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Generation of a Typical Meteorological Year for Global Solar Radiation in Taiwan

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Abstract: Solar energy technology is now a mature and environmentally friendly solution. Long-term and credible solar radiation data are required for energy assessments of solar applications. Due to the lack of a typical year and accurate, long-term global solar radiation data for Taiwan, data for the typical meteorological year (TMY) of global solar radiation from 30 weather stations across Taiwan of the Central Weather Bureau were gathered for this study. The database for solar radiation contains data for the 15 years between 2004 and 2018, except for one (Chigu) weather station which provides data for the 12 years between 2004 and 2015, which possesses credible data quality and meets the requirements of the TMY method. The minimum and maximum TMY global radiation observed from the 30 weather stations are 3421.8 and 5479.9 MJ/m^2 at the Zhuzihu (Station 2) and Tainan (Station 16) weather stations, respectively. The effects of topography, geography, and latitude on the global radiation distribution in Taiwan are discussed. A trend of increasing annual global radiation from the northeast to the southwest in the Taiwanese mainland, which is attributed to the combined effects of topography and latitude, is observed. This credible, long-term database for global solar radiation is a prerequisite reference for solar information for use in determining the performance of solar energy applications in Taiwan.

Keywords: global solar radiation; typical meteorological year; TMY3; Taiwan

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1. Introduction

Fossil fuels have been the main energy source for years. The use of renewable energy has received increasing public support around the world. In Taiwan, the "Framework for a Sustainable Energy Policy" was announced in 2008 [1]. The "Renewable Energy Development Bill" and the "Greenhouse Gas Emission Reduction and Management Act" were, respectively, enacted in 2010 and 2015. Solar energy is a key renewable energy resource in Taiwan. In order to promote research and development in the use of solar thermal energy, the purchase-based subsidy programs for solar water heaters (SWHs) were implemented in the periods 1986–1991 and 2000–2017 [2]. However, most systems were installed in the residential sector and there were few large-scale SWHs installed for thermal applications in the commercial and industrial sectors. Upon the termination of the subsidy program at the end of 2017, the enforcement of the "Greenhouse Gas Emission Reduction and Management Act" plays a role in promoting the application of solar energy, particularly in commercial and industrial sectors. Up-to-date and credible solar radiation data are a prerequisite for performing energy assessments of such large-scale solar applications in Taiwan, as carried out in many studies for various solar applications in different regions or countries [3–10].

Weather data, such as solar radiation data, varies significantly from year to year. To reduce the computational load for simulation and weather data handling, a typical year of weather data are used to represent the long-term weather data, instead of multiple years. Chan et al. [8] and Ohunakin et al. [9] reviewed a variety of typical weather data sets and recommended the approach of a typical meteorological year (TMY) originally developed by Hall et al. [11]. A TMY is composed of 12 typical months (named typical meteorological months, TMMs) for each of the twelve calendar months from the long-term database. The current version of the TMY method is TMY 3 [12] and this is used for this study.

Taiwan started to measure horizontal global solar radiation at several weather stations of the Central Weather Bureau (CWB) in the early 1950s. Measurements of global solar radiation have used modern pyranometers (Model PSP, Eppley Laboratory, Inc. (only one version: PSP, Eppley Laboratory Inc., Newport, RI, USA)) since 1982. Lin [13] investigated the quality of the global radiation data that was measured using this type of pyranometer by several weather stations of the CWB before April 2003, and he found underestimations of 15.2% to 32.6% for the measured data due to improper calibrations of the pyranometers. Since then, the global radiation data of the CWB has been carefully measured with the normally calibrated pyranometers. The calibration of the pyranometers installed at each CWB weather station is carried out on-site around once every two years by a technician sent from the calibration laboratory of the CWB with a certified standard pyranometer.

To the best of the authors' knowledge, few studies that have introduced nationwide data sets for solar radiation in Taiwan can be found in the literature. Ou et al. [14] generated the TMYs for global solar radiation using TMY2 [15], which is the precursory version of TMY3, for 26 weather stations of the CWB, as shown in Figure 1 and Table 1, but excluding Chigu (Station 14), Hengchun (Station 18), Pengjiayu (Station 27), and Dongidao (Station 28) weather stations. The database for solar radiation containing data for the 7 years between 1996 and 2002 was used in their study except for Matsu (Station 29) and Kinmen (Station 30)—weather stations that had only two years (2004–2005) of available data because they only started operating in 2004. Note that the data qualities for global radiation observed by the CWB before April 2003 were questionable (about 15.2% to 32.6% underestimations [13]). In addition, it has been reported [12] that no TMY for a site is produced if the pool of data are less than 10 years. Hsiao et al. [16] estimated downward solar irradiance (DSI) over the entire terrain of Taiwan from the 2006–2007 measurements of a multifunctional transport satellite (MTSAT), which was a geostationary satellite. Their DSI estimations were performed using the visible image data of the MTSAT satellite associated with the 40 m resolution digital terrain data in Taiwan. This process must consider the atmospheric effects of suspending aerosols and clouds and the blocking diffusion–reflection effect of the terrain slopes to calculate the DSI at each pixel-point of the MTSAT satellite data. It is generally agreed that satellite measurements are not as accurate as ground measurements because the satellite-derived data are the spatial averages over a finite area on the ground based on the image data, which are remotely measured at a certain distance above the earth's surface. A comparison of the hourly-integrated DSI results with the available hourly global radiation data observed by the CWB around Taiwan showed that the correlation coefficients were about 0.8 (for the high-altitude weather stations) to slightly higher than 0.9 (for the low-altitude weather station). Hsiao et al. attributed these deviations from the DSI estimations to the coarse resolution of the MTSAT pixel resolution and the effects of the subgrid cloud and fog.

This study uses long-term (2004–2018) records to generate the TMYs for global solar radiation for 30 weather stations across the terrain of the Republic of China (Taiwan), as shown in Figure 1 and Table 1. This area includes mainly the Taiwanese mainland and several remote islets. This credible, long-term database of global solar radiation will be a prerequisite reference for performing energy assessments of solar applications in Taiwan.

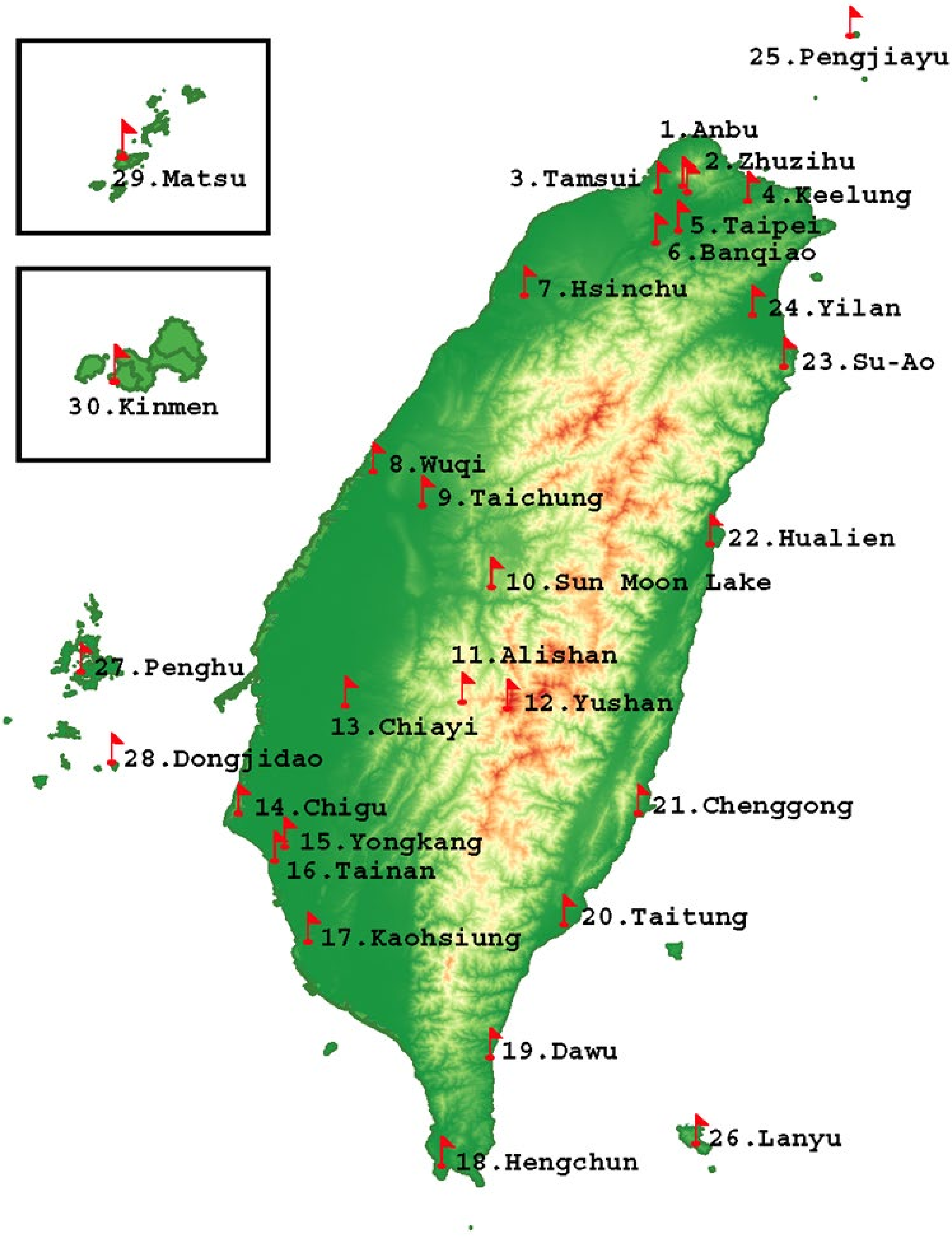

Figure 1. Locations of the 30 weather stations in this study.

Table 1. Weather stations for this study.

Number	Name	Longitude (°E)	Latitude (°N)	Altitude (m)	Remark
1	Anbu	121.53	25.18	837.6	
2	Zhuzihu	121.54	25.16	607.1	
3	Tamsui	121.45	25.16	19.0	
4	Keelung	121.74	25.13	26.7	
5	Taipei	121.51	25.04	5.3	
6	Banqiao	121.44	25.00	9.7	
7	Hsinchu	121.01	24.83	26.9	
8	Wuqi	121.52	24.26	31.7	
9	Taichung	120.68	24.14	84.0	
10	Sun Moon Lake	120.91	23.88	1017.5	
11	Alishan	120.81	23.51	2413.4	
12	Yushan	120.96	23.49	3844.8	
13	Chiayi	120.43	23.50	26.9	
14	Chigu	120.09	23.15	2.9	Abolished on 1 June 2016
15	Yongkang	120.24	23.04	8.1	
16	Tainan	120.20	22.99	40.8	
17	Kaohsiung	120.32	22.57	2.3	
18	Hengchun	120.75	22.00	22.3	
19	Dawu	120.90	22.36	8.1	
20	Taitung	121.15	22.75	9.0	
21	Chenggong	121.37	23.10	33.5	
22	Hualien	121.61	23.98	16.1	
23	Su-Ao	121.86	24.60	24.9	
24	Yilan	121.76	24.76	7.2	
25	Pongiayu	122.08	25.63	101.7	
26	Lanyu	121.56	22.04	324.0	
27	Penghu	119.56	23.56	10.7	
28	Dongjidao	119.67	23.26	43.0	
29	Matsu	119.92	26.17	97.8	
30	Kinmen	118.29	24.41	47.9	

2. TMY Methodology

Each TMM is examined separately and begins with establishing the specified daily weather parameters and sorting by month. A set of 12 long-term cumulative distributions (CDFs) covering the whole period of record, each for a separate calendar month, is then determined. Short-term CDFs for individual months of each calendar year for the entire period are also determined.

The long-term and short-term CDFs for each weather parameter x are given by the function $S_n(x)$ of

$$S_n(x) = \begin{cases} 0 & \text{for } x < x_1 \\ (k-0.5)/n & \text{for } x_k \le x < x_{k+1} \\ 1 & \text{for } x \ge x_n \end{cases} \quad (1)$$

where n is the total number of elements and k is the ranked order number. Equation (1) shows that $S_n(x)$ is an increasing function with a step size of $1/n$ at x_k and ranges between 0 and 1. Each candidate CDF is compared to its corresponding long-term CDF using Finkelstein–Schafer (FS) statistics [17] for each weather parameter as:

$$\text{FS} = \frac{1}{m}\sum_{k=1}^{m}\delta_k \quad (2)$$

where δ_k is the absolute difference between the long-term CDF and the candidate CDF at x_k and m is the number of daily readings over the entire period for the candidate month. The FS statistics measure the closeness of each candidate's short-term CDF to its long-term CDF. The lower the FS value for a month, the closer that month is to a typical month for a given weather parameter. In consideration of the different impacts of the weather parameters on FS statistics, a weighted sum (WS) (Equation (3)) of the FS statistics, instead of Equation (2), is used, as shown below.

$$\text{WS} = \sum_{j=1}^{J}\omega_j \times \text{FS}_j \quad (3)$$

with

$$\sum_{j=1}^{J}\omega_j = 1 \quad (4)$$

where J is the number of weather parameters considered in the study and ω_j is its corresponding weighting factor. The assignment of a weighting factor is intuitive and primarily depends on the intended use of the generated TMY.

Five candidate months with the lowest WS values are selected. According to TMY 3′s user manual [12], the persistence criterion is next used to determine which month of the five candidate months is finally used for constructing a TMY. The persistence of daily dry bulk temperature and global radiation is evaluated by determining the frequency (number of occurrences) and run length (number of consecutive days) above and below fixed long-term percentiles. The upper and lower limits for daily dry bulb temperature are set to be the 67th and 33rd long-term percentiles, respectively, while for global radiation, only a lower limit, the 33rd long-term percentile, is set. The month with the longest run, the month with the most runs, and the month with zero runs are excluded. The persistence data are used to select, from the five candidate months, the month to be used in the TMY. The highest-ranked candidate month in ascending order of the WS values that meet the persistence criterion is used in the TMY. However, Chan et al. [8] noted that this criterion could lead to the rejection of all five candidate months under the condition if record data are obtained with the empirical models or if only data for a small number of years is available. Pissimanis et al. [10] also argued that the persistence criterion may be subjective if a large number of weather parameters are used in the TMM selection process. Instead, they used the root-mean-square difference (RMSD) for the final selection of each TMM in the study:

$$\text{RMSD}_k = \left[\sum_{\ell=1}^{N_k}(x_{k\ell} - \overline{x}_\ell / N_k\right]^{1/2} \quad (5)$$

where the indices k and ℓ, respectively, denote the year and hour of the day, N_k is the number of hours for the k^{th} year, and $\overline{x}_\ell$ is the average value for the long-term data for the lth hour of the day. TMM is assigned to be the month with the smallest RMSD valuer. Argiriou et al. [18] also used the simple RMSD method as the final TMM selection criterion and reported that a satisfactory result was achieved in their study. This study uses the RMSD method for the final selection of each TMM from its corresponding five candidate months.

3. Data Base

3.1. Time Period for Collecting Data

Figure 1 and Table 1 show the 30 full-scale weather stations that are operated by the CWB on the Taiwanese mainland and offshore islets. A full-scale weather station is a station that collects routine measurements of most meteorological variables such as global solar radiation, ambient temperature, relative humidity, wind speed, and rainfall. The data for this study consists of hourly measurements from 2004 to 2018 [19], except for the Chigu weather station, which was discontinued in June 2016. Only 12 years (2004 to 2015) of weather data were collected from the CWB website [19] for the Chigu weather station, and 15 years of weather data were collected for the other weather stations that are listed in Table 1.

3.2. Missing Data

Large amounts of long-term information commonly feature missing measurements. This study classifies missing data points for global radiation as being caused by extreme weather events (e.g., typhoons) or due to malfunctions or regular maintenance of the instruments.

Typhoons are typical weather phenomena (around 3.2 typhoons/year between 1991 and 2020 [20]) in Taiwan. The dates for all typhoons in Taiwan between 2004 and 2018 were identified [20] and first marked in a list. The dates of all missing points were compared to this list. If the dates coincided within a marked two-day (the usual land stay time of a typhoon in Taiwan) window in the list, zero values of global radiation were assigned for each hour of these days. The operators of weather stations turned off pyranometers on days when there were typhoons.

All other missing data that is not due to typhoons is attributed to maintenance or the malfunction of pyranometers. This type of missing data were recreated using interpolation of a cubic spline [21], which is a piecewise cubic function that interpolates a set of data points and guarantees smoothness for variations between the data points. To determine how many consecutive missing hours can be safely interpolated using the cubic spline interpolation method, a sample of the measured hourly global radiation dataset, which is fully consecutive for a specific day, was randomly selected. A point around noon from the hourly dataset was removed and interpolated using the cubic spline interpolation with the remaining data points. The interpolated value was then compared to the actual value of the point. This process was repeated by removing one more consecutive point until the maximum deviation of the removed points from the actual value of the point exceeded 5%. The checking process was demonstrated twice, once for the day randomly selected from the clear days and the other selected randomly from the cloudy/rainy days. The cubic spline interpolation is sufficiently accurate ($\leq$ 5%) if the number of consecutive points is less than 4, so the maximum number of consecutive missing data points for measured hourly global radiation that can be interpolated is 3. If a day has more than 3 h of consecutive missing points, this day is considered to be missing and is interpolated using the cubic spline method and the daily dataset.

There is no interpolation if more than 3 consecutive days are missing. A month with more than 3 consecutive days of missing data are used for calculation but is disqualified as a TMM. In addition, TMY 3′s user manual [12] states that if more than 10 days of data are missing for a single month, this month is also disqualified as a TMM.

4. Results and Discussion

The assignment of the weighting factors for the weather parameters in Equation (3) is more or less intuitive and mainly dependent on the effect of each weather parameter on the performance of a specific solar energy application. For example, Cebecauer and Suri [22] proposed the use of weighting factors for global radiation, diffuse radiation, and ambient temperature that are, respectively, equal to 0.75, 0.20, and 0.05 for a GIS approach for a solar photovoltaic (PV) application. The National Renewable Energy Laboratory (NREL) of the United States of America developed two TMY products with full (1.0) weight: one for global radiation and the other for beam radiation.

Comparisons between the two sets of weighting factors for non-concentrating solar applications, including the factors that are used for the Solar GIS approach and the set that is used by the NREL, were made using the weather data for years 2004–2018 for the Taichung and Tainan weather stations (stations 9 and 16, respectively, in Table 1). Considering no beam radiation data for these two weather stations, the set of weighting factors for the Solar GIS approach is modified (global radiation = 0.95, ambient temperature = 0.05) for this study. The TMMs that are calculated using these two sets of weighting factors for the Taichung and Tainan weather stations are presented in Tables 2 and 3, respectively. The results in Tables 2 and 3 disclose that the use of these two sets of weighting factors in selecting TMMs results in only one different TMM for the Taichung and Tainan weather stations: the TMM for October 2006 for Case 1 (global radiation = 1.0) and 2005 for Case 2 (global radiation = 0.95 and ambient temperature = 0.05) for the Taichung weather station and the TMM for May 2014 for Case 1 and 2007 for Case 2 for the Tainan weather station. The differences in the monthly-averaged daily global radiation (on the bases of the cases obtained with the full weight of global radiation) are 1.86% and 2.48% for the two different TMMs for the Taichung and Tainan weather stations, respectively. As expected, this shows that there are slight differences in the TMMs that are generated using these two sets of weighting factors because the weights assigned in the two sets of weighting factors differ very little from each other. The full weight for global radiation is used in Equation (3) to calculate the TMY for simplicity.

Table 2. TMMs determined using two sets of weighting factors for the Taichung weather station: (1) global radiation = 1.0 and (2) global radiation = 0.95 and ambient temperature = 0.05.

Case	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	2006	2012	2006	2004	2006	2008	2011	2014	2006	2006	2009	2012
2	2006	2012	2006	2004	2006	2008	2011	2014	2006	2005	2009	2012

Table 3. TMMs determined using two sets of weighting factors for the Tainan weather station: (1) global radiation = 1.0 and (2) global radiation = 0.95 and ambient temperature = 0.05.

Case	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	2010	2012	2017	2012	2014	2012	2015	2012	2004	2011	2007	2016
2	2010	2012	2017	2012	2007	2012	2015	2012	2004	2011	2007	2016

Using this procedure for all months in the study period, a composite year (i.e., the TMY) of 12 concatenated TMMs is created for each weather station and the results are shown in Table 4. Using the selective TMM for each weather station, as shown in Table 4, the monthly global radiation for each TMM is calculated using the corresponding hourly database for global radiation (available in a publicly accessible repository, http://gitub.com/p47061105/TaiwanTMY), and the results are listed in Table 5. The respective minimum and maximum global radiation for the 30 weather stations is 3421.8 and 5479.9 MJ/m^2 at the Zhuzihu (Station 2) and Tainan (Station 16) weather stations. Annual global radiation increases from the northeast to the southwest.

Table 4. List of TMMs for the 30 weather stations for this study.

Station Number/Name	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1/Anbu	2006	2010	2009	2014	2012	2016	2016	2009	2011	2015	2012	2007
2/Zhuzihu	2011	2012	2015	2009	2014	2014	2004	2013	2016	2013	2005	2013
3/Tamsui	2007	2011	2014	2012	2015	2004	2017	2006	2017	2018	2006	2014
4/Keelung	2009	2010	2016	2014	2017	2012	2010	2009	2016	2017	2009	2004
5/Taipei	2013	2011	2006	2004	2017	2011	2018	2012	2008	2007	2018	2006
6/Banqiao	2006	2006	2014	2009	2004	2017	2005	2016	2018	2015	2013	2005
7/Hsinchu	2010	2006	2006	2005	2005	2017	2009	2009	2007	2015	2007	2009
8/Wuqi	2007	2004	2010	2012	2007	2009	2005	2013	2016	2004	2011	2013
9/Taichung	2006	2012	2006	2004	2006	2008	2011	2014	2006	2006	2009	2012
10/Sun Moon Lake	2010	2014	2005	2008	2015	2008	2015	2014	2009	2013	2009	2012
11/Alishan	2005	2015	2011	2008	2015	2014	2016	2016	2007	2006	2015	2016
12/Yushan	2017	2017	2011	2005	2010	2013	2011	2015	2016	2015	2016	2009
13/Chiayi	2013	2017	2007	2007	2006	2006	2012	2013	2004	2005	2016	2016
14/Chigu	2006	2015	2015	2009	2014	2005	2015	2009	2011	2016	2010	2008
15/Yongkang	2018	2018	2006	2005	2008	2014	2012	2015	2007	2012	2012	2012
16/Tainan	2010	2012	2017	2012	2014	2012	2015	2012	2004	2011	2007	2016
17/Kaohsiung	2013	2012	2014	2008	2008	2010	2010	2015	2004	2012	2012	2009
18/Hengchun	2005	2012	2004	2017	2015	2018	2018	2016	2006	2005	2018	2017
19/Dawa	2006	2016	2009	2004	2006	2009	2009	2018	2004	2005	2004	2009
20/Taitung	2017	2012	2006	2006	2005	2013	2011	2012	2008	2012	2017	2017
21/Chengong	2015	2012	2007	2012	2011	2013	2013	2015	2012	2015	2007	2016
22/Hualien	2013	2015	2005	2010	2010	2007	2012	2016	2011	2015	2018	2010
23/Su-Ao	2005	2006	2007	2016	2008	2008	2009	2012	2011	2017	2016	2005
24/Yilan	2017	2011	2009	2005	2011	2008	2010	2012	2015	2015	2013	2006
25/Pengjiayu	2008	2014	2016	2008	2012	2014	2009	2011	2018	2004	2016	2018
26/Lanyu	2007	2012	2006	2014	2013	2014	2011	2009	2016	2016	2006	2015
27/Penghu	2008	2014	2009	2016	2015	2008	2016	2012	2016	2015	2009	2015
28/Dongjidao	2013	2011	2015	2014	2007	2005	2015	2016	2013	2017	2009	2017
29/Matsu	2018	2016	2010	2009	2008	2005	2005	2004	2004	2009	2014	2004
30/Kinmen	2006	2014	2004	2010	2010	2014	2005	2006	2004	2005	2014	2008

Ou et al. [14] presented their TMY results over Taiwan in terms of contour distribution curves of the annual solar radiation, and Hsiao et al. [16] presented their estimated monthly DSI results over Taiwan in terms of 12 color maps, one for each month of 2006. Thus, only the range of annual solar radiation quantities for the investigated weather stations in these two studies can be compared with the present calculated results and is listed in Table 6. Obviously, the differences between the lowest and upper bounds for annual solar radiation among these three studies are noticeable. As highlighted previously, there were two defects in the study of Ou et al. [14] including (1) the use of debatable qualities of measured CWB data for global radiation before 2004 according to the argument of Lin [13], and (2) the period in the pool of data (7 years) used to generate the TMY is less than that required by the TMY method (no less than 10 years). The study of Hsiao et al. [16] used the data measured by a geostationary satellite in 2006–2007 to calculate the distributions of global radiation over the entire terrain of Taiwan. However, it is well-agreed that satellite measurements are not as accurate as ground measurements. In addition, the data were not from a long-term pool. Thus, these two previously published results are less credible than the present ones. Nevertheless, the incremental trend in annual solar radiation from the northeast to the southwest of the Taiwanese mainland, similar to the trend shown in the present work, was also observed from the contour distribution curves presented in the study of Ou et al. [14]

Table 5. TMY data for monthly global radiation ($\frac{MJ}{m^2}$) for the 30 weather stations in this study.

Station Number/Name	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Sum.
1/Anbu	179.62	208.55	282.76	349.30	354.37	374.06	494.62	440.12	330.78	248.30	186.55	179.65	3268.7
2/Zhuzihu	164.20	179.73	334.12	218.92	335.81	416.09	342.42	429.70	341.63	353.64	197.38	208.13	3421.8
3/Tamsui	190.44	213.37	308.74	321.57	435.22	441.43	580.10	490.31	469.13	309.13	247.17	200.91	4208.1
4/Keelung	141.76	178.63	252.12	313.84	397.27	445.67	630.05	565.90	354.30	250.23	173.73	137.00	3840.5
5/Taipei	186.92	209.80	249.61	371.37	438.10	421.69	547.94	429.09	368.22	273.89	248.54	202.06	3947.2
6/Banqiao	214.77	224.03	257.07	318.59	451.30	434.64	603.76	509.89	419.07	304.32	231.09	189.91	3968.5
7/Hsinchu	231.26	224.59	276.61	353.47	422.42	460.72	570.72	506.62	456.43	405.70	270.44	212.41	4391.1
8/Wuqi	263.62	303.24	374.62	429.72	507.76	486.03	560.38	516.30	471.91	453.63	297.14	281.21	4945.6
9/Taichung	355.97	332.78	416.85	417.28	484.45	487.79	573.82	496.54	486.37	483.21	376.07	326.58	5237.7
10/Sun Moon Lake	311.97	310.18	342.28	318.25	359.59	390.65	457.56	400.69	367.36	388.29	329.75	276.01	4252.6
11/Alishan	359.17	331.43	387.33	379.50	372.37	376.03	408.91	330.54	326.02	374.32	359.04	348.19	4352.8
12/Yushan	400.85	385.51	456.67	412.03	454.42	471.16	547.76	468.82	411.77	524.81	376.57	394.10	5304.5
13/Chiayi	351.67	332.32	434.81	474.24	566.83	483.25	550.59	480.96	508.74	469.35	320.19	324.11	5297.1
14/Chigu	380.60	391.62	453.95	439.48	527.92	489.00	579.36	483.06	533.14	459.80	348.86	325.76	5412.6
15/Yongkang	336.12	351.04	383.23	445.50	539.81	470.92	511.31	464.71	440.55	461.17	341.67	315.96	5062.1
16/Tainan	366.81	369.90	482.78	498.13	550.66	537.61	572.01	481.67	457.07	464.28	348.68	350.34	5479.9
17/Kaohsiung	342.94	363.43	463.19	484.57	548.18	518.64	546.12	488.83	447.62	465.65	329.77	327.45	5326.4
18/Hengchun	335.57	414.00	447.52	486.01	518.02	505.44	523.87	460.64	456.74	449.28	375.64	323.97	5296.7
19/Dawa	276.22	319.26	345.00	411.85	499.42	531.17	551.18	516.73	462.86	434.28	325.72	251.87	4925.6
20/Taitung	289.65	297.98	338.25	430.25	560.46	588.17	678.33	585.66	484.83	451.15	330.13	302.22	5337.1
21/Chengong	232.33	259.12	296.97	328.47	402.78	561.51	661.58	552.57	488.42	416.07	312.95	256.76	4769.5
22/Hualien	201.38	220.22	286.63	303.06	420.74	499.39	623.50	552.67	438.94	342.35	255.14	221.22	4365.2
23/Su-Ao	166.25	189.63	252.48	332.22	385.58	505.51	581.22	582.96	399.17	273.58	191.91	170.51	4031.0
24/Yilan	171.19	212.05	282.50	337.25	402.22	458.92	630.85	559.38	435.54	277.87	189.70	156.94	4114.4
25/Pengjiayu	162.32	186.79	290.64	377.78	477.04	533.40	748.67	663.66	516.22	399.85	230.50	186.63	4773.5
26/Lanyu	219.97	240.67	307.95	364.64	419.61	431.12	541.76	423.75	371.95	368.67	251.38	229.60	4171.1
27/Penghu	218.22	235.57	343.08	424.50	498.01	527.09	611.54	529.94	478.05	410.44	298.95	256.43	4811.8
28/Dongjidao	283.88	293.42	380.38	470.03	575.94	532.77	621.03	557.39	510.96	455.64	307.64	261.34	5250.4
29/Matsu	195.47	247.70	289.66	358.42	419.64	407.83	601.57	518.26	379.56	339.09	215.17	194.03	4166.4
30/Kinmen	287.77	258.95	324.43	384.80	442.75	456.21	622.04	545.34	466.73	417.45	311.93	281.43	4799.8

Table 6. Comparison of the range for the estimated annual solar radiation in Taiwan from different studies.

Source	Ou et al. [6]	Hsiao et al. [8]	Present Study
Annual solar radiation (MJ/m^2)	3102–5775	3797–6587	3422–5748

Of the 30 weather stations used in this study, 24 stations (stations 1–24, Table 1) are located on the Taiwanese mainland and the other 6 stations (stations 25–30, Table 1) are located on six different remote islets, as shown in Figure 1. The Taiwanese mainland is a leaf-shaped island straddling the Tropic of Cancer. Five mountain ranges run from north-northeast to south–southwest. The land slopes gently to broad plains/basins in the west. In the central part of the Taiwanese mainland, the precipitous mountains contain more than 200 peaks with elevations of over 3000 m that descend to the Pacific Ocean in the east [23].

As shown in Figure 1, stations 10, 11, and 12 (Sun Moon Lake, Alishan, and Yushan, with respective elevations of more than 1000 m) are located in the Central Mountain Range. Stations 19–24 (Dawu, Taitung, Chenggong, Hualien, Su-Ao, and Yilan) are located from south to north along the narrow eastern coastal plains. Stations 1 and 2 (Anbu and Zhuzihu) are located on Yangming mountain, which is a volcanic mountain in the north of the Taiwanese mainland. The broad western plains/basins are the sites for stations 3–7 (Tamsui, Keelung, Taipei, Banqiao, and Hsinchu), stations 8 and 9 (Wuqi and Taichung), and stations 13–18 (Chiayi, Chigu, Yongkong, Tainan, Kaoshiung, and Hengchun). These latter station groups are distributed in the northern, central, and southern parts of the west Taiwanese mainland, respectively.

The Northeast Monsoon dominated the weather in Eastern Taiwan in the months of November–March. During this season, moist ocean air is blown southwest and lifted upward by the Central Mountain Ranges on the Taiwanese mainland. These mountain ranges run almost parallel to the eastern coastland and orographic rain is frequent. Stations 22–24 are located on the windward side of the mountains, so global radiation levels are low for these stations during these months (see Table 5). Stations 8–18 are located on the leeward side of the mountain ranges, so the Northeast Monsoon has a negligible effect and their global radiation levels are higher than those of stations 22–24 located on the windward side. It shows a significant topographic effect between the western and eastern planes during the Northeast Monsoon season. The weather stations in the north of the Taiwanese mainland (stations 1–7) have no shelter from the Northeast Monsoon, so during the Northeast Monsoon season, the global radiation that is measured by these weather stations is lower than for the stations in the central and southern parts of the western plains of the Taiwanese mainland.

Figure 1 and Table 1 show that the horizontal distance between the two weather stations on Yangming mountain (Anbu (Station 1) (at 121.52° E, 25.18° N) and Zhuzihu (Station 2) (at 121.54° E, 25.16° N)) is short but their elevations are noticeably different, at 837.6 m for Aubu and 607.1 m for Zhuzihu. However, the annual global radiation that is measured by both stations differs by about 200 $\frac{MJ}{m^2}$ (Table 5). This shows the effect of altitude on global radiation.

The extraterrestrial radiation on a horizontal plane on any day (H_o) theoretically defines the maximum global radiation that is incident on the ground, and is expressed as [24]:

$$H_0 = \frac{24 \times 3600}{\pi} G_{sc} \left[1 + 0.033 \cos\left(\frac{360^\circ \times n}{365} \right) \right] \times \left\{ \cos\phi \cos\delta \sin\omega_{sunset} + \frac{\pi}{180^\circ} \sin\phi \sin\delta\, \omega_{sunset} \right\} \quad (6)$$

$$\delta = 23.45^{\circ} \times sin\left(360^{\circ} \times \frac{284+n}{365}\right) \quad (7)$$

$$\omega_{sunset} = \cos^{-1}(-\tan\phi\tan\delta) \quad (8)$$

where G_{sc} is the solar constant, n is the nth day in a year, ϕ is the latitude, δ is the declination angle, and ω_{sunset} is the hour angle (in degrees) at sunset time. For a specified set of times in a day, H_o is the same for the same latitude, regardless of the longitude. The latitudes of the Taichung weather station (Station 9 at 120.68° E, 24.14° N) and Hualien (Station 22 at 121.61° E, 23.98° N), which are, respectively, located on the west and east sides of the mountain ranges, are close to each other; however, the annual global radiation figures in Table 5 (5237.7 and 4365.2 MJ/m^2 for stations 9 and 22, respectively) differ significantly. This is evidence of a significant topographic effect on global radiation between the east and west sides of the Taiwanese mainland. The extraterrestrial annual radiation, as integrated with Equation (6) over a year at the midlatitude between these two weather stations (= 24.08° N) is 12,059 MJ/m^2, is greatly higher than both ground-measured results in Table 5. It is known that a reduction in the intensity of solar radiation due to absorption, scattering, and reflection by the species in the atmosphere occurs as the sun's rays pass through the atmosphere; local variations in the atmosphere, such as those due to the topographic effect, have additional effects on the reduction extent.

Geography also has an effect on global radiation for the weather stations used in this study. The Kinmen weather station (Station 30 at 118.29° E, 24.41° N) is on a remote islet in the Taiwan Strait and its latitude is close to that of the Taichung weather station (Station 9 at 120.68° E, 24.14° N) on the Taiwanese mainland. The annual global radiation for the Taichung weather station (5237.7 MJ/m^2) is significantly greater than the value for the Kinmen weather station (4799.8 MJ/m^2). Hengchun weather station (Station 18 at 120.75° E, 22.00° N) is located at the southern end of the Taiwanese mainland and the Lanyu weather station (Station 26 at 121.56° E, 22.04° N) is located in the western Pacific. Their latitudes differ slightly from each other but the annual global radiation for the Hengchun weather station (5296.7 MJ/m^2) is significantly greater than that for the Lanyu weather station (4171.1 MJ/m^2). The extraterrestrial annual radiation, integrated with Equation (6) over a year at the midlatitude between these two weather stations (= 22.02° N), is 12231 MJ/m^2. By comparing two figures of the extraterrestrial annual radiation at 24.08° N and 22.02° N, it shows a gradual increment in the extraterrestrial annual radiation along with lower latitude; in other words, moving to a more southerly location. This altitude effect can explain the general tendency for enhancing global radiation by reducing the latitude of the weather station observed from Table 5, no matter which side of the Taiwanese mainland the weather station is located, either broad western plains/basins or narrow eastern coastal plains.

5. Conclusions

Nationwide TMY data for global solar radiation is calculated using TMY3 for the 30 weather stations of the CWB that are distributed throughout Taiwan. The database for solar radiation was collected in the 15 years from 2004 to 2018, except for the Chigu weather station for which global radiation data are only available from 2004 to 2015, to assure the collected data quality and meet the requirements of the TMY3 method. Missing data points for solar radiation in the CWB database were interpolated, as much as possible, using the available neighboring data with care (inaccuracy $\leq$ 5%).

Topography, geography, and latitude affect global radiation values. The minimum and maximum global radiation for the 30 weather stations is, respectively, 3421.8 and 5479.9 MJ/m^2 at the Zhuzihu (Station 2) and Tainan (Station 16) weather stations. Annual global radiation increases from the northeast to the southwest on the Taiwanese mainland, which fits the combined effects of topography and latitude. The calculated hourly databases for the TMYs of all investigated weather stations of the CWB are now available in a publicly accessible repository: http://gitub.com/p47061105/TaiwanTMY. This up-to-date, long-term database of solar global radiation is a scientific reference for performance assessments of solar energy applications in Taiwan.

However, while ground measurements in a monotonous landscape with low terrain may reliably represent climate within a radius of a few tens of kilometers, in mountains, close to the sea, and urban centers, and in rapidly changing landscapes, the representative climate may be limited to a few kilometers. Knowledge of the spatial variability of global radiation data are required to meet the need of assessing solar applications accurately. Present global radiation data are available at 24 discretely distributed weather stations in the Taiwanese mainland. Therefore, there is a demand for creating a quality gridded database for global radiation in the Taiwanese mainland through spatial interpolation methods. This issue remains to be studied in the future.

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Nomenclature

CDF	cumulative distribution function
CWB	central weather bureau
DSI	downward solar irradiance, equivalent to global horizontal solar radiation
FS	Finkelstein–Schafer statistics, Equation (2)
G_{sc}	solar constant
H_0	extraterrestrial horizontal daily radiation, Equation (6)
MTSAT	multifunctional transport satellite
NREL	national renewable energy laboratory
PV	photovoltaic
RMSD	root-mean-square difference, Equation (5)
TMM	typical meteorological month
TMY	typical meteorological year
WS	weighting sum, Equation (3)
Greek	
δ	(1) absolute difference between the long-term and the candidate CFDs; (2) declination angle, Equation (7)
ϕ	latitude
ω_{sunset}	hour angle at sunset time, Equation (8)

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