Use of High-Resolution Numerical Models and Statistical Approaches to Understand New Zealand Historical Wind Speed and Gust Climatologies

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ABSTRACT

This paper describes how a combination of high-resolution numerical modeling, a robust homogenization algorithm, and local pressure observations have been used to understand and reconcile time series of daily, seasonal, and annual peak wind gusts recorded at observing sites in the Cook Strait region of New Zealand. The homogenization algorithm consists of corrections for the relocation of masts, changes in instrumentations, data acquisition and signal processing, surrounding surface roughness, and measurement heights. In addition, a statistical method, penalized maximal F test (PMFT), was used to assess the homogeneity of the wind speed time series and detect and eliminate all remaining, undocumented, artificial (i.e., nonclimatic) breakpoints. A three-dimensional time-dependent computational fluid dynamics (CFD) simulation was carried out using the Gerris model to characterize the turbulence environment at the mast sites and to estimate topographic speedup effects. Trends in magnitudes and frequencies of the homogenized seasonal and annual peak wind gusts are evaluated and presented for the Cook Strait region. The pressure gradients between pairs of stations were used to study the correlation between the gust wind speeds and the pressure field. A high-resolution convection-resolving numerical weather prediction model [the New Zealand Convective-Scale Model (NZCSM)] was employed to aid the interpretation of results and analyze wind trends. The trend in gust speeds is also shown to be consistent with larger-scale NCEP–NCAR reanalysis pressure trends. The homogenization algorithm showed promising results in eliminating the artificial breakpoints and trends. Overall, strong correlations were found between the homogenized gust speeds, the pressure field across the region, and NZCSM predictions.

1. Introduction

Wind-gust climatologies have important uses in estimating wind-induced loads on structures, assessment of long-term gust wind speed trends, and possible effects of climate change on magnitudes and frequencies of extreme winds. Engineers generally have available to them design wind speeds valid for a region that have been derived from examining sets of observational gust records homogenized for upwind fetch (i.e., surface roughness z_0), mast height, and in some cases underlying topography effects. Gust forecasts for particular sites are also important for weather warnings, and accounting for how the local topography influences the gust climatology can improve their accuracy and aid interpretation of both

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forecasts and observations. Additionally, there has been recent attention internationally on mean near-surface wind speed trends, particularly after a decreasing (“stilling”) trend in mean wind speeds at many locations around the world was noted by [Roderick et al. \(2007\)](#). To date, only a few unpublished reports on the short-term wind speed trends for some regions of New Zealand have been done, and no effort has been made to rigorously homogenize New Zealand’s wind speed time series, a necessary prerequisite for examining temporal trends in wind speeds. Most of the unpublished reports were based on the data recorded prior to the 1990s and before the widespread modernization to automatic weather stations (AWS) in New Zealand, which saw the replacement of most Munro anemometers with light cup anemometers ([Reid 1996](#)). However, there does exist a recent analysis by [Statistics New Zealand \(2017\)](#), which indicated a decreasing trend in the prevalence of high wind speed days at many locations. This latest study is only available online at the Statistics New Zealand website and appears to have made no attempt to homogenize station records and the analysis only carries a medium quality rating.

Therefore, this paper aims, by way of example, to illustrate how a combination of high-resolution numerical modeling, a robust homogenization algorithm, and local pressure observations can be used to reconcile and evaluate time series of daily, seasonal, and annual peak wind gusts in the extreme wind environment of the Cook Strait (Wellington) region of New Zealand ([Fig. 1](#)). It also aims to document the homogenization procedure for the purposes of future users of the joint Australian and New Zealand Standard (AS/NZS) 1170.2 design wind-loading standard and others wishing to conduct trend analyses.

The Cook Strait gust observing sites examined here are Wellington Aero {National Institute of Water and Atmospheric Research (NIWA) Climate Database [CLIDB (NIWA, CliFlo 2018)] Agent Number 3445} and Brothers Island (Agent Number 4395). Cook Strait makes up most of region W(ellington) of the Australia and New Zealand wind-loading standard ([Standards Australia/Standards New Zealand 2011](#)) and has had historically higher north, northwest, and south directional multipliers than other AS/NZS regions of New Zealand. This has consequently imposed greater design loads on buildings there. Although, it is also true that wind loading dominates the structural design for exposed coastal and hilly locations in other parts of New Zealand. Thus, another aim of this study was to develop a methodology that can be extended to other stations so accurate estimates of homogenized extreme gusts can be obtained for the purposes of updating the design wind standard for other New Zealand design regions. The analysis presented here also allows

estimates of the impact of changes in instrument type and observing practice, and also the relocation of the mast at Wellington Aero in 1993 and 1994, to be evaluated and thus reconcile important early region “W” gust records with more recent ones.

Another motivation is that the period from January 2013 to June 2018 has been notable for a high number of wind-related losses [\$828 M (2017 NZD) ([Fig. 2](#))] in New Zealand. This period included a very powerful southerly storm in June 2013 with sustained 10-min mean speeds of 28.6 m s^{-1} (103 km h^{-1}) and gusts reaching 38.9 m s^{-1} (140 km h^{-1}) at Wellington Aero that stripped vegetation from scrub, felled mature pine trees, and lifted roofs of several houses on exposed ridges. The storm in 2013 and the recent spate of other storms around the country, for example, three extratropical cyclones (Cook, Fehi, and Gita) that impacted New Zealand with severe winds in 2017 and 2018, have raised many questions from the local media, public, and engineers about whether this heightened activity is likely to continue because of climate change, and how “cyclical” it is. Unfortunately, in New Zealand, issues around station-mast moves, the need to accurately account for directional hill-shape effects, changes in instrumentation, recording methodology, instrument exposure, and undigitized records have made such questions difficult and/or too time-consuming to answer.

In trying to partially answer these questions for region W, an initial inspection of raw long-term wind records held in CLIDB (NIWA, CliFlo 2018) at Wellington Aero was done and the need to apply a robust homogenization procedure for this site was obvious ([Fig. 3](#)) because of the significant shift in the “raw” wind speed time series around 1993–94. [Figure 3](#) shows that while the June 2013 southerly was the worst in 25 years, it did not seem as strong as many northerly storms of either the mid-1970s or early 1990s and all were dwarfed by the 1968 Wahine storm [see [Revell and Gorman \(2003\)](#) for a description of that storm]. Factors that may have contributed to the ~1993 shift were the change in the anemometer type, from a heavy-cup Mark II Munro (hereafter, MK II) to a light Vaisala WAA151 cup anemometer, a change in data acquisition procedure, adoption of the WMO-recommended 3-s moving average for gusts ([WMO 2014](#)), a change in anemometer height from 11 to 7 m, and also a site relocation ([Fig. 4](#)). All these changes have resulted in an “apparent” but likely artificial drop of around 7 m s^{-1} in the average (1972–93 vs 1994–2017) annual maximum gust and an “apparent” drop of 4 m s^{-1} in the average (1972–93 vs 1994–2017) annual maximum 10-min mean speed (dashed lines in [Fig. 3](#)).

FIG. 1. Color-filled contour map of May 2014–Dec 2015 average daily maximum surface gust speeds (m s^{-1}) as estimated from 0300 UTC NZCSM +9- to +33-h forecasts. Directional wind roses are shown for three climate stations where winds are influenced by Cook Strait. The inset shows the location of Cook Strait within New Zealand, and the red cross marks the location of the NZCSM Cook Strait grid point referred to in the text.

The rest of this paper is organized as follows. A description of the observing stations and data used in this study is provided in section 2. In section 3 the homogenization procedure that eliminates the artificial shift and results in a more “realistic” time series (solid lines in Fig. 3) is described. In section 4, the computational fluid dynamics (CFD) modeling of turbulence environment and hill-shape effects, along with the larger-scale

numerical weather models New Zealand Convective-Scale Model (NZCSM) and NCEP–NCAR reanalysis are described. To provide a check on consistency and representativeness of the Wellington Aero records independent observational surface pressure records, wind records from Brothers Island (Fig. 1) and objective numerical weather model analyses were also examined and these comparisons are presented in section 5. In section 5, results are presented along with the comparison with other independent records and finally conclusions are presented in section 6.

2. Data

The mean and gust wind speed data presented in this paper are from Wellington Aero and Brothers Island, along with the pressure data from Paraparaumu Aero, Wellington Aero, Kaikoura, and Castlepoint. Key details about the sites, data availability, and sensor locations are provided in Tables 1 and 2.

Baring Head is another Cook Strait area station with wind records; however, neither peak gust information nor the direction of the gusts are recorded here, so it was unsuitable for the purposes of this study. Daily and hourly maximum gust speeds, 10-min mean speeds, and directions were extracted from CLIDB (NIWA, CliFlo 2018) for Wellington Airport for the period 1972–2017. For the same period, hourly surface pressure records for Paraparaumu Airport and Wellington Airport were obtained, and for southerly winds, the surface pressure

FIG. 2. Time series from Jan 1968 to Jul 2018 of insured losses (inflation adjusted to 2017 NZD) related to storm events where wind damage was a major factor (i.e., not counting storm events where losses were primarily due to flood or coastal erosion) contributing to losses. Loss numbers are from the NZ Insurance Council website (<http://www.icnz.org.nz/natural-disaster/historic-events>), and details assisting with the attribution to wind are from this website and also NIWA’s historic weather event website (hwce.niwa.co.nz).

FIG. 3. Time series of raw annual maximum 10-min mean wind speeds (black dotted line; 1972–2017), and the raw annual maximum wind gusts at Wellington Aero (1960–2017) classified by direction, where northerly (red dotted line with a black circle) is wind directed from either NW, N, or NE and the southerly (green dotted line with a black triangle) is directed from either SE, S, or SW. Also shown are the impacts of all the correction/homogenization (red and green solid line) procedures undertaken in this paper. Note that the 1960–71 gust records were taken from paper records of monthly maximum gusts. For the purposes of clarity, the gust curves have been artificially shifted by $+30 \text{ m s}^{-1}$ (N) and $+10 \text{ m s}^{-1}$ (S).

data from Castlepoint and Kaikoura were extracted for the period 1979–2017. All records were visually inspected and subjected to a robust homogenization algorithm to detect and remove low-quality data and

artificial shifts (section 3). Calibration dates were also inspected for step changes in gust and pressure parameters as well as for hourly wind records, and all found to be of good quality. Paper records of monthly maximum gusts at Wellington Aero were also obtained for the years 1960–71.

3. Homogenization process and quality control

One of the reasons for fewer wind speed trend analyses being conducted compared to other climate variables, such as temperature and precipitation, is the issue of data homogeneity (Pryor et al. 2009). Great variability of wind on all time scales and in three-dimensional space makes the analysis of this variable difficult compared to most other meteorological variables (Azorin-Molina et al. 2014). This is particularly true for gust wind speeds because they are extremely sensitive to the anemometer response characteristics (Miller et al. 2013). Using wind speed observations directly without homogenization and correction for these factors can introduce considerable errors on the order of 10%–40% in subsequent analyses (Masters et al. 2010; Powell et al. 1996; Safaei Pirooz et al. 2018). Therefore, it is essential to detect and eliminate all the breakpoints to ensure that time series are free of any artificial shifts or trends and reflects the real climatology as accurately as possible.

In the present study, initially the penalized maximal F test (PMFT) was performed on deseasonalized maximum

FIG. 4. Aerial image (Google EarthTM) of Wellington Airport showing the location of Wellington Aero anemometer masts prior to and after the 1993/94 airport redevelopment.

TABLE 1. Key details on the climate stations in this paper, including station name, NIWA climate database agent number, longitude, latitude, and comments. Note the datum for longitude and latitude is WGS84 and for Wellington Aero and Brothers Island the longitude and latitude are the coordinates of the anemometer masts.

Name	Agent No.	Longitude (°E)	Latitude (°S)	Comment
Wellington Aero	3445	174.8056	41.3314	Anemometer to west of runway and adjacent to road and seawall, gust records available from 1994 to the present, flat and open exposure, near sea level
Wellington Aero	3445	174.8114	41.3317	Anemometer on mast above terminal at airfield, gust records available from 1972 to 1993; monthly max records (paper) from 1960 to 1971
Brothers Island	4395	174.4419	41.1031	Anemometer on mast with base at 68 m adjacent to steep cliff of small rocky island, gust records available from 1997
Paraparaumu Aero	3145	174.984	40.907	Hourly pressure records available from 1961, flat and open exposure on ground near airfield, near sea level
Castlepoint	2591/2592	176.2118	40.9042	Hourly pressure records available from 1983 (gap from 1990 to 1993)
Kaikoura	4507/4506	173.691	42.421	Hourly pressure records available from 1979 (station moved in 1991)

daily and monthly average gust time series in order to detect the breakpoints (Wang 2008). Available metadata of stations were inspected to determine whether or not the detected breakpoints were caused by documented changes in the stations. Then the data were subjected to the proposed homogenization algorithm (section 3b).

a. PMFT

Various statistical approaches have been developed to detect documented and undocumented shifts. Reeves et al. (2007) conducted a comprehensive review of these methods and compared the performance of eight of them. They concluded that a common-trend two-phase regression model-based, maximal F test (Wang 2003) (TPR3) for detecting mean shifts in time series, was optimal for most climate data time series. TPR3 tests the null hypothesis [Eq. (1)] against the alternative hypothesis [Eq. (2)] to determine whether or not there is a mean shift μ at time k in the time series X_t with a linear trend β :

$$H_0: X_t = \mu + \beta t + \varepsilon_t, \quad t = 1, 2, \dots, N, \quad (1)$$

$$H_a: \begin{cases} X_t = \mu_1 + \beta t + \varepsilon_t, & t \leq k, \\ X_t = \mu_2 + \beta x_t + \varepsilon_t, & k - 1 \leq t \leq N, \end{cases} \quad (2)$$

where $\mu_1 \neq \mu_2$, and ε_t is an identically and independently distributed (IID) Gaussian variable of zero mean and unknown variance. (Wang 2003) showed that the most probable point at which the changepoint happens is the one associated with

$$F_{\max} = \max_{1 \leq k \leq N-1} F_c(k), \quad \text{where} \quad (3)$$

$$F_c(k) = \frac{\text{SSE}_0 - \text{SSE}_A}{\text{SSE}_A / (N - 3)}, \quad (4)$$

where SSE_0 and SSE_A are the sum of squared errors of H_0 and H_a , respectively.

Later, Wang et al. (2007) demonstrated that unequal sample sizes (i.e., number of data points before and after the breakpoints) results in an uneven distribution of the false alarm rate, and significantly affects the power of

TABLE 2. Key details about the wind and pressure sensors at the climate stations in this paper, including base elevation, height of sensor, and remarks.

Station	Parameter	Base elevation (m)	Height of sensor above base elevation (m)	Remarks
Wellington Aero	Wind speed	3	11 (prior 1993), 7 (present)	MK II/WAA151
	Wind direction	3	11 (prior 1993), 7 (present)	MKII/WAV151
	Pressure	4	2	Regular checks and well calibrated
Brothers Island	Wind speed	68	10	WAA151
	Wind direction	68	10	Damped potentiometer
Paraparaumu Aero	Pressure	5	2	Regular checks and well calibrated
Castlepoint	Pressure	4/120	Likely 2	Station shift in 1990 (SYNOP only prior to 1995, daytime SYNOP only prior to 1990)
Kaikoura	Pressure	108/105	Likely 2	Regular checks and well calibrated (SYNOP only prior to Dec 1991)

FIG. 5. Deseasonalized (a) raw daily maximum gusts and (b) monthly average of daily gusts for all directions as recorded at Wellington Aero from 1972 to 2017. The red trend line is the multiphase regression fit to the time series.

detection of TPR3, so that the test applies a lower level of confidence near the middle of the time series than the specified value. To eliminate these undesirable effects of the unequal sample size, Wang (2008) proposed a penalty function [Eq. (5)], in which the penalty factor, $P(k)$, was constructed empirically [for details, see Wang (2008)]:

$$PF_{\max} = \max_{1 \leq k \leq N-1} [P(k)F_c(k)]. \quad (5)$$

As a result, regardless of the location of breakpoints, PMFT performs at about the specified nominal level of confidence, which for this study is 0.95. Later, Wang and Feng (2013) developed a software package to perform PMFT. PMFT identifies a mean shift or breakpoint when the $PR_{\max}$ is greater than the critical value corresponding

to the nominal level of confidence, otherwise the time series is homogenous at the nominal level of confidence (Wang 2003, 2008).

To perform the test for the gust wind speed time series of Wellington Aero, the daily and average monthly data were initially deseasonalized by subtracting the data points from the average of each season over the whole period from 1972 to 2017. Figure 5 shows that at the Wellington Aero the only breakpoint at the 95% level of significance for both deseasonalized daily and monthly time series was detected in 1993, when the major changes took place at this station. In the case of Brothers Island, since the only factor that has affected the recorded wind speeds is the local hill, no breakpoints were detected in the time series. However, the mean of the gust speeds was shifted by

about 3.5 m s^{-1} because of the wind speedup caused by the hill (see [section 5b](#)).

b. Homogenization algorithm

[Figure 6](#) shows the homogenization algorithm used for computing correction factors that account for various systematic errors discussed in the previous sections.

Initially, the gust ($\hat{u}$) and 10-min mean ($\bar{U}$) wind speeds data are quality controlled and reduced. We exclude $\bar{U}$ with values of less than 5.5 m s^{-1} . Following the Pasquill stability class ([Pasquill 1961](#)) (after [Wieringa 1973](#); [Masters et al. 2010](#)) in the majority of conditions (i.e., day or nighttime, and cloud coverage), when $\bar{U}$ is greater than 5.5 m s^{-1} , the atmospheric boundary layer (ABL) is nearly neutral. In relatively strong winds, turbulence provides enough mixing in the ABL to suppress most thermal effects, thus the ABL can be treated as neutrally stable ([Cook 1985](#)). In addition, $\hat{u}$ values that are greater than $\bar{U}$ plus 5 times the standard deviation σ_u , are considered as noise or anomalous gusts ([Masters et al. 2010](#)), and are excluded from the analysis. Then, $\bar{U}$ and $\hat{u}$ are used to compute the gust factor (GF), turbulence intensity I_u and z_0 using Eqs. (6)–(8) ([Holmes 2015, 2017](#)),

$$\text{GF}(T, \tau, z, z_0) = \frac{\hat{U}(\tau, z, z_0)}{\bar{U}(T, z, z_0)} = 1 + g(T, \tau, z)I_u(z), \quad (6)$$

$$I_u(z) = 1/\ln(z/z_0), \quad \text{and} \quad (7)$$

$$z_0 = z \exp(-1/I_u), \quad (8)$$

where $g(T, \tau, z)$ is the peak factor [Eq. (11)] whose values for MKII and WAA151 were taken from the wind-tunnel results of [Safaei Pirooz and Flay \(2018b\)](#).

To be able to accurately analyze and compare the wind speed trends, and carry out further climatological studies, directional z_0 and measurement height z should be converted to common values. In this study, we converted all the recorded wind speeds to the equivalent wind speeds over an open-country terrain with a z_0 of 0.02 m ([Standards Australia/Standards New Zealand 2011](#)) and $z = 10 \text{ m}$. For this purpose, initially the friction velocity u_* based on each measured $\bar{U}$ were calculated using the logarithmic-law velocity profile [Eq. (9)], then the corresponding gradient wind speeds U_g were computed [Eq. (10)]. Since U_g is not affected by the surface roughness, it can be used as a reference to calculate the standard u_* over $z_0 = 0.02 \text{ m}$ [Eq. (10)]. Then, the calculated standard u_* , $z_0 = 0.02 \text{ m}$, and $z_0 = 10 \text{ m}$ are substituted in Eq. (9) to find the standard $\bar{U}$. The process is elaborated upon in [Irwin \(2006\)](#) and [Masters et al. \(2010\)](#).

$$U(z) = \frac{u_*}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) \right], \quad (9)$$

$$\frac{U_g}{u_*} = \frac{1}{\kappa} \left[\ln \left(\frac{u_*}{f z_0} \right) + 1 \right], \quad (10)$$

where κ is von Kármán's constant (0.4), and $f = 2\Omega \sin \phi$ is the Coriolis parameter. Last, dividing the standard $\bar{U}$ by the measured $\bar{U}$, the mean-speed correction factors can be obtained.

When analyzing gust wind speeds, the response characteristics of anemometers and the gust duration play essential roles. In New Zealand before the 1990s, mainly MKII anemometers with chart recorders were used and then replaced with light cup anemometers with digital recorders. Before the digital recording systems, the effective gust duration was only a function of the anemometer response, which for MKII was about 1 s ([Holmes et al. 2014](#)). However, since the 1990s, the WMO-recommended 3-s moving-average definition has been accepted and adopted by meteorological stations all over the world. These changes in the anemometer type and data acquisition process have had a significant effect on gust speed time series. To convert the gust data recorded by the previous measuring system to the equivalent AWS 3-s gusts, [Safaei Pirooz and Flay \(2018b\)](#) carried out wind-tunnel tests and computed peak factors [Eq. (11)] and gust factors [Eq. (6)] for these two measuring systems at various effective gust durations using random process and linear system theory ([Davenport 1964](#)). Knowing the peak factors g for MKII and WAA151 and using Eq. (6), the gust speed correction factors are calculated for this study:

$$g = \sqrt{2 \ln(vT)} + \frac{0.5772}{\sqrt{2 \ln(vT)}}, \quad (11)$$

$$v = \frac{\int_0^\infty f^2 S_u(f) df}{\int_0^\infty S_u(f) df}, \quad (12)$$

where v is the cycling rate, which is a characteristic frequency representing the width of the spectrum; f is frequency; $S_u(f)$ is the power spectral density of the longitudinal velocity component; and T is the observation period.

The possible effects of topography are considered carefully by investigating the photographs of mast locations, and also calculated directional z_0 , which are explained in detail in [sections 4a](#) and [5a](#). It has been demonstrated in previous studies that the topography

FIG. 6. A schematic diagram of the steps undertaken in the homogenization algorithm.

multipliers provided in wind-loading standards are not capable of accurately accounting for the wind speedup effects in complex terrain (e.g., [Safaei Pirooz and Flay 2018a](#); [Flay et al. 2015](#)). Therefore, here we eliminated all the major topography effects on anemometer

measurements using the high-resolution CFD simulation utilizing Gerris ([section 4a](#)).

Last, after applying the correction factors to the raw daily data, PTMF is performed again to test whether or not any other shifts remain. In the case of detection of

any remaining breakpoints, the quantile-matching (QM) adjustment algorithm (Wang et al. 2010) is used, which empirically matches the probability distributions of all segments (i.e., before and after the breakpoint) to adjust the shape of the distribution. Figure 6 summarizes the homogenization algorithm.

4. Models

Models that are used in this paper either to examine hill-shape effects (Gerris) or to describe larger-scale spatial patterns (NZCSM) or longer-term trends (NCEP–NCAR reanalysis) are described in this section.

a. Gerris

From the photograph of Brothers Island (Fig. 7a) the proximity of the mast to the steep cliff at the southern end of the island shows clearly that significant acceleration effects of the topography are likely and that the use of a CFD model capable of resolving flows around steep slopes such as Gerris (Popinet 2003) is needed. Gerris can also be used to model and understand the turbulence environment at mast locations. Figure 7b shows directional z_0 calculated for Wellington Aero at two mast locations, before and after 1993. As can be seen, there is a considerable difference between the z_0 values for the west and northwest directions at the new mast location (1994–2017). Here, the roughness length values are much higher than for 1972–93, considering that for these directions the wind flows over about 1 km of water (Lyll Bay) before reaching the mast (see Figs. 4 and 8). It seems that the hills located about 2 km to the west generate strong turbulent eddies in high wind conditions that can affect the gust speed measurements. Gerris is used to investigate whether, and to what extent, these hills influence the measurements at the new mast location.

Three-dimensional time-dependent simulation of flow over Brothers Island station was made using Gerris, which uses a time-varying adaptive grid to solve the Navier–Stokes equations. Gerris (Popinet 2003) is a CFD model that has performed well in the Bolund model intercomparisons (Bechmann et al. 2011) and in analyzing the role of channeling in a severe wind event on the west coast of the South Island (Turner et al. 2012), and for studies over exposed and complex terrain in New Zealand (King et al. 2012; Revell et al. 2015). The quad/octree finite-volume spatial discretization used in Gerris provides flexibility and allows accurate and efficient tracking of flow features.

For the Brothers Island simulation, the lower boundary is based on a digital terrain model (in

NZTM coordinates) with contours every 20 m in the vertical, as higher-resolution lidar data were not available for the island. A uniform flow of 10 m s^{-1} was set at the inlet of the computational domain. For the Wellington Aero simulation, the lower boundary was based on very high-resolution lidar data, which resolves features on scales down to less than a meter. At the inflow boundary a logarithmic wind profile of the form,

$$U = \frac{u_*}{\kappa} \left[\ln \left(\frac{z + z_0}{z_0} \right) \right] = 1.8111 \times \ln \left(\frac{z + 0.02}{0.02} \right), \quad (13)$$

was specified, with a roughness length of 0.02 m, friction velocity u_* of 0.724 m s^{-1} , and a speed of approximately 10 m s^{-1} at 5 m above the surface.

Figure 8 shows the simulation setup for a flow over Wellington Aero from the southwest showing the terrain, including the roughly 100-m-high hills to the west of Lyall Bay, the grid mesh and the mast location, all colored with the standard deviation of the wind speed. To generate the turbulent flows, a surface drag, which had been tuned to give best results in flows over the Belmont Hills at similar 5-m vertical resolution and 10-m horizontal resolution as described in (Revell et al. 2015), was applied at the lowest model level. The model was run for 30 simulated minutes and then values were sampled for a further 30 min to generate wind statistics.

b. NZCSM

Since 2014, NIWA has produced and verified (Carey-Smith and Andrews 2016) on a four-times-per-day cycle high-resolution convection-resolving NZCSM +36-h forecasts (+42 h since November 2015 and +48 h since July 2017). This numerical weather prediction model is a local configuration of the Met Office Unified Model, featuring a nonhydrostatic dynamical core (called New Dynamics and ENDGame from July 2017), semi-implicit time stepping and semi-Lagrangian advection and terrain-following vertical levels. The New Dynamics core is described in (Davies et al. 2005). The underlying orography used by NZCSM is created at the model resolution of 1.5 km from the Global Land One-kilometer Base Elevation (GLOBE) source dataset with a horizontal resolution of 1 km (GLOBE Task Team et al. 1999). The model orography is lower than in reality, because it requires smoothing to prevent numerical instabilities from arising because of overproduction of two grid length features during the course of the forecast. The forecast output includes maximum 3-s gust estimates for each 30-min period in the forecast. The gusts are diagnosed based on estimates of the

FIG. 7. (a) Photograph of Brothers Island and (b) effective roughness calculated for the Wellington Aero station at two mast locations before (dashed) and after (solid) 1993.

standard deviation of the horizontal wind σ_u from the mean 10-m-height speed. The gust diagnostic method is described in (Lock et al. 2017) with the key features being that the estimates depend on stability (Panofsky et al. 1977) and universal turbulence spectra (Beljaars 1987).

While the 4-yr period of NZCSM operations cannot be used for long-term trend analysis, the time series of maximum daily gusts at three locations, namely, Wellington Aero, Brothers Island, and Cook Strait (Fig. 1), are extracted from NZCSM and compared with the homogenized daily gusts of Wellington Aero and

Brothers Island, in order to provide a check on measured and modeled gust speeds in the most recent period of the time series and also aid the interpretation of results (section 5e).

c. NCEP–NCAR reanalysis

The NCEP–NCAR reanalysis project (Kalnay et al. 1996) uses a forecast system to perform data assimilation using data from 1948 to the present. The data assimilation is done by the recovery of climate data from various sources, such as land surface, satellites, ships, aircraft,

FIG. 8. View from the south of southern Wellington showing the local terrain, Lyall Bay, the grid, and the location of the wind mast at Wellington Airport, all colored with the standard deviation of the wind speed for a Gerris simulation with wind from the southwest direction. Blue colors correspond to less than 2 m s^{-1} , and red colors to more than 4 m s^{-1} for a logarithmic profile background wind speed of 10 m s^{-1} at a height of 5 m.

and other data. The recovered data are quality controlled and assimilated using a data assimilation system (more details in Kalnay et al. 1996). In this study, time series of surface pressure from NCEP–NCAR

Reanalysis 1 datasets were extracted for the nearest grid points to the north [Paraparaumu (P1); 40.0°S , 175.0°E] and south [Wellington Aero (P2); 42.5°S , 175.0°E] of Cook Strait, and also Kaikoura (P3: 42.5°S , 172.5°) and

FIG. 9. View from the southeast of South Wellington showing a SW-to-NE cross section through the wind mast at Wellington Airport with horizontal and vertical scales indicated. Colors correspond to the standard deviation of the wind speed for a Gerris simulation with wind from the southwest direction. Contours are every 0.5 m s^{-1} starting at 0.5 m s^{-1} at the uppermost contour, for a logarithmic profile background wind speed of 10 m s^{-1} at a height of 5 m.

TABLE 3. Directional mean and gust wind speed correction factors for Wellington Aero.

Direction	$\bar{U}$ correction factors		$\bar{u}$ correction factors	
	1972–93	1994–2017	1972–93	1994–2017
N	0.935	0.917	1.031	1.020
NE	1.026	0.964	0.983	1.003
E	1.120	0.998	1.175	1.070
SE	0.927	0.909	0.977	0.998
S	0.847	0.868	0.893	0.964
SW	0.779	0.825	0.863	0.949
W	1.032	0.952	1.237	1.093
NW	0.936	0.914	1.214	1.087

Castlepoint (P4: 40.0°S, 177.5°E) stations. The correlations between the larger-scale NCEP reanalysis pressure trends, pressure gradients between the pairs of stations, and homogenized gust wind speeds were obtained and are compared in [section 5c](#).

5. Results

a. CFD results

In the case of Brothers Island, the location of the mast was specified and horizontal (u and v) and vertical (w) components of the flow were generated at each time step, and while these fluctuated about initially they usually converged to steady state values (i.e., fluctuations about the mean of less than a few percent) after 500 time steps (around 2 min). Horizontal (2D) and 3D (i.e., including w) steady values were divided by the upwind speed at 10-m height to obtain the hill-shape multiplier for that direction, where the direction was varied by rotating the terrain in 10° increments from 0° to 350°. Accounting for the altitude of the anemometer being 78 m above the sea surface (which is the relevant terrain category in all directions as the island is only 150 m long) also has to be done to isolate the hill-shape effect. To do this, further division by factors of 1.27 [the $M_{z,cat}$ factor for 70-m-terrain category 1 from [Standards Australia/Standards New Zealand \(2011\)](#)—designated TopoZ] or 1.31 (using a power-law profile and assuming a value for α of 0.14—designated TopoP) were applied to the 2D and 3D steady-state values to obtain four sets of possible hill-shape multipliers for each 10° increment. Overall, the trends for each option were very similar, although clearly they were different by a constant factor depending on the choice of altitude adjustment factor. The incorporation of the vertical component tended to have a slight effect only, but was greatest for winds directed 90°–210° and this is not surprising given the proximity of the cliff in that sector. (The directional correction factors for the Brothers Island are shown in [Fig. 10](#).)

FIG. 10. Directional correction factors calculated for Brothers Island by CFD simulation using Gerris. The factors account for the wind speedup due to the steep hill where the mast is located.

One of the issues raised in the process of homogenization of the winds recorded at Wellington Aero, was the appropriateness of the terrain category specified upstream of the observation point. In the case of Wellington Aero when winds are from the westerly quarter an open-water category is used, because Lyall Bay extends over 1 km upstream. However, looking at the cross section in [Fig. 9](#), it is clear, in the Gerris runs at least, that the largest components of the turbulence experienced at the mast site are generated by shedding of eddies by the 100-m-high hills on the western side of Lyall Bay rather than locally—so a slightly larger roughness length may be more appropriate. The Gerris results for winds from north and northwest are consistent with the values calculated using the recorded gust and mean wind speeds [Eq. (8) and [Fig. 7b](#)].

b. Homogenized data

The correction factors for wind speeds are computed using the homogenization algorithm, and the results for the Wellington Aero and Brothers Island stations are shown in [Table 3](#) and [Fig. 10](#), respectively. These factors are applied to the raw maximum daily gusts to produce homogenized time series, and the results for Wellington Aero and Brothers Island are shown in [Figs. 11](#) and [12](#), respectively. The computed correction factors demonstrated that not compensating for the systematic errors in the wind speed measurements and topography effects can cause significant errors of over 40% (Brothers Island) and 20% (Wellington Aero).

FIG. 11. Wellington Aero homogenized time series of (a) daily anomalies and (b) monthly average of maximum daily gusts anomalies. The dashed trend lines are the linear regression fits to the time series.

Figure 11 shows both raw and homogenized time series of the deseasonalized maximum daily and monthly average of maximum daily gust speeds from Wellington Aero. It can be seen that the homogenization algorithm successfully eliminated the breakpoints in the time series in the 1990s, mainly caused by the site relocation, instrument changeover, and adaptation of WMO 3-s-gust definition. Therefore, the artificial trend resulting from the breakpoint in the gust time series was also removed, and the homogenized time series were produced reflecting the real change in the gust wind speed trend.

In the case of Brothers Island, there has not been any major change in the location of the mast and instrumentations, thus there are no breakpoints in the time series as shown in Fig. 12. However, the wind speedup due to the

presence of the steep hill has resulted in overestimation of gust speeds by about 3.5 m s^{-1} .

The results of the homogenization show that the proposed algorithm detected and eliminated all the artificial breakpoints in the time series and removed the effects of topography. In all the following sections, the homogenized data are used for analyses.

c. Gust speed trend and pressure gradients

Local pressure records can be used to check for consistency of the gust records because the strong channeling effect of Cook Strait results in a robust relationship between northerly gusts at Wellington Aero and positive pressure gradients between Paraparaumu Aero and Wellington Aero (Reid 1996) (Fig. 13a), and also between southerly gusts at Wellington Aero and positive

FIG. 12. Brothers Island homogenized time series of (a) maximum daily gusts (solid darker lines are 30-point moving averages) and (b) monthly average of maximum daily gusts and similar curves for Wellington Aero over the same period (solid darker lines are 12-point moving averages).

pressure gradients between the Kaikoura and Castlepoint stations (Fig. 13b). For all days with a maximum daily gust being northerly at Wellington Aero, the maximum hourly pressure difference between the Paraparaumu and Wellington Aero stations within that day was calculated. A scatterplot of the maximum daily 3-s gust speed at Wellington Aero for northerlies versus the coincident daily maximum hourly pressure difference (hPa) between Paraparaumu Aero and Wellington Aero station pressures is given in Fig. 13a and this confirms the strong relationship for northerlies with an r^2 value of 0.704 obtained for the whole period, r^2 values of 0.678 and 0.773 were obtained for the pre-1993 and post-1994 periods, respectively. Note that the scatter is much greater ($r^2 = 0.061$) and the relationship is weaker for southerlies (not shown) so the Paraparaumu–Wellington pressure

gradient cannot be exploited to confirm trends in southerly gusts. However, pressure gradients between Kaikoura and Castlepoint stations were used and are well correlated with the southerly gust speeds at Wellington Aero. As can be seen in Fig. 13b, the correlation between the daily maximum southerly gusts at Wellington Aero and the pressure gradient (Kaikoura–Castlepoint) had r^2 values of 0.508 and 0.629 before and after 1993, respectively. Graphically, there appears to be a shift left (i.e., a decrease in pressure gradient for the same gust speeds of around 0.8 hPa) for the early period that is likely an artifact of an undersampling of hourly pressure gradients in determining the daily maximum. This undersampling is due to there being only a few daytime synoptic (SYNOP) (0600, 0900, 1200, 1800 UTC) MSLP observations available for Castlepoint prior to around 1990. Note, full SYNOP (3 hourly)

FIG. 13. Correlation between the maximum daily gusts and pressure gradients. (a) Northerly maximum daily gust speeds at Wellington Aero vs the coincident daily maximum hourly pressure difference (hPa) between Paraparaumu Aero and Wellington Aero for the period from 1972 to 2017. (b) Southerly maximum daily gust speeds at Wellington Aero vs the coincident daily maximum hourly pressure difference (hPa) between Kaikoura and Castlepoint for the period from 1979 to 2017.

records were available in the period 1990–95 and hourly thereafter (see remarks in Table 2).

Figure 14a compares the time series of northerly daily maximum gust speeds and the corresponding pressure gradients between Paraparaumu and Wellington Aero calculated from the recorded data at these stations.

From an inspection of the surface pressure data for days with a maximum daily gust being northerly at Wellington Aero there was found to be a drop in the average pressure difference of 0.395 hPa (2.688–2.292 hPa) (Paraparaumu minus Wellington Aero) between the periods of 1972–93 and 1994–2017. For

FIG. 14. (a) Time series for the period from 1972 to 2017 of northerly daily maximum gust speeds at Wellington Aero (blue line; darker line is the 12-point moving average) and daily maximum pressure difference between Paraparaumu Aero and Wellington Aero (yellow line; darker line is 12-point moving average). (b) Time series for the period from 1979 to 2017 of southerly daily maximum gust speeds at Wellington Aero (blue; darker line is the 12-point moving average) and daily maximum pressure difference between Kaikoura and Castlepoint (yellow; darker line is 12-point moving average).

the same period the change in the average of northerly gusts was about -0.131 m s^{-1} . In the southerly case (Fig. 14b); the average pressure difference (Kaikoura minus Castlepoint) recorded after 1993 has decreased by 0.25 hPa compared to the period of 1983–92 (if it is accepted that the 0.8-hPa shift left is an artifact of the undersampling prior to 1995). This would be consistent with the average of southerly daily maximum gust speeds decreasing by 0.186 m s^{-1} (1979–93 vs 1994–2017). For both northerly and southerly cases, the relationships between the daily gusts and pressure gradients are strong, particularly for data recorded after 1993.

Further comparisons were made by comparing the monthly averages of daily maximum gust wind speeds and pressure gradients calculated using station data and also NCEP data in Fig. 15, with the darker lines showing 12-point moving averages of the parameters. Figure 15a illustrates that the monthly average of maximum northerly gust speeds at Wellington Aero agree well with the monthly average of maximum pressure difference between Paraparaumu and Wellington, and also NCEP data (P1–P2; see Fig. 1 inset for locations) for the period from 1972 to 2017, with r^2 values of 0.632 and 0.483, respectively. However, this agreement is more obvious for data recorded after 1987, with r^2

FIG. 15. Time series of monthly average of maximum gust anomalies at Wellington Aero (dark blue line is a 12-point moving average), monthly average anomalies of the mean sea level pressure difference (green line), and monthly average of the larger-scale NCEP surface pressure difference (yellow line). (a) Northerly gust speeds and pressure differences between Paraparaumu and Wellington from 1972 to 2017. (b) Southerly gusts and pressure differences between Kaikoura and Castlepoint from 1979 to 2017.

values between the monthly average of maximum northerly gust speeds and pressure gradient, and NCEP data being 0.848 and 0.559, respectively. Before this date, there is a slight difference between wind speeds and pressure gradients. On examination of the site histories, it was found out that the barometers at both Paraparaumu and Wellington stations were replaced in 1987, which could explain the difference between the wind speeds and the pressure gradients recorded prior to this date.

The comparison between the monthly averages of daily maximum southerly gust wind speeds at Wellington Aero and the corresponding pressure gradients obtained using data from Kaikoura and Castlepoint stations, and NCEP data (P3–P4; see

Fig. 1 inset), is shown in Fig. 15b. There is a good agreement between the wind speed and pressure gradient trends with an r^2 value of 0.559 and also between the wind speed and NCEP data with an r^2 of 0.399. These relationships are even stronger for data recorded after 1993 when the barometers were replaced at the stations (r^2 between the southerly wind speeds and pressure gradient is 0.675 and r^2 between the wind speeds and NCEP is 0.411). Overall, in both the northerly and southerly cases, excellent agreements were achieved between the trends of wind speeds and pressure gradients, and the results were also consistent with the larger-scale pressure data obtained from the NCEP reanalysis database.

FIG. 16. Average hourly variation of mean sea level pressure for the period from 1972 to 2017 at Paraparaumu Aero and Wellington Aero for the period after 1993 (dotted) and for the period prior to 1993 (dashed).

Figure 16 also illustrates how overall pressures have increased over the region by around 0.5 hPa over the last 20 years compared to the 20 years prior. Figure 16 also confirms that any changes in daily maximum gusts are not due to any potential changes in diurnal patterns.

d. Trend in magnitudes and frequencies of maximum daily gusts

Here we briefly present the trends of two parameters of maximum gusts recorded at Wellington Aero: 1) the magnitude of annual and seasonal average of maximum daily gust speeds; 2) the annual and seasonal frequencies of maximum daily gusts exceeding the 90th, 95th, and 99th percentiles of the whole period (1972–2017), which are 23.5, 26.13, and 31.09 m s^{-1} , respectively. Figures 17 and 18 show the trends in magnitudes and frequencies, respectively.

Although there is a slight increase ($0.063 \text{ m s}^{-1} \text{ decade}^{-1}$) in the magnitude of the annual average of daily gusts (Fig. 17a), the annual occurrence of extreme wind gusts (Fig. 18a) has decreased by 1.2 days decade^{-1} (90th percentile), 0.9 days decade^{-1} (95th percentile), and 0.2 days decade^{-1} (99th percentile). Seasonally, in spring there is an increasing trend in both magnitude ($0.192 \text{ m s}^{-1} \text{ decade}^{-1}$) and occurrence of extreme winds (0.45, 0.35, and 0.002 days decade^{-1} in the 90th, 95th, and 99th percentiles, respectively). While the magnitudes of average of maximum daily gusts have remained almost constant in summer, autumn, and winter. The frequencies of occurrence of extreme gust winds in autumn and winter decreased by 0.8 and 0.5 days decade^{-1} at the 90th percentile, respectively. However, in summer

the frequency of occurrence of extremes remained almost the same for the 95th and 99th percentiles over the whole period, and in the 90th percentile there is a slight decrease in the frequency of the extreme winds ($0.28 \text{ days decade}^{-1}$). It is interesting that our limited analysis presented here supports a small decreasing trend in extreme gust speeds noted by Azorin-Molina et al. (2016) who briefly reviewed global gust wind speed trends.

e. Comparison with NZCSM

Maximum daily gust wind speeds predicted by NZCSM at three locations, namely, Wellington Aero, Brothers Island, and Cook Strait (Fig. 1) for the period from 1 June 2014 to 28 February 2018, were compared and correlated with the homogenized data from Wellington Aero and Brothers Island. The results of the correlations along with the root-mean-square errors (RMSE) are summarized in Table 4.

As can be seen in Table 4, very strong correlations, which are mainly above 0.75, were found between the NZCSM predictions and the homogenized data. The high correlations between the NZCSM values at Cook Strait (open/exposed location) and Wellington Aero and between Cook Strait and Brothers Island (0.756 and 0.821, respectively), along with similar trends and low RMSE values demonstrate that NZCSM has provided daily gust speed predictions that are in a good agreement with the measured wind speeds. The relatively low correlation between Wellington Aero NZCSM values and homogenized data (0.597) is due to the fact that the

FIG. 17. Annual and seasonal average of maximum daily gust speeds for Wellington Aero from 1972 to 2017. Dashed lines are the linear regression lines.

FIG. 18. Annual and seasonal number of days exceeding the 90th, 95th, and 99th percentiles for Wellington from 1972 to 2017. Dot-dashed lines are the linear regression lines.

TABLE 4. Correlations between the predictions of NZCSM at three locations, namely, Wellington Aero, Brothers Island, and Cook Strait (Fig. 1), and homogenized maximum daily gusts at Wellington Aero (Wgtn Aero) and Brothers Island (Bros). Numbers in the parentheses are root-mean-square errors (m s^{-1}).

	NZCSM Cook Strait	NZCSM Wgtn Aero	NZCSM Bros Island	Wgtn Aero homogenized	Bros Island homogenized
NZCSM Cook Strait	1				
NZCSM Wgtn Aero	0.840	1			
NZCSM Bros	0.907	0.869	1		
Wgtn Aero, homogenized	0.756 (3.81)	0.597 (4.70)	0.777 (3.98)	1	
Bros Island, homogenized	0.821 (3.07)	0.721 (3.78)	0.784 (3.46)	0.862	1

homogenization algorithm removes the local features and converts the effective roughness to a common value (i.e., 0.02 m). While, NZCSM, because of its high-resolution grid size (1.5 km), can account for topographic and land-use variations at that scale in its predictions. However, for wind trend and extreme value analyses, it is preferable to convert the measurements to a common standard, which the proposed homogenization algorithm has successfully done. This can also be seen in the high correlation (0.862) between the homogenized data from Brothers Island and Wellington Aero.

Figure 19 compares the time series of homogenized maximum daily gusts at Wellington Aero with NZCSM predictions at Cook Strait (Fig. 19a), and at the Wellington Aero location (Fig. 19b). The RMSE values between the homogenized maximum daily gusts at Wellington Aero, and NZCSM predictions at Cook Strait and at the Wellington Aero location are 3.81 and 4.7 m s^{-1} , respectively. It is clear that the overall trends of maximum daily gusts agree well, and NZCSM provides good predictions of maximum daily gust wind speeds here.

6. Conclusions

This paper has described a homogenization algorithm that compensates for the topography effects and the systematic errors affecting the anemometer measurements, using statistical approaches and high-resolution numerical simulations. The algorithm has been applied to homogenize the wind speeds recorded in the Cook Strait region of New Zealand and study the gust climatology of this region.

The homogenization process detected and eliminated all breakpoints in the time series resulting from changes in instrumentation and data acquisition procedures, site relocation, measurement height, and local topography features. The directional effective roughness lengths were computed, showing that at a station

the effective roughness could vary considerably by direction. A three-dimensional time-dependent CFD simulation using Gerris was carried out to investigate the effects of local topography on anemometer measurements and also to compute correction factors accounting for the wind speedup effects on Brothers Island. As shown in this study, at Wellington Aero, despite the wind flowing over about 1 km of water from the westerly direction, the effective roughness is much higher than what can be estimated by looking at the map because of the effects of hills located around 2 km away from the mast. The calculated roughness lengths were therefore used to adjust the speeds to a standard category 2 terrain roughness (Standards Australia/Standards New Zealand 2011) that allowed a more realistic and accurate regional wind climate to be determined, which was free of artificial and local terrain effects. The homogenization results showed that not correcting for the measuring system, surrounding roughness and topography and site relocation introduced errors on the order of 20%–40%.

Annual and seasonal trends in the magnitudes of average of maximum daily gusts, and frequencies of occurrence of extreme winds were also investigated. Annually, a small overall increasing trend (1972–2017) in the magnitude of average of maximum daily gusts was found, while for the annual maximum gusts a slight overall decreasing trend was noted for the period 1960–2017 (Fig. 3). More frequent and increasing daily gusts occurred in spring, while the magnitudes of average of daily gusts have remained nearly constant in other seasons. Also, the frequency of extreme winds in summer, autumn, and winter decreased over the considered period.

The predictions of a high-resolution convection-resolving numerical weather prediction model (NZCSM) for the period from 2014 to 2018, were compared and correlated to the homogenized data from the Wellington Aero and Brothers Island stations. Strong correlations between the homogenized data and NZCSM

FIG. 19. Comparison between the maximum daily gusts predicted by the high-resolution weather prediction model (NZCSM) and the homogenized daily gusts recorded at Wellington Aero for the period from 1 Jun 2014 to 28 Feb 2018. The darker lines are 30-point moving averages. The NZCSM predictions are at (a) an exposed-over-sea point in Cook Strait (the correlation and RMSE values are 0.759 and 3.81 m s^{-1} , respectively) and (b) the mast location of Wellington Aero (the correlation and RMSE values are 0.597 and 4.7 m s^{-1} , respectively).

predictions were achieved, showing that NZCSM is capable of predicting the daily gusts with high accuracy, and also demonstrating that the homogenization algorithm successfully removed all the local topography effects. Also, to ensure the consistency and representativeness of the obtained gust wind speed trends, gust wind speeds were compared with the pressure field across the Cook Strait region and also larger-scale NCEP–NCAR reanalysis pressure trends.

The method of reconstruction and homogenization algorithm can be applied to other sites in complex terrain to create synthetic gust climatologies from reanalysis datasets or to remove local terrain effects from existing observations in order to establish improved

regional design wind speeds and understand long-term wind speed trends.

The work reported here is now being extended to homogenize the long-term wind data records for many more stations across New Zealand, and this will allow for the investigation of national trends in mean, annual, and seasonal extreme wind speeds, and a comparison with global trends as reviewed by [McVicar et al. \(2012\)](#), who reviewed mean speeds, and [Azorin-Molina et al. \(2016\)](#), who briefly reviewed global gust speed trends.

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