

1 **An Improved Typical Meteorological Year for Solar Energy**  
2 **Simulations in Rarotonga, Cook Islands**

3 Timothy Anderson\*

4 *Department of Mechanical Engineering, Auckland University of Technology, Auckland,*  
5 *New Zealand*

6 Department of Mechanical Engineering

7 School of Engineering, Computer and Mathematical Sciences

8 Auckland University of Technology

9 Private Bag 92006 Auckland 1142

10 Phone: +64 9 921 9999 Extn: 8075

11 Email: [timothy.anderson@aut.ac.nz](mailto:timothy.anderson@aut.ac.nz)

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## 13 **An Improved Typical Meteorological Year for Solar Energy** 14 **Simulations in Rarotonga, Cook Islands**

15 Many of the Pacific’s small island-nations have traditionally used diesel  
16 generators in the operation of their electricity grids. That said, more recently  
17 there has been a move towards greater use of renewable energy sources for  
18 electricity, in particular solar energy. A challenge to this, however, is ensuring  
19 that there is appropriate typical meteorological year data to facilitate an  
20 understanding of the output from these systems (especially at utility scale).  
21 Although there are numerous typical meteorological year datasets for the Pacific  
22 island-nations many of these are based on satellite inferred data.

23 In this study, a typical meteorological year was developed for the island of  
24 Rarotonga, Cook Islands, using ground-based measurements. When compared to  
25 an existing typical meteorological year derived from satellite data, it was found  
26 that the satellite significantly overpredicted global horizontal irradiation for much  
27 of the year. This over-prediction was found to be due, at least in part, to the  
28 satellite data not resolving the effect of water in the atmosphere, (clouds and  
29 rainfall) on the solar irradiation correctly. On this basis it demonstrates that  
30 although typical meteorological year derived from satellite data are a useful  
31 starting point for energy simulations in the Pacific island-nations, there is a need  
32 to improve these datasets to support their transition to renewable electricity  
33 generation.

34 **Keywords:** Rarotonga; Cook Islands; typical meteorological year; solar energy;  
35 satellite data

### 36 **Introduction**

37 With concerns growing around the environmental impact of current energy sources in  
38 electricity generation many countries are exploring the use of renewable sources, such  
39 as solar energy, to replace these. The desire for a transition to renewable energy use in  
40 electricity generation is particularly pronounced in the small island-nations of the South  
41 Pacific, where diesel generators have long been the mainstay of electricity grids (Raturi  
42 et al, 2016), and where rising sea-levels are viewed as an existential crisis (Teaiwa,

43 2019). In fact, in 2011, the Cook Islands government set itself the ambitious goal of  
44 having “100 percent of its electricity to be provided by renewable energy in 2020”  
45 (Government of the Cook Islands, 2011).

46 Although there is a strong desire to see a transition to renewable energy use in  
47 their electricity sectors, diesel generators still represent a significant feature of many  
48 small island nations electricity infrastructure. In the case of the Cook Islands, 2016  
49 estimates had fossil-fuel (diesel) generators providing over 75% of the nation’s  
50 electricity (~32 GWh p.a.) (Central Intelligence Agency, 2021) despite their ambition to  
51 have “50 percent of the Cook Island’s electricity.... provided by renewable energy in  
52 2015” (Government of the Cook Islands, 2011).

53 One reason for the continuing reliance on fossil fuel generators is the inability of  
54 these small nations to access the necessary capital (beyond foreign aid) to develop  
55 renewable-energy based electricity infrastructure (Weir, 2018), and this is often  
56 underpinned by a lack of certainty on the likely performance of such systems. To  
57 minimise this uncertainty, there is a need to have reliable ‘typical’ meteorological  
58 datasets that can be used to model the ‘typical’ output from renewable energy systems,  
59 particularly solar energy systems which are widely used in the region.

60 Globally, there are numerous ‘typical’ meteorological datasets (file types) used  
61 in building and solar energy simulations (Ladybug Tools, 2021) including EnergyPlus  
62 weather (EPW), ASHRAE’s International Weather for Energy Calculations  
63 (IWEC/IWEC2) and Typical Meteorological Years (TMY/TMY2/TMY3). All these file  
64 types incorporate similar information (typically at 1-hour intervals across a 12-month  
65 period): solar radiation, temperature, wind speed, humidity, and other information  
66 pertinent to their end use, but with an overarching goal of predicting the ‘typical’ long-  
67 term behaviour of energy systems.

68           In the context of Pacific countries, access to typical meteorological year data for  
69 energy simulations would be invaluable, and fortuitously many datasets already exist  
70 for this purpose. However, on closer inspection, it is apparent that many of these files  
71 are constructed using data inferred from satellite-based measurements (Lawrie and  
72 Crawley, 2019, Huang et al, 2014).

73           Whilst satellite-based measurements are useful for developing typical weather  
74 years, they do have several shortcomings. They often have poor spatial resolution which  
75 would appear to be poorly suited to the analysis of small, isolated islands (Hijmans et al,  
76 2005). Similarly, they often have poor temporal resolution, meaning weather data needs  
77 to be synthesized between images. Moreover, for tropical environments (such as many  
78 small Pacific island-nations), the models used in analysing satellite imagery struggle to  
79 accurately resolve the effect of clouds and suspended water vapour on the local  
80 meteorology, leading to large errors in the solar radiation they infer at ground level  
81 (Badosa et al, 2013, Sengupta et al, 2021). As such, typical meteorological years for  
82 solar energy simulations based on this data, for small Pacific islands, should be treated  
83 with a degree of caution.

84           Reflecting on this point, it is worth considering the case of the Cook Islands.  
85 The Cook Islands is a small self-governing nation, in free association with New  
86 Zealand, located in the South Pacific Ocean 3000km north-east of New Zealand. It has a  
87 relatively small population, approximately 20,000, scattered over a dozen islands and  
88 over 2,000,000 km<sup>2</sup> of ocean, though nearly  $\frac{3}{4}$  of the nation's population resides on the  
89 island of Rarotonga (Cook Islands Statistics Office, 2018), which has an area of less  
90 than 68 km<sup>2</sup>.

91           As mentioned previously, the Cook Islands have indicated a desire to have all  
92 their electricity generated from renewable sources, with solar energy being an obvious

93 candidate. Now although typical meteorological years have been developed for the  
94 Cook Islands, including Rarotonga (Lawrie and Crawley, 2019, Huang et al, 2014),  
95 these have been derived from satellite data and so are likely to suffer the limitations  
96 described above. As such, there is a need to develop a more accurate typical  
97 meteorological year for Rarotonga, based on ground station observations. This would  
98 facilitate more accurate predictions of the long-term energy production of solar energy  
99 systems on the island, and ultimately assist the Cook Islands progress towards their goal  
100 of 100% renewable electricity.

## 101 **Method**

102 At its core, a typical meteorological year is a composite of 12 typical meteorological  
103 months that each provide the best representation of the long-term meteorology at a  
104 particular location. These months are concatenated to form a single year containing  
105 actual time-series meteorological measurements recorded at hourly intervals, although  
106 they may contain interpolated values for short periods where data was missing from the  
107 base records (Wilcox and Marion, 2008).

108 In the creation of a typical meteorological year, it is desirable to draw upon the  
109 largest possible database to ensure that there are smaller differences between the  
110 selected months and the long-term characteristics of each month. Hence, for this study,  
111 meteorological data (solar radiation, wind speed, temperature, humidity etc.) recorded  
112 by the National Institute of Water and Atmospheric Research's Rarotonga EWS weather  
113 station (21.20109S, 159.81329W – adjacent to the Cook Islands Meteorological Service  
114 headquarters) was drawn from New Zealand's National Climate Database (CliFlo) for  
115 the period between 2000 and 2019 (CliFlo, 2021).

116 As the starting point for determining the appropriate typical meteorological  
117 months, the “combined daily data observations at midnight” for each day in the sample

118 period were inspected for completeness (the combined observations include values for  
119 the wind gust speed and direction, rainfall, temperature, vapour pressure and mean sea  
120 level atmospheric pressure, and global solar irradiation on a horizontal plane). Any  
121 months with missing solar irradiation data were automatically excluded from the sample  
122 pool, as was data for February 29 in leap-years.

123         Having refined the sample pool, the combined daily data observations for each  
124 individual month across the pool were examined to determine the most representative  
125 months using a method similar to the “Sandia Method” described by Wilcox and  
126 Marion (2008). To do this, the cumulative distribution functions for both the short-term  
127 (daily average) and long-term (daily average across all years) for all observed  
128 parameters were constructed. Using the cumulative distribution function, it was possible  
129 to determine the month’s Finkelstein–Schafer (*FS*) statistic (Finkelstein and Schafer,  
130 1971) from Equation 1.

$$131 \quad FS = 1/n \sum_{i=1}^x \delta_i \quad (1)$$

132 where  $\delta_i$  is the absolute difference between the long-term cumulative distribution  
133 function and the candidate month’s cumulative distribution function, and  $n$  is the  
134 number of daily readings in a month. This represents the monthly average absolute  
135 difference between the short and the long-term cumulative distribution functions.

136         On its own however the Finkelstein–Schafer (*FS*) statistic is of limited value, as  
137 in developing a typical meteorological year some parameters are more important than  
138 others. To account for this, a weighted sum (*WS*) of the Finkelstein–Schafer statistics  
139 (Equation 2) was used to determine the months with the lowest weighted sums.

$$140 \quad WS = \sum w_i FS_i \quad (2)$$

141 where  $w_i$  is the weighting for each meteorological parameter and  $FS_i$  is its Finkelstein–  
142 Schafer statistic.

143           The weightings applied to the various meteorological parameters are shown in  
144 Table 1. These weightings were chosen to reflect the relative importance of these  
145 parameters to solar energy and building simulations and are broadly in line with the  
146 “Sandia Method” weightings for humidity, temperature, wind and global solar radiation  
147 noted by Wilcox and Marion (2008). It is worth noting that the Typical Meteorological  
148 Year could be slightly improved through the inclusion of Direct Normal Irradiance  
149 readings (Wilcox and Marion, 2008). However, Direct Normal Irradiance was not  
150 recorded at the Rarotonga EWS weather station and so was not used in the development  
151 of the Typical Meteorological Year. That said, Direct Normal Irradiance can be derived  
152 using models such as that developed by Ridley et al (2010) if needed.

153           At this point, a strict adherence to the “Sandia Method” (Wilcox and Marion,  
154 2008) would eliminate months based on the frequency and duration of persistence runs  
155 in temperature and solar radiation (i.e. simultaneous days with data below the 33rd or  
156 above the 67th percentile). However, a preliminary examination of the data found that  
157 this led to a situation where months would be eliminated in favour of others that were  
158 clearly not representative of the month’s meteorology. This was primarily a result of  
159 there being very little variation in the mean daily temperature across a month.  
160 Therefore, this step was not undertaken. Instead, the month with the lowest weighted  
161 sum of the Finkelstein–Schafer statistics was taken to be the typical meteorological  
162 month for the year.

163           Having determined the appropriate typical meteorological months, based on the  
164 “combined daily data observations at midnight”, the hourly meteorological records from  
165 the National Climate Database (CliFlo) for these months were compiled into a typical  
166 meteorological year. This year consisted of 8760 readings for global horizontal  
167 irradiance, dry-bulb and dew-point temperatures, relative humidity, atmospheric

168 pressure, wind speed and direction. Because the typical meteorological year data  
169 consists of monthly data from various years, the start and finish of each month was  
170 examined for discontinuities in the temperatures, humidity, pressure, and wind speed (as  
171 the transition occurs at night, solar radiation is not affected). Where these  
172 discontinuities occurred, the data was smoothed for several hours either side to provide  
173 an appropriate transition. As an extension to this, it is possible to increase the robustness  
174 of the typical meteorological year by adding a statistical perturbation as suggested by  
175 Farah et al (2018), though this was not done in this study.

176 Finally, to demonstrate the typical meteorological year, it was utilised to  
177 determine the monthly global horizontal irradiance (as a principal indicator of the  
178 energy generated by solar-energy systems) and compare it to that from the satellite  
179 derived typical meteorological year developed by Lawrie and Crawley (2019).

## 180 **Results**

181 Having outlined the method, the typical meteorological months used to develop the  
182 typical meteorological year were found to have covered nearly every year in the sample  
183 period (except 2011 and 2012, where no solar radiation data was recorded). In Table 2,  
184 these months are compared with the months selected by Lawrie and Crawley (2019) for  
185 their typical meteorological year (Rarotonga.Intl.AP.918430\_TMYx.2004-2018).

186 From a cursory examination of Table 2, it is obvious that there are differences in  
187 the months that have been selected for the typical meteorological year in this study  
188 compared to those derived previously. The result of this becomes apparent when  
189 looking at the monthly global horizontal irradiation, as shown in Figure 1.

190 From Figure 1, it can be seen that there is significant variation in the irradiation  
191 values for the months selected from the satellite data (Lawrie and Crawley, 2019) to  
192 those chosen from the ground measurements used in this study. This variation is most

193 apparent in the summer months, which are typically the ‘wet season’ in the tropics, thus  
194 lending credence to the point made previously regarding the effect of water vapour on  
195 satellite derived solar radiation measurements.

196 To explore this issue further, it was decided to examine the data for March 2009  
197 taken from the satellite and the ground station. In Figure 2 it can be seen that, on a daily  
198 basis, there can be marked differences in the radiation from the two sources. Moreover,  
199 the days with the most extreme differences tend to be those with heavy rainfall, thus  
200 supporting the notion that solar radiation derived from satellite data may not be accurate  
201 in humid and cloudy conditions.

202 Finally, it is worth noting, that even during winter (dry season), there are  
203 significant differences in the data from the satellite and the ground station (Figure 1).  
204 This is most obvious in July and August, where the years the monthly data was drawn  
205 from in both typical meteorological years aligned. Although less pronounced than the  
206 summer variation, there is still a significant variation in the irradiation values which  
207 again calls into question the accuracy of the satellite derived data for small Pacific  
208 islands in general.

## 209 **Conclusions**

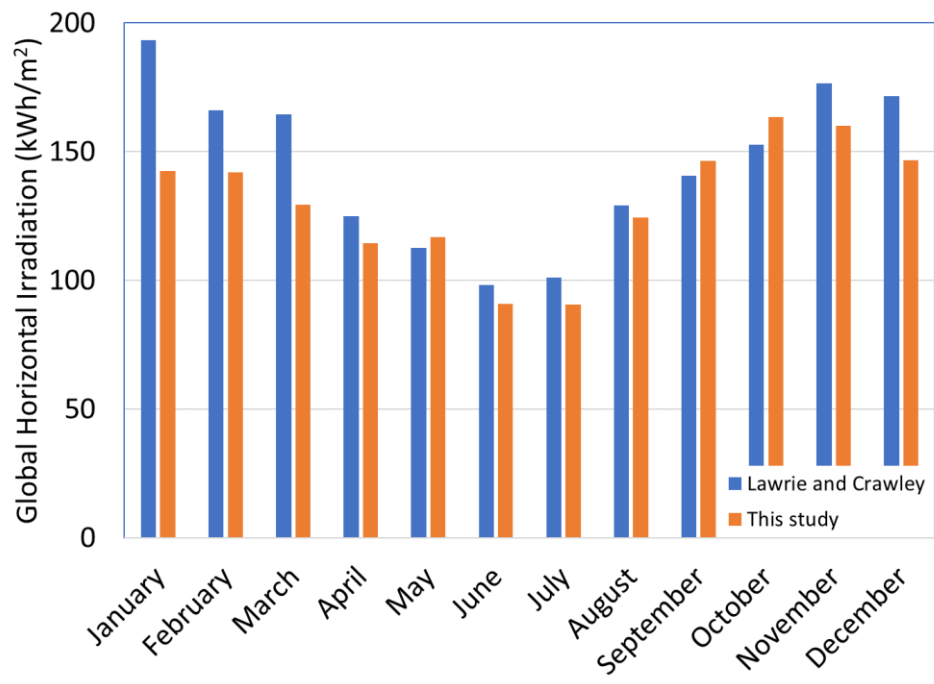
210 In this work an improved typical meteorological year dataset was developed for use in  
211 solar energy simulations on the island of Rarotonga, Cook Islands. The dataset was  
212 based on ground-level measured meteorological data and was compared with an  
213 existing typical meteorological year dataset derived from satellite measurements. The  
214 results showed that the satellite derived dataset tended to overpredict the global  
215 horizontal irradiation across the year. A closer inspection found that the differences  
216 between the two datasets could, in part, be attributed to the presence of water vapour  
217 and clouds not being accurately accounted for in the satellite data.

218           Whilst not aiming to undermine the progress made towards delivering typical  
219 meteorological year datasets for the small Pacific island-nations in the form of satellite  
220 derived data, it does raise the issue of how this may be improved (if not using ground  
221 measurements). Such improvements would in turn help facilitate the small island-  
222 nations of the Pacific in their transition to renewable electricity generation.

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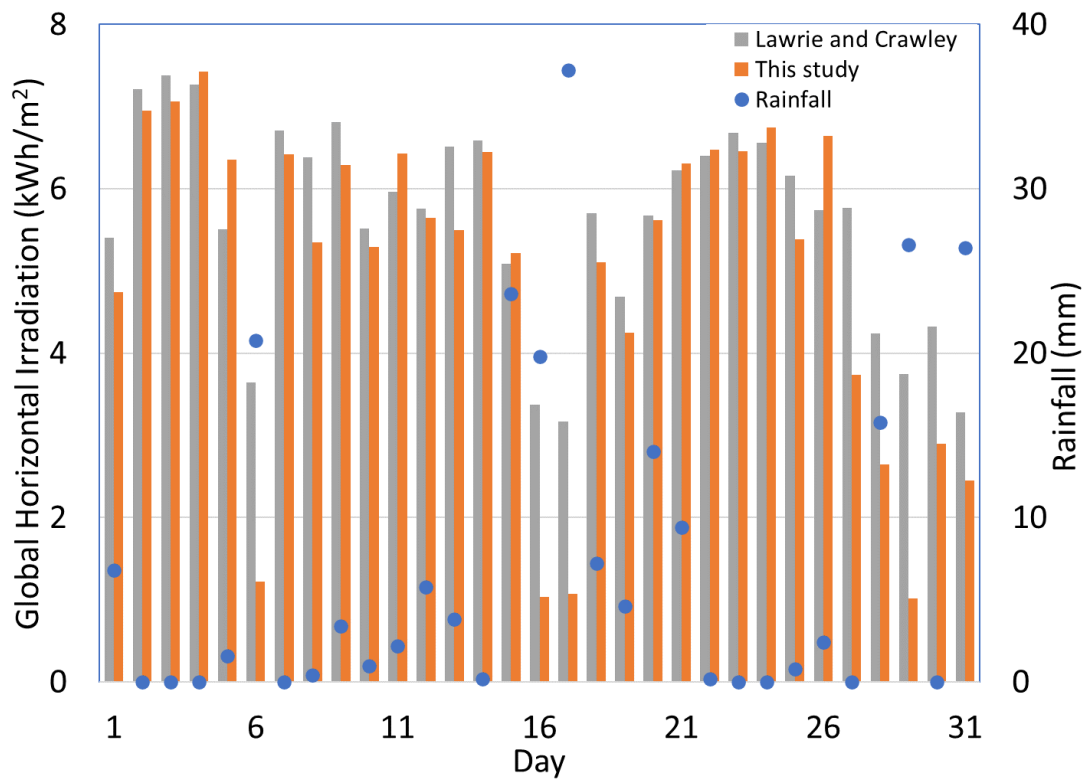


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262 Figure 1: Global horizontal irradiation for months from satellite (Lawrie and Crawley)

263 and ground readings (This study)

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266 Figure 2: Global horizontal irradiation for March 2009 from satellite (Lawrie and

267 Crawley) and ground readings (This study), and rainfall measured at ground level

268 Table 1: Weighting factors for the meteorological parameters.

<b>Parameter</b>	<b>Weighting</b>
Wind gust speed	2/20
Rainfall	1/20
Mean sea level atmospheric pressure	2/20
Vapour pressure	1/20
Minimum temperature	1/20
Maximum temperature	1/20
Mean temperature	2/20
Global Irradiation	10/20

270 Table 2: Months selected for the typical meteorological year

<b>Month</b>	<b>Year (Lawrie and Crawley, 2019)</b>	<b>Year (This Study)</b>
January	2011	2008
February	2012	2003
March	2009	2003
April	2006	2005
May	2011	2005
June	2016	2018
July	2014	2014
August	2013	2013
September	2012	2005
October	2017	2000
November	2010	2004
December	2010	2017