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High-resolution mesoscale wind-resource assessment of Fiji using the Weather Research and Forecasting (WRF) model

Kunal K. Dayal^{1*}, Gilles Bellon², John E. Cater³, Michael J. Kingan¹, and Rajnish N. Sharma¹

¹ Department of Mechanical Engineering, University of Auckland, Auckland 1023, New Zealand.
Email: kday202@aucklanduni.ac.nz

² Department of Physics, University of Auckland, Auckland 1010, New Zealand.

³ Department of Engineering Science, University of Auckland, Auckland 1010, New Zealand.

Abstract

This study presents a high-resolution mesoscale wind-resource assessment of the small island developing state (SIDS) of Fiji using a 10-year simulation of the Weather Research and Forecasting (WRF) model with convection-permitting resolution. Our analysis evaluates the wind speed and Weibull distributions, diurnal and seasonal wind speed patterns, resource maps of annual and seasonal wind speed, power density, model statistical analysis and interannual wind speed variability. The results reveal that the WRF-model simulated wind resource parameters are in good agreement with observations at 24 existing weather stations. At 55 m above ground, the annual mean wind speed and wind power density varies from 1.5 m/s to 8 m/s and 50 W/m² to 300 W/m², respectively, for onshore land areas. Higher wind speeds are observed during austral winter than in austral summer. Forty high wind-resource areas are identified in this study, which were previously unknown. This indicates that there is potential for utility-scale wind power generation at selected locations with wind speed and power density greater than 6.4 m/s and 300 W/m² (NREL, Wind Power Class 3). An estimated 1000 MW theoretical potential installed capacity is available for utility-scale wind power applications on Viti Levu and Vanua Levu.

Key words:

Wind energy, resource assessment, Wind power, WRF, Fiji

1. Introduction

Climate change and air pollution have propelled a steady growth of renewable electrical energy generation, and in particular wind energy on the global scale. Over the last decade, the global installed capacity of wind energy grew from 159 GW in 2009 to 651 GW in 2019 [1, 2]. This is an exponential growth with an estimated doubling time of approximately 4 years.

Moreover, work is in progress in many countries with new resource assessments, wind farm construction permits and developments [1, 2].

Wind-resource assessment at different scales is fundamental for energy-resource modelling and site identification for the development of wind farms to support renewable electricity generation. Numerous methods are available for wind-resource assessment from microscale to mesoscale applications with each having its own benefits and disadvantages [3]. For microscale wind-resource assessment of a specific site or location within a domain of 10 – 20 km, microscale linear models like the Wind Atlas Analysis and Application Program (WAsP) are used. The model uses ground-based measured wind data for wind resource evaluation and resource mapping at a resolution of 50 m $\times$ 50 m or less within the domain around a site [3]. For regional wind-resource assessment of a country or a group of islands, numerical models can be used to simulate the wind-resource for the region of study [3]. The most common numerical weather prediction (NWP) model used for atmospheric studies, which includes resource mapping, is the Weather Research and Forecasting (WRF) model [4]. The usefulness of the WRF model is its ability to simulate the atmospheric processes from the ground level to the stratosphere 20 km above. It provides an approximation of the surface atmospheric parameters like surface winds. It also has the advantage of generating mesoscale wind resource maps at different heights for resource identification, theoretical potential evaluation and for creating high-resolution wind data at km scale at locations whereby measurements are not available.

The WRF model has been used for wind energy resource mapping in Palestine [5], assessing wind resource in Greece [6], modelling wind resource in complex terrain in Portugal [7], determining wind power characteristics of Oahu, Hawaii [8], assessing offshore wind resource off the Atlantic Iberian coast and in the Gulf of Thailand [9, 10] and for predicting wind energy resources in Tanzania [11]. In these studies, the model assisted in creating new knowledge about mesoscale wind resources and their characteristics, identified and classified the wind-resource sites and provided useful information for power generation purposes. To date, most downscaling studies for atmospheric parameters have been conducted in the mid-latitude regions of the Northern Hemisphere and relatively few have examined semi-arid or tropical locations in the Southern Hemisphere.

Fiji is a small island developing state (SIDS), which is located between the latitudes of 12°S – 22°S and longitudes of 177°E – 178°W in the tropical Southwest Pacific region. There are 332 islands in Fiji with a total land area of 18,333 km², with 110 islands inhabited. Around 87

% of the total land area is occupied by the two largest islands of Viti Levu and Vanua Levu, with areas of approximately 10,400 km² and 5,540 km², respectively. The islands of Fiji are mountainous and of volcanic origin, with maximum altitude of 1300 m above mean sea level. The overall climate in Fiji is categorized as a tropical marine climate with two seasons, which are classified as austral summer (wet season) extending from November to April and austral winter (dry season) from May to October.

In Fiji, electricity generation is from a mixture of renewable (hydro, biomass and wind) and conventional (industrial diesel and heavy fuel oil) power stations [12]. In the year 2019, 1060 GWh of electricity was generated with 58 % (611 GWh) from renewable and 42 % (450 GWh) from conventional power plants. The specific contribution from renewable energy-based power plants include: 53 % (559 GWh) from hydropower, 4.6 % (49 GWh) from biomass-based independent power producers and 0.25 % (2.7 GWh) from wind [12]. Fiji aims to achieve 100 % electricity generation from renewable energy sources by 2030 [13]. The extent to which wind electricity generation can contribute to this goal is unknown. Mapping wind resources on the mesoscale level will assist the SIDS of Fiji in terms of wind resource identification and quantification.

Several wind-resource assessment studies have been conducted in Fiji using the Wind Atlas Analysis and Application Program (WAsP) [14 - 21] and WindPRO [22]. These studies are confined to micro-scale locations covering small areas surrounding a measuring station in the range of 5 – 10 km². Moreover, a recent study in Fiji using 5 – 6 years of measured automatic weather station wind data in WAsP identified three potential wind farm sites that can be further investigated for utility-scale wind power applications. The WAsP modelling revealed that each of these three sites could incorporate a minimum of 10 MW using Vergnet 275-kW wind turbines to support the electricity grid network [23]. To the knowledge of the authors, to date, no validated mesoscale wind-resource assessment has been carried out for the SIDS of Fiji.

Previous studies on the evaluation of the WRF model for simulating surface winds and the diurnal cycle of wind speed for the SIDS of Fiji showed that the standard 1.33 km by 1.33 km grid resolution in a 20 km – 4 km – 1.33 km grid nesting set up may not be an appropriate grid size to evaluate the surface winds for Fiji; as it was suspected that the topography was not properly resolved and a grid sensitivity study was recommended [24]. Following that recommendation, a grid sensitivity study of the WRF model for simulating the surface winds for the SIDS of Fiji was conducted and it was concluded that the 1 km by 1 km grid

resolution of the 15 km – 5 km – 1 km grid configuration was appropriate to evaluate the wind resources for the SIDS of Fiji [25].

In this paper, we aim to answer two research questions:

- I. Can the Weather Research and Forecasting (WRF) model be used to simulate the wind flow around the Fijian Islands in order to get sufficiently accurate information on the wind resources/potential?
- II. Do the WRF simulations reveal sites that are promising for wind power that have not yet been identified?

This paper is an enhancement of the WRF mesoscale wind resource assessment approach applied to small tropical islands from an initial study [24] followed by a grid sensitivity study [25] to finally, the decade-long mesoscale wind resource assessment of Fiji. This study is also an application and evaluation of the mesoscale wind resource modelling using the WRF model.

Therefore, we present the high-resolution mesoscale wind-resource assessment of the SIDS of Fiji, which includes the analysis of the wind speed and the Weibull distributions, diurnal and annual wind speed patterns, resource maps for wind speed and power density. The study also presents the 10-year annual variability of wind speed and the model validation against ground-based observations via a model statistical analysis. The purpose of this study is to test a methodology to assess mesoscale wind-resource on tropical islands and to provide an assessment of the wind-resource in Fiji. Section 2 of this work describes the methodology, the results are presented in section 3, then discussed in section 4 and the conclusions are presented in section 5.

2. Methodology

2.1 Study area and wind measuring stations

Figure 1 shows the model topographical height contours at a resolution of 30-arc-seconds for the study area, which covers the larger islands and the smaller islands in the surrounding waters and is marked with the locations of 24 automatic weather stations (AWSs) of Fiji Meteorological Services. Time series and uninterrupted measured wind data is available for 3 years (2016 – 2018) from the 24 AWSs at an elevation of 10 m above ground level. This data is used for the model validation exercise for the surface winds.

The individual station locations are shown in Figure 1, where fourteen stations are located on Viti Levu, five on Vanua Levu and five on the outer islands. Eleven stations are located on the leeward side of the two larger islands: Keiyasi, Labasa, Momi, Nadarivatu, Nadi, Rakiraki, Rarawai, Seaqaqa, Sigatoka, Wainikoro and Yaqara stations. Eight stations are located on the windward side of the two larger islands: Korolevu, Lomaivuna, Nausori, RKS Lovoni, Saqani, Suva, Tokotoko and Udu stations. The five stations located on the outer islands are Koro Island, Levuka, Viwa, Vunisea and Yasawa stations.

Figure 1. Topographical map of the study area (Fiji) with the locations of the AWSs.

A summary of the characteristics of the AWSs from which the wind observations are retrieved is shown in Table 1. The elevation of the AWSs is given in metres above sea level (m a.s.l.). The model terrain elevation of each AWS is the 1 km $\times$ 1 km grid cell average taken from the grid cell in which the AWS is located.

Table 1. Details and position of AWSs.

Station Name	Latitude (° S)	Longitude (° E)	Elevation (m a.s.l.)	WRF Elevation (m a.s.l.)
Keiyasi	-17.8795	177.7552	89.8	63.7
Koro Island	-17.3450	179.4184	108.8	80.1
Korolevu	-18.2129	177.7304	25.7	41.5
Labasa	-16.4333	179.4000	8.5	13.1
Levuka	-17.6403	178.8186	41.5	43.1
Lomaivuna	-17.8714	178.3601	122.1	128.5
Momi	-17.8952	177.2668	43.8	25.9
Nadarivatu	-17.5676	177.9632	824.1	761.8
Nadi	-17.7599	177.4448	20.7	14.9
Nausori	-18.0464	178.5591	5.7	4.9
Rakiraki	-17.3404	178.2214	8.1	3.4
Rarawai	-17.5564	177.6814	9.3	17.0
RKS Lovoni	-17.7260	178.5551	17.1	14.1
Saqani	-16.4749	179.7089	30.0	43.2
Seaqaqa	-16.4758	179.1578	101.8	109.5
Sigatoka	-18.1422	177.5039	6.7	12.0
Suva	-18.1475	178.4536	6.6	15.6
Tokotoko	-18.2186	178.1700	4.9	6.2
Udu	-16.1411	-179.9947	43.7	0.3
Viwa	-17.1494	176.9117	2.0	1.0
Vunisea	-19.0469	178.1654	31.9	86.3
Wainikoro	-16.3044	179.5586	15.1	15.3
Yaqara	-17.4330	177.9774	20.0	11.2
Yasawa	-16.6984	177.5746	40.0	5.1

2.2 Model and simulation set-up

The study uses the Weather Research and Forecasting (WRF) model version 3.9.1.1 of the Advanced Research (ARW) solver, a widely used community mesoscale model developed by the National Centre for Atmospheric Research (NCAR) [26, 27]. The dynamical downscaling method was used for running simulations, whereby coarse resolution output from an analysis using a General Circulation Model (GCM) are used as initial and boundary conditions to drive a regional numerical model to simulate atmospheric parameters via nesting, considering the local conditions [28 - 30].

The initial and boundary conditions for the SIDS of Fiji were obtained from 6-hourly NCEP-FNL (Final) Operational Global Analysis data at 1° $\times$ 1° grid resolution [31]. The static

fields for the topography were obtained from the USGS GMTED2010 dataset. The land-water masks, land use/land cover classification, albedo etc. were obtained and interpolated from the 21-class MODIS and MODIS FPAR. These were taken from the National Center for Atmospheric Research (NCAR) database, at a resolution of 30-arc-seconds [32]. Time varying sea surface temperatures (SSTs) were supplied to the model from NCEP-NOAA at a grid resolution $0.083^\circ \times 0.083^\circ$ [33].

The input data from NCEP-FNL were downscaled by the WRF model using three nested domains as illustrated in Figure 2. The outermost domain is referred to as d01, the second d02 and the innermost as d03 (which is also the domain shown in Figure 1).

Figure 2. Simulation domains.

The two-way nesting approach was applied for the parent-child grid interaction, where the flow of information goes from the coarser domain to the finer domain, with feedback from the inner domains. All domains are centred at a latitude of 17.73°S and longitude of

177.94°E, which corresponds to the centre of Viti Levu using the Mercator projection as recommended for low latitudes [26, 27].

The spatial coverage of each of the three domains are: d01 = 1500 km × 1500 km (100 × 100 grid cells), d02 = 755 km × 755 km (151 × 151 grid cells) and d03 = 401 km × 401 km (401 × 401 grid cells) at a horizontal resolution of 15 km × 15 km, 5 km × 5 km and 1 km × 1 km, respectively. The vertical spacing of the three domains consist of 30 terrain-following vertical coordinates, including eight levels below 1 km, as meteorological parameters of interest are in the lower part of the atmosphere, close to the surface. A timestep of 10 seconds is used in d03 following a 3:1 parent-child grid timestep ratio to ensure numerical stability as recommended in refs. [26 and 27]. The choice of 15 km – 5 km – 1 km nested grids follows the recommendation of the earlier grid sensitivity study [24], in keeping with the standard practice of using a 3:1 or 5:1 parent-grid ratio [26, 27].

The well-tested tropical suite of the WRF physics parameterization scheme was used for the model physics options [26, 27]. The parameterization of deep convection was only used on the larger domains (d01 and d02), as the vertical fluxes due to convection updrafts and downdrafts and the compensating motion outside the clouds cannot be resolved explicitly at grid scales of 5 km and above [26, 27]. The remaining physics options are the same for all three domains as shown in Table 2.

Table 2. Physics Parameterization

Parameterization Options	
Long-wave radiation	RRTMG
Short-wave radiation	RRTMG
Microphysics	WRF Single-Moment 6-class
Surface Layer	MM5 Similarity
Planetary Boundary Layer	Yonsei University
Cumulus	New Tiedtke
Land Surface Model	Noah

Simulations for the 10 years were performed in monthly segments on the New Zealand eScience Infrastructure (NeSI) High Performance Computer – Mahuika. The model was initiated from 3 days prior to the start of each month and these 3 days are the model spin-up time and are excluded from the analysis. The model is set to restart every 2 days to avoid model drift as recommended for longer simulations [26, 27]. Even though a period of one year has been considered adequate to capture the diurnal and seasonal variations for wind resource assessment [34], in our case, we use 10 years of simulations to provide a better

representation of the diurnal and seasonal variations. The simulation results discussed in the paper are 1-hourly 10-metre-elevation wind speeds retrieved from the simulation on the innermost domain (d03) considering the grid cell containing the AWS as representative of the station.

2.3 Model Validation

The validation of a numerical weather prediction (NWP) model can be done according to various methodologies that complement each other [35]. Five statistical parameters are used for the model evaluation. The Root Mean Square Error (RMSE) is defined as:

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2 \right]^{\frac{1}{2}}, \quad (1)$$

in which M_i is the simulated variable at the i^{th} data point, O_i is the corresponding observed variable and N is the total number of simulation-observation pairs of values.

The mean Bias was used for the evaluation of data tendency. A positive (negative) bias means the simulations overestimate (underestimate) the measured values:

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (M_i - O_i). \quad (2)$$

The Standard Deviation Error (STDE) was used to evaluate the dispersion of the error between the observed and the simulated data:

$$\text{STDE} = \left[\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2 - \text{Bias}^2 \right]^{\frac{1}{2}}. \quad (3)$$

The RMSE, Bias and STDE was used to evaluate the hourly-simulated wind speed against the observed wind speed.

Most emphasis is given to STDE, and this assumption comes from the fact that, even if a simulation has a high RMSE or Bias, if the STDE is low it means that the error is somewhat constant and can be seen as an offset and the simulation physics is correct. If the simulation has a high STDE, the error is more scattered and the simulations have low physical meaning [36, 37].

The surface wind speed distribution is well approximated by a Weibull distribution [38, 39] and this distribution is therefore used to evaluate the model-simulated wind distributions against observed wind distributions. The Weibull distribution is a two-parameter function,

219 mathematically represented by a probability density function (PDF), $f(u)$ while the
220 cumulative distribution function is represented by $F(u)$. These functions are defined as:

$$f(u) = \frac{k}{A} \left(\frac{u}{A}\right)^{k-1} e^{-\left(\frac{u}{A}\right)^k} \quad (4)$$

221 and

$$F(u) = 1 - e^{-\left(\frac{u}{A}\right)^k}, \quad (5)$$

222 where u is the reference wind speed at the height of measurement, k the non-dimensional
223 shape parameter, and A the scale parameter whose dimension coincides with that of u (m/s).
224 Note that $k, A, u > 0$. The scale parameter, A , indicates on average how windy the site is,
225 whilst the shape parameter, k , indicates how ‘peaked’ the distribution is. The model and the
226 measured Weibull A and k parameters are used for comparison.

227 The Pearson correlation coefficient was used to evaluate the diurnal cycle of wind speed and
228 the Weibull probability density functions. The Pearson correlation coefficient is a statistical
229 measure that quantifies the strength of the relationship between the relative variation of two
230 variables; in our case, the simulated and the measured yearly averaged diurnal values and the
231 Weibull parameter values.

232 **2.4 Resource maps**

233 The 10-year 1 km $\times$ 1 km model simulation results from domain 3 (d03) were used to
234 generate the annual mean wind speed, seasonal mean wind speed and wind power density
235 resource maps at 55 m elevation, which is equivalent to the typical wind turbine hub height.
236 This was done to assist in identifying potential wind resource sites for utility-scale wind
237 power applications.

238 **2.5 Interannual wind speed variability**

239 Interannual wind speed anomalies were calculated by subtracting the measured long-term
240 mean wind speed from the model annual mean wind speed for individual stations for 10-
241 years. These were plotted to study the variation of the wind speeds from year to year.

242 **3. Results**

243 This section presents the results in two parts: the model validation and the resource maps.

244 **3.1 Model Validation**

245 The 10-metre-elevation results for the parameters used to validate the model against ground-
246 based measurements, include: the model statistical analysis, wind speed distribution and

Weibull PDFs, and the diurnal and annual wind speed patterns. The model results are compared with locations where the measurements are available from AWSs.

3.1.1 Model Statistical Analysis

Tables 3 – 5 present the model statistical analysis for 3 years for the leeward side, windward side and the outer islands AWSs, respectively. These also present the 3-year averaged wind speed diurnal cycle correlation between the model and the measurements for individual station locations. The mean bias for 3 years across all 24 AWSs is 0.62 m/s, which is a 20.2 % overestimate in comparison with the measured wind speed. The mean RMSE is 2.22 m/s, the mean STDE is 2.00 m/s and the mean diurnal cycle correlation is 0.81 for the locations tested.

Table 3. Wind statistics from the leeward side AWSs (2016 – 2018)

Station	Measured Mean (m/s)	WRF Mean (m/s)	Bias (m/s)	Bias %	RMSE (m/s)	STDE (m/s)	Correlation (%)
Keiyasi	1.15	1.86	0.71	61.9	1.51	1.34	0.99
Labasa	1.57	2.94	1.37	87.3	1.99	1.44	0.91
Momi	4.14	3.20	-0.94	-22.6	2.23	2.03	0.70
Nadarivatu	2.81	3.54	0.73	25.9	2.00	1.87	0.58
Nadi	2.77	2.79	0.02	0.7	1.68	1.68	0.89
Rakiraki	6.10	5.53	-0.57	-9.4	2.30	2.23	0.95
Rarawai	1.77	1.61	-0.17	-9.4	1.38	1.37	0.99
Seaqaqa	1.36	2.20	0.83	61.2	1.78	1.57	0.97
Sigatoka	1.89	2.41	0.53	27.8	1.38	1.28	0.98
Wainikoro	1.65	3.49	1.84	111.1	2.61	1.85	0.94
Yaqara	3.98	3.93	-0.05	-1.3	1.73	1.73	0.86
Average	2.65	3.05	0.39	30.3	1.87	1.67	0.89

Table 4. Wind statistics from the windward side AWSs (2016 – 2018)

Station	Measured Mean (m/s)	WRF Mean (m/s)	Bias (m/s)	Bias %	RMSE (m/s)	STDE (m/s)	Correlation (%)
Korolevu	3.30	3.88	0.58	17.5	1.85	1.76	0.94
Lomaivuna	1.98	2.61	0.63	31.8	1.65	1.52	0.97
Nausori	1.94	3.08	1.14	58.9	2.59	2.32	0.90
RKS Lovoni	2.06	3.95	1.89	91.8	2.67	1.89	0.10
Saqani	2.80	4.17	1.36	48.7	4.15	3.92	0.47
Suva	2.36	3.24	0.88	37.4	2.22	2.04	0.93
Tokotoko	2.57	3.18	0.61	23.6	2.18	2.09	0.95
Udu	5.36	4.80	-0.56	-10.5	1.96	1.88	0.72
Average	2.80	3.61	0.82	37.4	2.41	2.18	0.75

Table 5. Wind statistics from the outer islands' AWSs (2016 – 2018)

Station	Measured Mean (m/s)	WRF Mean (m/s)	Bias (m/s)	Bias %	RMSE (m/s)	STDE (m/s)	Correlation (%)
Koro Island	3.94	4.47	0.53	13.4	2.00	1.93	0.69
Levuka	3.82	5.15	1.33	34.7	2.79	2.46	0.85

Viwa	3.84	5.92	2.08	54.0	3.47	2.78	0.92
Vunisea	4.02	4.58	0.56	13.9	2.60	2.54	0.52
Yasawa	6.27	5.87	-0.39	-6.3	2.49	2.45	0.68
Average	4.38	5.20	0.82	21.9	2.67	2.43	0.73

Since the mean STDE for all AWSs is low, which is below the border threshold of ± 2.50 m/s, this indicates that the model adequately captures the physical processes [35, 36 and 37]. The 10-metre-elevation model errors reported are assumed to be the equivalent at higher elevations of interest, for instance at the hub-height of 55 m.

3.1.2 Wind Speed Distribution and Weibull PDFs

The wind speed distribution provides site-specific information in terms of the Weibull A and k parameters. Tables 6 – 8 present the wind speed distribution parameter analysis for 3 years for the leeward side, windward side and the outer islands, respectively. Higher Weibull A (> 4 m/s) and k (> 2) parameters are observed and modelled at Momi, Rakiraki, Yaqara, Udu, Koro Island, Levuka, Vunisea, Viwa and Yasawa. These sites are considered windy and have little variation from the mean wind speed, which indicates the presence of consistent, regular wind resources.

Table 6. Weibull Wind Distribution parameters for leeward side AWSs (2016 – 2018)

Station	Measure d Weibull A (m/s)	WRF Weibul l A (m/s)	Weibul l A Bias	Bias %	Measure d Weibull k	WRF Weibul l k	Weibul l k Bias	Bias %	Weibull Correlatio n
Keiyasi	1.17	2.02	0.85	72.5	1.17	1.21	0.05	4.0	0.95
Labasa	1.70	3.35	1.65	97.5	1.35	2.69	1.34	99.5	0.60
Momi	4.56	3.63	-0.93	-20.3	1.99	2.31	0.31	15.8	0.95
Nadarivatu	3.15	4.07	0.92	29.5	1.71	2.17	0.46	26.6	0.90
Nadi	3.03	3.17	0.14	6.0	1.65	2.33	0.68	41.3	0.95
Rakiraki	7.11	6.21	-0.90	-12.6	2.44	2.42	-0.02	-0.7	0.97
Rarawai	1.91	1.79	-0.12	-6.3	1.40	1.42	0.02	1.8	1.00
Seaqaqa	1.48	2.44	0.96	64.8	1.23	1.42	0.19	15.8	0.94
Sigatoka	2.11	2.69	0.58	27.6	1.58	1.47	-0.11	-7.1	0.98
Wainikoro	1.88	3.99	2.11	112.6	1.40	2.28	0.89	63.7	0.59
Yaqara	4.47	4.32	-0.15	-3.2	2.24	1.96	-0.28	-12.7	0.99
Average	2.96	3.43	0.46	33.5	1.65	1.97	0.32	22.55	0.89

Table 7. Weibull Wind Distribution parameters for windward side AWSs (2016 – 2018)

Station	Measure d Weibull A (m/s)	WRF Weibul l A (m/s)	Weibul l A Bias	Bias %	Measure d Weibull k	WRF Weibul l k	Weibul l k Bias	Bias %	Weibull Correlatio n
Korolevu	3.65	4.31	0.67	18.3	1.94	2.14	0.20	10.3	0.96

Lomaivun									
a	2.15	2.91	0.76	35.4	1.54	1.73	0.18	11.8	0.95
Nausori	2.71	3.45	0.75	28.0	1.51	1.82	0.31	20.4	0.94
RKS	2.32	4.36	2.05	89.3	1.64	2.39	0.75	45.4	0.62
Saqani	2.40	4.66	2.26	95.5	1.27	2.65	1.39	120.8	0.52
Suva	2.58	3.68	1.10	42.7	1.76	1.80	0.04	2.2	0.92
Tokotoko	2.96	3.52	0.56	19.2	1.80	1.58	-0.21	-11.9	0.98
Udu	6.02	5.35	-0.68	-11.2	2.44	2.37	-0.07	-2.7	0.97
Average	3.10	4.03	0.93	39.6	1.74	2.06	0.32	24.5	0.86

Table 8. Weibull Wind Distribution parameters for outer islands' AWSs (2016 -2018)

Station	Measured Weibull A (m/s)	WRF Weibull A (m/s)	Weibull A Bias	Bias %	Measured Weibull k	WRF Weibull k	Weibull k Bias	Bias %	Weibull PDF Correlation
Koro	4.47	5.02	0.55	12.4	2.06	2.57	0.50	24.7	0.95
Levuka	4.30	5.78	1.48	35.2	1.75	2.85	1.10	63.2	0.76
Vunisea	4.66	5.10	0.44	9.6	2.02	2.03	0.01	0.5	0.99
Viwa	4.20	6.59	2.39	57.2	1.63	2.51	0.88	54.2	0.67
Yasawa	7.19	6.64	-0.56	-7.6	2.61	2.88	0.27	10.3	0.98
Average	4.97	5.83	0.86	21.4	2.01	2.57	0.55	30.6	0.87

The comparison of the Weibull PDFs provides an opportunity to visualise and compare the measured and the modelled wind speed and its frequency of occurrence. Figures 3 – 6 present the comparison of the 3-year modelled and the measured Weibull PDFs together with the 10-years modelled long-term average (WRF LA) for the leeward side, windward side, outer islands and for all the AWSs, respectively. These figures also list the Weibull A and k parameters for each PDF.

Figure 3. Comparison of the Weibull PDFs for the Leeward Side Stations.

Figure 4. Comparison of the Weibull PDFs for the Windward Side Stations.

Figure 5. Comparison of the Weibull PDFs for the Outer Islands Stations.

Figure 6. Comparison of the Weibull PDFs for all 24 AWSs.

The comparison between the modelled and observed Weibull PDFs show that the model agrees moderately well with the observations (with an average correlation of 0.88 for 24 AWSs). Nonetheless the model tends to record lower frequency of lower wind speeds of 1 – 2 m/s on the leeward and the windward sides of the larger islands, and 1 – 3 m/s for the outer islands compared with the observations. The opposite is seen for wind speeds from 3 – 6 m/s for the leeward side, 3 – 8 m/s for the windward side, and 5 – 10 m/s for the outer islands. Similar model behaviour is also observed for all the 24 AWSs shown in Figure 6. This indicates that the model tends to overestimate lower wind speeds and underestimate medium to higher wind speeds. The measured Weibull A and k parameters are slightly lower in magnitude than modelled. The mean Weibull PDF correlation across all stations is 0.88, with 0.89 for the leeward side, 0.86 for the windward side and 0.87 for the outer islands indicating that the results are in good agreement. The 3-year and the 10-year modelled Weibull PDFs have little variation in terms of the Weibull A and k parameters and the Weibull PDFs correlation is almost 1, which shows that the 3-year period is representative of the 10-year period used in the simulations.

3.1.3 Diurnal Wind Speed Patterns

The diurnal wind speed pattern is the variation of wind speed over a 24-hour period. For a tropical island, it is a representation of the land-sea breeze circulation and provides useful information about the strength of the wind speed during different times of the day. Figures 7 – 10 present a comparison of the modelled (WRF) and the measured (M) diurnal wind speed patterns for 3 years together with the 10-year modelled long-term (WRF LA) average for all the AWSs, the leeward side AWSs, the windward side AWSs and the outer islands' AWSs, respectively. Note that the diurnal cycles of individual stations are not included in this paper, but rather an average across all stations, stations on the leeward side, windward side and the outer islands is used.

Figure 7. Diurnal wind speed pattern for all 24 AWSs.

Figure 8. Diurnal wind speed pattern for the Leeward Side AWSs.

Figure 9. Diurnal wind speed pattern for the Windward Side AWSs.

Figure 10. Diurnal wind speed pattern for the Outer Islands AWSs.

The model simulated diurnal cycle for 3 years and 10 years is generally in good agreement with the observations. The overall diurnal cycle for all the 24 AWSs is similar to the diurnal cycles on the leeward and the windward sides. Comparison of the 3 year and the 10-year modelled diurnal cycles shows little variation, with a correlation of almost 1 (Figure 7). The model is able to capture the diurnal cycle patterns for both sides of the larger islands, although it systematically overestimates the wind speed. For the leeward and the windward sides of the larger islands, a strong diurnal cycle is observed and modelled, which can be seen in Figures 8 and 9. For the outer islands, which are relatively smaller, a weaker diurnal cycle is observed (Figure 10), which is expected for small tropical islands as ventilation prevents the genesis of the land-sea breeze circulation [40]. This small observed diurnal cycle is not correctly simulated by the WRF model, which only simulates a small early-morning increase in wind speed. This is probably caused by the lack of representation of small-scale topography in the model, which can reduce the efficiency of the ventilation process. The model performance is better on the leeward-side stations with a smaller estimate of the mean diurnal wind speed in comparison with the windward-side and the outer-islands stations.

3.1.4 Seasonal Cycle of Wind Speed

Figures 11 – 14 present the comparison of the modelled (WRF) and the measured (M) seasonal cycle of wind speed for the 3-year period together with the 10-year modelled long-term (WRF LA) average for the leeward side, windward side, outer islands and for all the AWSs, respectively.

Figure 11. Seasonal cycle of wind speed for the Leeward Side AWS.

Figure 12. Seasonal cycle of wind speed for the Windward Side AWSs.

Figure 13. Seasonal cycle of wind speed for the Outer Islands AWSs.

Figure 14. Seasonal cycle of wind speed for all the 24 AWSs.

The model-simulated seasonal cycle of wind speed is in good agreement with the observations for the study period. The model successfully captures the seasonal cycle of wind speed for either sides of the larger islands and for the outer islands, although modelled wind speed is overestimated in comparison with the measurements. Again, this overestimation is smaller for the leeward side of the larger islands than for the windward side and the outer islands. A similar model behaviour is observed for the seasonal cycles for all the AWSs. As per the station plots, slightly higher wind speeds are observed during austral winter (May – October), during which the southeast trade winds are more persistent than during austral summer (November to April), during which the wind climatology is mostly dominated by synoptic systems. Little variation can be observed between the 3-year and the 10-year modelled seasonal cycle.

3.2 Resource Maps

3.2.1 Long-term-mean Wind Speed Map at 55 m

The long-term-mean wind speed map represents the spatial distribution of the average wind speed over the simulation. These maps at higher heights such as at the hub-height of a wind turbine are useful for identifying potential wind resource sites that can be used for utility-scale wind power applications and for siting wind turbines for wind farms. Figure 15 presents the 55-metre-elevation long-term-mean wind speed map for the SIDS of Fiji. Ten years of data was used to calculate the long-term mean. The 55-metre-elevation has been chosen because a typical wind turbine hub height, which is suitable for power generation in the SIDS

of Fiji, has a hub height of 55 m. Note that wind turbines with a hub-height of 55 m are employed at the existing Butoni wind farm in Fiji [12].

Figure 15. Long-term-mean 55-metre-elevation wind speed map of Fiji.

The 10-year average wind speed varies from a minimum of around 1.5 m/s to a maximum of 8 m/s over the islands, with minima in the inland valleys and the maxima on the crest of the islands' mountains. The long-term-mean nearshore and offshore wind speed varies from 5 m/s to 8 m/s. The dominant wind direction is south-easterly and the blocking effect of the islands can be seen in their wakes as well as in the upwind flow; this blocking effect means that the flow is diverted around the islands, accelerating the wind on the sides of the islands, particularly in the channel between the two main islands. Following the NREL Wind Power

Classification [41] using the 50-meter-elevation reference, numerous potential wind resource locations on shore can be identified with wind speeds greater than 6.4 m/s, which corresponds to Wind Power Class 3.

3.2.2 Seasonal Wind Speed Maps at 55 m

The seasonal wind speed map represents the seasonal spatial distribution of the average hourly wind speed over a season in a year. Figures 16 and 17 present the 55-m-elevation mean seasonal wind speed map of Fiji for the two seasons of austral summer and austral winter calculated using 10 years of data.

Figure 16. Seasonal 55-metre-elevation wind speed map of Fiji for austral summer.

Figure 17. Seasonal 55-metre-elevation wind speed map for austral winter.

Higher wind speeds are simulated during austral winter in comparison with austral summer over both onshore land and offshore open sea areas, but the distribution patterns are the same. This seasonal cycle follows that of the large-scale southeasterlies. The seasonal wind speed patterns at 55-metre-elevation essentially identifies the same general wind resource areas as the long-term-mean wind speed map with wind speeds greater than 6.4 m/s (Wind Power Class 3) for onshore land areas considered suitable for utility-scale wind power applications using the NREL Wind Power Classification [41]. Note that, these areas are smaller in austral summer.

3.2.3 Long-term-mean Wind Power Density Map at 55 m

The long-term-mean wind power density at the hub-height of a wind turbine is also useful in identifying potential wind resource sites for utility-scale wind power applications. Figure 18 presents the 55-metre-elevation long-term-mean wind power density map calculated using 10 years of data. The plotted values are the wind power density area-averaged over a 1 km × 1 km grid cell using a constant air density of 1.225 kg/m³.

Figure 18. Long-term-mean 55-metre-elevation wind power density map of Fiji.

The 10-year average wind power density varies from 50 W/m² to 300 W/m² at various locations depending on its topography and geographic location for the onshore land area of the major and the smaller islands. The offshore wind power density varies from 100 W/m² to 300 W/m² from near-shore areas to open sea areas, respectively.

3.2.4 Interannual Wind Speed Variability

The interannual wind speed variability refers to the magnitude of fluctuation in the annual mean wind speed on a year-to-year basis at a site. It is an important consideration for the assessment of the long-term wind resource and for the confirmation of the consistency of the wind speed over a time period of multiple years. To evaluate the interannual wind speed variability, the variance of the wind speed anomaly for the model is plotted and the interannual wind speed anomalies for the measured and the modelled wind speed are plotted separately.

Figure 19 presents the 10-year mean variance of the 10-metre wind speed anomaly for the model for the 24 AWSs. The variance of the model anomaly varies with a minimum of 0.03 m/s at Nadi to a maximum of 2.02 m/s at Viwa with an average of 0.68 m/s for the 24 AWSs. Eighteen out of twenty-four stations have the variance of the model anomaly less than 1 m/s.

Figure 19. Variance of wind speed anomaly for 10 years for 24 AWSs.

The interannual wind speed anomaly of the model and the measurements is the difference between the annual mean and the long-term mean for each. Figures 20 – 22 and Figures 23 – 25 present the interannual wind speed anomalies of the measured and model for the 24 AWS

437 locations for the leeward side, windward side and the outer islands at 10 m elevation,
 438 respectively.

439
 440 Figure 20. Measured interannual wind speed anomalies for the leeward side AWSs.

441
 442 Figure 21. Measured interannual wind speed anomalies for the windward side AWSs.

Figure 22. Measured interannual wind speed anomalies for the Outer Islands AWSs.

Figure 23. Model interannual wind speed anomalies for the leeward side AWSs.

Figure 24. Model interannual wind speed anomalies for the windward side AWSs.

Figure 25. Model interannual wind speed anomalies for the Outer Islands AWSs.

The trends in the interannual wind speed anomalies for the model and the measurements on the leeward side, windward side and the outer islands show that there is little variation (< 0.8 m/s) in the measured and the modelled wind speed over the 3 – 10 year period. Since there is little variability in the wind speed, energy production would not change significantly from year to year.

3.2.5 Systematic Bias in Wind Power Density

An evaluation of the systematic bias in wind power density at the 24 AWSs for 3 years is presented in Table 9. This shows the overestimation of the model wind speed. Wind power density is calculated using the measured and the modelled wind speed measurements and the difference is calculated to determine the systematic bias in the 10-metre wind power density at the 24 AWSs. The wind power density (WPD) is calculated using the standard equation ($WPD = \frac{1}{2} \rho V^3$, where ρ is the air density and V is the wind speed) with site-specific air density ranging from 1.084 kg/m^3 to 1.168 kg/m^3 . The site-specific air density has been estimated using the WAsP Air Density Calculator which is a function of altitude (elevation in metres above sea level) and mean air temperature at the same altitude. A lapse rate of 6.5 K/km and a sea level pressure of 1013.25 hPa are assumed and the estimate is based on a standard atmosphere. WAsP software uses the barometric reference data from CFSR reanalysis database [42].

The systematic bias computed for wind power density is assumed to be the error in the energy production as it is a function of power density and the other parameters considered in the energy calculation equation are constant. The systematic bias for wind power density is

assumed to be constant with height, as the non-linear relationship of wind power density and wind speed has been considered in the systematic bias at 10-metre elevation. A lower systematic bias can be expected at higher heights for the wind power density in a similar manner to the wind speed bias.

The mean systematic bias in the wind power density at the 24 AWSs is 9.68 W/m^2 , which is an overestimation of 33.8 %. The systematic bias is less than 15 W/m^2 at 13 AWSs, $15 - 30 \text{ W/m}^2$ at 6 AWSs and greater than 30 W/m^2 at 5 AWS. Even though it is assumed that the wind speed bias is constant with height, there is a chance that this bias will be smaller at higher elevations as there will be little surface friction at the hub-height of 55-metres in comparison with that at an elevation of 10-metres.

Table 9. Systematic Bias for Wind Power Density (WPD) for all AWSs at 10 m

Station	Measured Mean (m/s)	WRF Mean (m/s)	D3 = 1 km Bias(m/s)	Measured WPD (W/m^2)	WRF WPD (W/m^2)	Bias (W/m^2)
Keiyasi	1.15	1.86	0.71	0.88	3.73	2.85
Koro Is	3.94	4.47	0.53	35.38	51.67	16.29
Korolevu	3.30	3.88	0.58	20.95	34.05	13.10
Labasa	1.57	2.94	1.37	2.26	14.84	12.58
Levuka	3.82	5.15	1.33	32.44	79.50	47.05
Lomaivuna	1.98	2.61	0.63	4.49	10.28	5.79
Momi	4.14	3.20	-0.94	41.30	19.07	-22.23
Nadarivatu	2.81	3.54	0.73	12.03	24.04	12.02
Nadi	2.77	2.79	0.02	12.39	12.66	0.27
Nausori	1.94	3.08	1.14	4.26	17.06	12.80
Rakiraki	6.10	5.53	-0.57	132.56	98.76	-33.80
Rarawai	1.77	1.61	-0.16	3.24	2.44	-0.80
RKS	2.06	3.95	1.89	5.10	35.96	30.86
Saqani	2.80	4.17	1.37	12.80	42.27	29.48
Seaqqa	1.36	2.20	0.84	1.46	6.17	4.71
Sigatoka	1.89	2.41	0.52	3.94	8.17	4.23
Suva	2.36	3.24	0.88	7.68	19.86	12.19
Tokotoko	2.57	3.18	0.61	9.91	18.78	8.87
Udu	5.36	4.80	-0.56	89.62	64.36	-25.26
Viwa	3.84	5.92	2.08	33.07	121.17	88.10
Vunisea	4.02	4.58	0.56	37.84	55.96	18.12
Wainikoro	1.65	3.49	1.84	2.62	24.80	22.18
Yaqara	3.98	3.93	-0.05	36.79	35.42	-1.37
Yasawa	6.27	5.87	-0.40	143.46	117.72	-25.74
Average	3.06	3.68	0.62	28.60	38.28	9.68

4. Discussion

The modelling exercise using 10 years of data presents an opportunity to quantify and validate the wind-resource for the SIDS of Fiji for the first time at a mesoscale level. The overall model performance is in good agreement with the ground-based measurements. The WRF mesoscale NWP model can successfully reproduce the observed wind climate on the ground. High wind resource areas are identified at higher altitude inland areas of the larger islands of Viti Levu and Vanua Levu, nearshore land areas on the eastern and the western sides of the larger islands and the nearby onshore areas adjacent to the channel between the two larger islands.

Mesoscale wind resource maps of the long-term-mean wind speed and the long-term-mean wind power density at 55-meter-elevation can be compared with the NREL Wind Power Classification [41]. This reveals forty potential wind resource locations with wind speed and power density greater than 6.4 m/s and 300 W/m² (these values corresponds to Wind Power Class 3 for the 50 metre classification, which is considered feasible for utility-scale wind power applications). For the two main islands of Viti Levu and Vanua Levu where the national electricity grid is available, there are more than 500 km² (500 × 1 km × 1 km grid cells) of areas on each island where the wind speed and the power density are greater than the Wind Power Class 3 thresholds. Using the rule-of-thumb that 1 km × 1 km of spatial area is required to site a 10 MW wind farm with 37 × 275 kW wind turbines having 5-rotor diameter (160 m) spacing across and downstream using a 6 x 6 array size [43, 44 and 45], the total available potential wind resource area of 1000 km² (1000 × 1 km × 1 km) corresponds to an estimated 1000 MW theoretical potential installed capacity. To confirm this, micro-siting with a higher resolution model is required to make a decision considering the terrain complexities and the errors associated with the mesoscale modelling.

For the smaller outer islands there is also potential for wind power development for rural electrification as the wind resource is available. However, such a development would have to be complimentary to other power systems such as diesel power plants which currently provide electricity in these locations. Outer islands like Gau, Ovalau, Taveuni and Kadavu can accommodate a few MW scale wind farms as there are isolated mini-grid electricity networks, which are mostly supported by diesel power plants and a micro-scale hydropower plant in the case of Taveuni.

Other work has identified outer island sites of Gau [14], Kadavu [20] and Taveuni [17] as potential sites for rural electrification, which the current mesoscale work also identifies. Comparing the results of this study with a recent WAsP microscale wind resource study undertaken by the authors [23], the WRF model is able to successfully identify the three reported potential utility-scale wind farm sites of Rakiraki, Nabouwalu and Udu. Looking at the seasonal cycle of wind speed, the measured and the modelled wind speed seasonal variability is small (< 1 m/s) over a period of 3 – 10 years at all sites where measurements are available. The annual wind speed variability is low because Fiji is situated in the Southeast Trade winds zone, which are steady large-scale winds. The interannual variability is small as well (~ 0.8 m/s). The small natural variability of wind speed guarantees regular energy production.

The El-Nino, La-Nina and the ENSO events are the main modes of interannual variability observed on the ground. These are also captured by the model and are the cause of crests and the troughs of the interannual wind speed anomalies in Figures 20 – 25. According to the NASA Earth Observatory [46], El-Nino events occurred between 2009 – 2010, 2014 – 2016 and 2018 – 2019, La Nina events occurred between 2008 – 2009, 2010 – 2012 and 2017 – 2018 and ENSO events occurred between 2014 – 2016.

The WRF model has a tendency to overestimate lower wind speeds and underestimate higher wind speeds [34]. The overestimation of wind speed can be observed at the following station locations where the measured wind speed is low: Keiyasi, Labasa, Seaqaqa, Wainikoro, Nausori, Saqani and RKS on the larger islands (% Bias > 49 %). The underestimation of wind speed can be observed at Rakiraki, Udu and Yasawa whereby the measured wind speeds are medium to high. Similar model behaviour is reported for studies done for Greece [6] and Hawaii [8].

The results generated by numerical weather prediction models are only approximate due to simplifications of the topography and the physical processes which they use in order to make the problem tractable [7]. There is a substantial difference in terms of the wind speed measurements available at 10-metre-elevation from AWSs, which are essentially measurements made at a single point, whereas the wind speeds calculated using the model are the grid cell average which corresponds to an area of $1 \text{ km} \times 1 \text{ km}$. The grid cells are relatively large with an assumed topography and roughness that can be very different from the real conditions [47]. Also, the measurements are made at an elevation of 10-metres,

where structures in the close vicinity might influence the measurements. Such effects are not included in the WRF mesoscale model.

There is also a possibility that the stations are out of calibration, as for these sites, the model is able to capture the diurnal cycle pattern, which is similar to the measured and the long-term average diurnal cycles but there is overestimation of wind speed.

The terrain representation in the model can also contribute to errors. In Table 1 there are differences in the model and the real elevation at almost all station locations of between -62.4 m (-8%) and 54.4 m (170.5%). For most stations where the topography is less resolved in the model than the real topography, there is an overestimation of wind speed. These include the 6 AWSs mentioned earlier where there is a positive larger difference between the model and the measurements indicating overestimation of wind speed.

Significant sources of error in any numerical weather prediction model (such as the WRF model presented in this paper) include: the initial and the boundary conditions (in our case we are using coarse resolution output results from GCMs, which is almost the same for the entire domain as the resolution is around $100\text{ km} \times 100\text{ km}$); resolution of the domain (in our case it is an average of $1\text{ km} \times 1\text{ km}$); terrain and vegetation characteristics (in our case we used average values for each $1\text{ km} \times 1\text{ km}$ grid cell); nudging and assimilation techniques; and the complexity of the terrain effects and their representation in the model (in our case we have seen differences) [48]. The choice of the physical schemes can also contribute to errors in the model, as these schemes are based on many assumptions, and these assumptions may fail, or give an inadequate response to certain synoptic forcing, limiting their application.

In terms of the applicability and value, the finest reanalysis data available globally is ERA5 that is available at $31\text{ km} \times 31\text{ km}$ grid resolution every hour since 1979, this research created high-resolution wind resource data at $1\text{ km} \times 1\text{ km}$ resolution for the recent decade (2009-2018) for the whole of Fiji, even in locations where ground-based measurements are not available. This data has been used for potential wind resource site identification and to evaluate the theoretical potential of wind energy for Fiji. It can also be used to evaluate the technical potential by coupling it with a microscale model. The advantage of the microscale model (WAsP) is that it uses the wind atlas and generalisation methodology, which removes all the terrain influence from the model data going upwards to the free stream wind speed (geostrophic wind speed) and works downwards taking into account high-resolution terrain

data to create a generalised wind climate which can be used at a predicted site to evaluate the wind resources with greater accuracy than the input data from the model [41].

5. Conclusions

This study presents a high-resolution mesoscale wind-resource assessment of the small island developing state (SIDS) of Fiji using a 10-year simulation of the Weather Research and Forecasting (WRF) model with convection-permitting resolution. Our analysis evaluates the wind speed and Weibull distributions, diurnal and annual wind speed patterns, model statistical analysis, resource maps of annual and seasonal wind speed, power density and interannual wind speed variability and anomalies.

The results revealed that the WRF model simulated wind-resource parameters are in good agreement with the observations. The model can be reliably used to simulate the wind flow around the Fijian Islands in order to get reliable information on the wind resource. At 55 m above ground, the annual mean wind speed and wind power density varies from 1.5 m/s to 8 m/s and 50 W/m² to 300 W/m², respectively, for onshore land areas. Higher wind speeds are observed during austral winter than in austral summer. Forty high wind-resource areas are identified in this study, which were previously unknown. This indicates that there is potential for utility-scale wind power generation at selected locations with wind speed and power density greater than 6.4 m/s and 300 W/m² (NREL Wind Power Class 3 at an elevation of 50 m).

As the first mesoscale wind resource modelling exercise for the SIDS of Fiji for the recent decade (2009 – 2018), our study supports the idea that the SIDS in the Pacific can utilize their wind-resource to ease its dependence on diesel-based power generation. It also provides a methodology for mesoscale wind-resource assessment for the SIDS in the Southwest Pacific together with the identification and verification of potential wind resource sites.

In future work, it is recommended that the WRF model results are coupled with the linear wind flow model WAsP. Such an approach could improve the accuracy of the wind speed prediction by taking into account high-resolution micro-scale features of the topography and vegetation characteristics. This could also assist in determining the accuracy of the wind speed prediction as well as evaluating the wind energy potential for the identified locations from the high-resolution mesoscale wind resource mapping exercise.

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