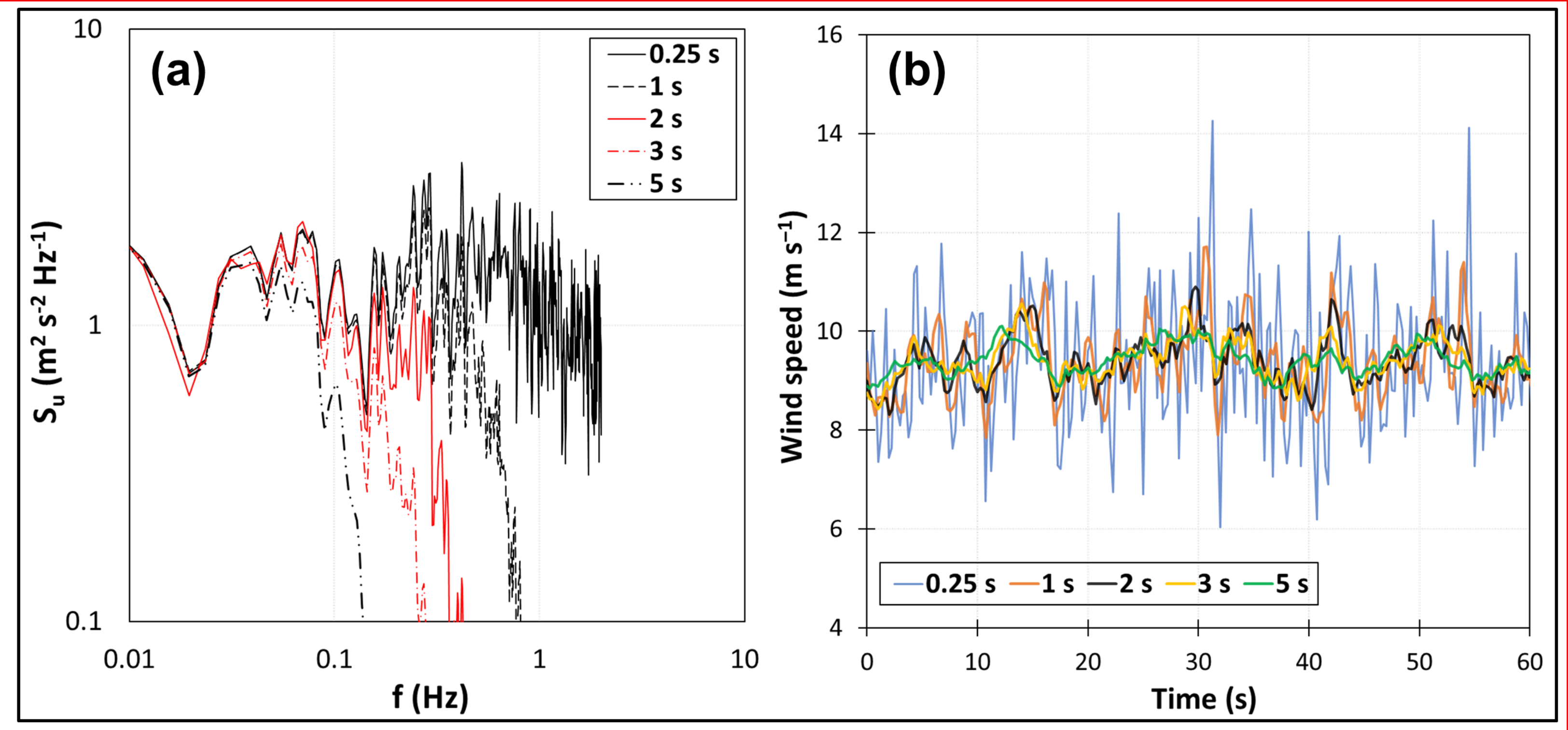

Figure 5. Effect of applying moving average to the wind speed recorded by a WAA151 anemometer in a turbulent wind with I_u=32.4% and $\overline{U}$ =10.1 m s⁻¹: (a) Power spectral densities; (b) Wind speed time series.

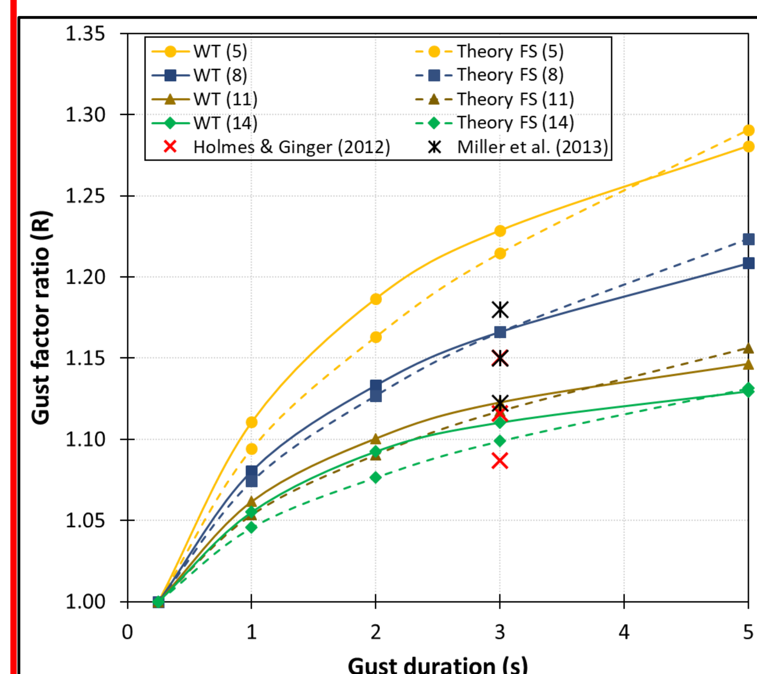

Figure 6. Comparison between the gust factor ratios obtained from WT tests and the theoretical approach (i.e. FS conditions), and those reported by Holmes and Ginger [4] and Miller et al. [5].

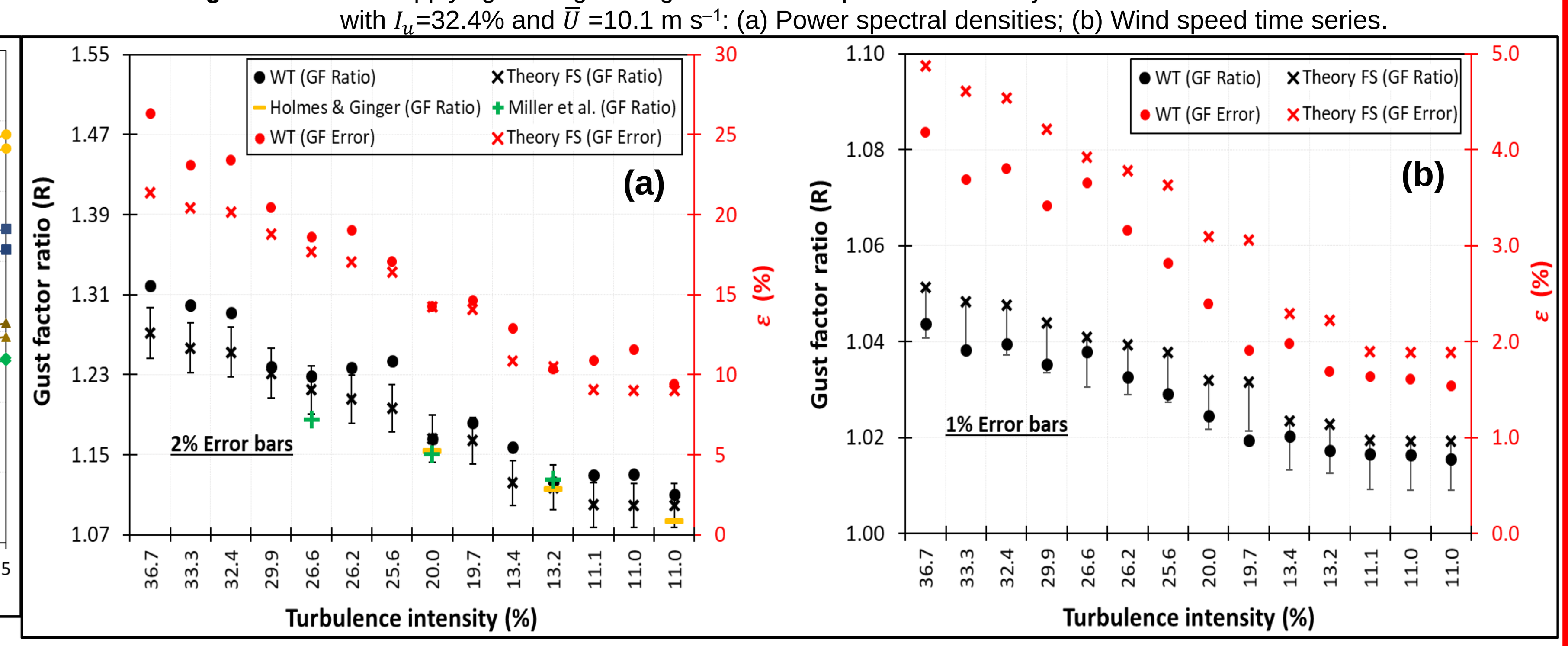

Figure 7. Gust factor ratios and errors between: (a) 3-s and raw measurements (4 Hz); (b) 3-s and 2-s gusts

DISCUSSION

Excellent agreement was achieved between the differences and gust factor ratios computed from the WT tests, the theoretical approach, and values reported in the literature.

Change in the gust duration can result in breakpoints in wind speed time series. Also, gust duration can significantly affect the subsequent analyses, such as trend and extreme value analyses. Results demonstrated that the difference between high and low gust-duration gust measurements can be as large as 30 – 35%. Therefore, the gust duration must be taken into account when homogenising historical wind data.

WT experiment, theoretical approach and FS measurements are complementary methods contributing to better understanding of the differences between wind measuring instruments and recording procedures, including gust duration. Unlike the theoretical approach, in WT experiments, the true response characteristics of both the anemometer and the data logger are accounted for. However, on the other hand, compared with the atmospheric boundary layer (ABL), the replicated turbulence in the WT is at higher frequencies and contains much smaller turbulence integral length scales. However, for the theoretical FS approach, the turbulence length scales corresponding to the FS ABL can be used.

An alternative approach is to conduct FS experiments, as they do not require any assumptions and simplifications in both the anemometer response characteristics and the ABL turbulence. However, in this approach the experiments are less controllable compared to the wind tunnel.

CONCLUSIONS

To summarise, the major findings of this experimental study are:

1. The results show that increasing the effective gust duration reduces both the gust and peak factors, resulting in an underestimation of maximum gust wind speeds and an overestimation of minimum gust wind speeds.
2. The maximum difference between gust factors obtained for high (e.g. 3-s to 5-s) and low (raw, unfiltered measurements) gust durations reached values of 25% – 30% for the high turbulence, and up to 5% – 10% for low turbulence conditions.
3. Gust factor ratios, an important parameter that allow the measurements from a specific gust duration to be converted to other gust durations of interest, are reported for various gust durations as a function of turbulence intensity.
4. The differences and gust factor ratios computed in this study can be applied directly to full-scale measurements, and can be used in several research areas. These factors clearly play an essential role in meteorological, climatological and wind engineering studies.

The results of the present study are being used in several ongoing research projects by the authors.

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Acknowledgements: The authors are grateful to the New Zealand MetService and NIWA for providing the anemometers for the tests. The study is partly funded by three projects: (i) New Zealand Ministry of Business, Innovation and Employment, “New Zealand Natural Hazards Platform”; (ii) Swedish Research Council, “Detection and attribution of changes in extreme wind gusts over land” (2017-03780); and (iii) Spanish Ministry of Science, Innovation and Universities, “Evaluación y atribución de la variabilidad de la velocidad media y las rachas máximas de viento: causas del fenómeno “stilling” (RTI2018-095749-A-I00). C. Azorin-Molina is also supported by RYC-2017-22830. The authors also would like to thank Dr. Yin Fai Li, Wind Tunnel Engineer at the University of Auckland, for the fruitful discussions and helpful suggestions regarding the wind-tunnel experiments.