Effect of Solar Position Calculations on Filtering and Analysis of Solar Radiation Measurements

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Abstract

An important step in the analysis and aggregation of solar radiation measurements is quality filtering of the measured values, and most of these tests rely on calculations of the solar position. Such calculations can be performed at different degrees of precision by using algorithms of various complexities. In this work, two solar position calculation methods are used to process one-minute measurements of direct, global and diffuse irradiances from two different locations, and the resulting aggregated and derived quantities at various time scales are compared in order to look for variations in the final products. The differences are found to be mostly irrelevant, except for clearness indices, which are useful in models deriving solar data from satellite observations, so the higher precision calculations are still recommended for such applications. In any case, the differences against non-filtered data can be quite large, stressing the importance of quality checks.

Keywords: solar position, data quality, solar resources

1. Introduction

For the determination and characterisation of available solar resources, the highest accuracies can be achieved by direct on-site measurements, usually collected at one-minute resolution. These measurements are then aggregated temporally to obtain averaged values at diverse time scales, such as 5-, 10-, 15-, 30-minute, or hourly, daily, monthly and up to yearly totals or averages, depending on the application. Given the difficulties involved in the measurement of solar radiation (Panday and Katiyar, 2013), from sensor uncertainties to instrument operation and maintenance, one should not simply average all available data within the desired intervals with the assumption that all measured values are correct; even in well-maintained stations some method of data quality assurance should be used in order to filter out values that are questionable or clearly wrong. The Baseline Surface Radiation Network's (BSRN) recommended checks (Long and Dutton, 2002) are some of the most commonly applied, being an international standard, but other methods can be found (Journee and Bertrand, 2011; Kendrick et al., 1994; Long and Shi, 2009; Moradi, 2009; NREL, 1993; Pashiardis and Kalogirou, 2016; Schwandt, 2014; Younes et al., 2005), some of them even custom-made for a specific project or user. In any case, the most basic quality checks are based on the maximum solar radiation available at any given time.

Solar radiation availability is driven mainly by the sun's position with respect to the observer. Before reaching the surface of the earth, the radiation emitted by the sun must traverse the earth's atmosphere, and this process results in an attenuation of the original energy. Therefore, incoming solar radiation is studied in two steps: first, the so-called extraterrestrial radiation, which is the solar energy arriving at the top of the earth's atmosphere, unaffected along its path from the sun; and second, the radiation arriving at the surface, after atmospheric absorption and scattering.

Due to the eccentricity of the earth's orbit around the sun, the sun-earth distance changes through the year by around +/-1.7%. This is reflected in a slow cyclic change of around +/-3.3% in the extraterrestrial beam radiation, I_{0b}, measured on a plane perpendicular to the direction of the sun rays, and at any given time is the same for all locations on earth (or zero for places on the night-side). However, the extraterrestrial horizontal radiation, I_0, which is I_{0b} projected on a horizontal surface at the top of the atmosphere, depends both on the time of the day and the location on earth (apart from the time of the year, which determines I_{0b}).

Atmospheric attenuation of solar radiation depends fundamentally on the amount of air that light must traverse from the top of the atmosphere to reach a given location, and is furthermore affected by clouds, aerosols and other phenomena. Thus, under clean skies, locations at sea level see decreased levels of radiation as compared to places at high altitudes. However, latitude plays a larger role. At any particular site, variations in solar radiation are determined

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by the continuous changes in the apparent height of the sun above the local horizontal; indeed, attenuation increases rapidly as sun elevations decrease, for and locations at higher latitudes the sun does not always reach high elevations, especially in winter. Moreover, and also for any given location, the sun does not follow the same diurnal path in the sky through the year as the planet revolves around the sun, because the earth's axis of rotation is not perpendicular to the plane of its orbit, but has a 23.5° tilt.

The geometry-related points described above must be considered and quantified when computing the solar position for the site of interest at all times. As geographical and astronomical knowledge has improved through the years, algorithms and their inputs have improved, reaching accuracies of the order of 1/1000 of a degree in the solar position, at the cost, however, of more complex equations. Different methods exist and can be used, from ones comprising few equations to others even requiring current measurements of some parameters; usually, the simpler methods can be applied for any year (within reasonable limits, as the sun-earth geometry changes at the scale of millenia), although with lower accuracies; more advanced methods specify the range of time within which they keep their high accuracy, some covering a few years, and some covering centuries.

Solar resource applications often need data on real or near real time, with quality checks applied at the same time. Even with ever-faster computer processing available, higher speeds are always desirable, so faster algorithms are an advantage. Alternatively, look-up tables of the solar position can be prepared in advance, so that the positions need not be calculated on-the-fly. In all cases, when developing a framework for solar resource assessment, one of the decision points is which solar algorithm to adopt, and currently there is no standard or recommended practice on this regard. With the different options available, the question arises of whether using one or another will result in noticeably different results at the level of the variables useful for solar resource assessment and applications such as solar plant operations, forecasting, etc. This work presents an investigation of possible differences in quality-filtered, aggregated solar data using measurements from three years, taken at two locations; two years are taken from one site, one year from the other.

2. Methodology

As mentioned above, the objective in this work is to compare whether the use of different "solar calculators" (short for solar position calculation methods), when assessing the quality of solar radiation measurements, results in different conclusions in the characterisation of solar resources. This section describes the measured data analysed here, the solar calculators used, the quality checks applied on the data, and the comparison metrics.

2.1. Solar Radiation Data

Measurements from two locations equipped with high-precision monitoring stations were used here. Both stations collected data with Kipp and Zonen instrumentation, comprising thermoelectric sensors and a sun tracker to measure separately the direct normal (Gb), global horizontal (G), and diffuse horizontal (Gd) irradiances, at one-minute resolution.

One station is located in Doha, Qatar, 25.33° N, 51.43° E, 20 m AMSL, and is operated by the Qatar Environment and Energy Research Institute (QEERI) (Perez-Astudillo and Bachour, 2014); from this station, two full years were studied, 2014 and 2015, identified from here on as DOH14 and DOH15. The second station is located at Dar Es Salam University, Tanzania, 6.78° S, 39.20° E, 96 m AMSL (ESMAP, 2016), and one year of data was used, from 1/June/2015 to 31/May/2016, denoted here as DES15.

Data of varying quality is represented by these datasets. In general, the QEERI station provides measurements of higher quality, with the lowest amount of 'bad' data in the DOH14 dataset. The DES15 set shows some long periods of bad data, most likely due to tracking or shading issues. These datasets provide thus the opportunity to test whether the differences in solar calculations have different effect on data that deviates at varying degrees from the limits of the tests (note also that these limits depend on the calculated solar positions).

The BSRN quality checks were applied on the one-minute data, and entries that fail the tests were discarded and considered as missing. The remaining entries, hereby called "valid", were then used to calculate irradiance averages at time scales of 15, 30 and 60 minutes, daily, monthly, and yearly. Table 1 shows the input data ('source') used to derive each averaged value. Missing source entries, either because there is no measured/averaged value or because the (one-minute) value failed QC (quality checks), were not counted in the calculation of averages, i.e., the averages are the sum of valid irradiances divided by the total number of valid source entries in the interval.

To avoid unrepresentative averages when many source entries are missing, minimum numbers of valid data were imposed on each average. The 15-, 30- and 60-minute averages were only calculated if 50% or more of the minutes (at least 7, 15, and 30, respectively) within the interval were valid; otherwise, the average was reported as missing. For daily averages, the minimum acceptable was 80% of the daytime hours in that day, a number that varies with day length through the year. For monthly and yearly averages, 75% of the days within that month or year, respectively, must have a valid average.

Tab. 1: Data used for calculation of different aggregated values, after quality filtering is done on the one-minute data.

Averaged interval	Source data
15 min	1-min
30 min	1-min
60 min (hourly)	1-min
Daily	hourly averages
Monthly	daily averages
Yearly	daily averages

2.2. Solar Position

Two different algorithms were used for this study. The first one, identified here as 'NO' (NOAA, 2018), is from NOAA, the USA's National Oceanic and Atmospheric Administration. The second, called here 'SP' is the MIDC SolPos v2.0 algorithm (SolPos, 2001) from NREL, the USA's National Renewable Energy Laboratory.

For both algorithms, the solar position was calculated for every second of each year (in the case of SP, since NO is year-independent) at each of the sites and from these values, one-minute averages were calculated. This was done because the base solar measurements used are also one-minute averages. Then, 15-, 30- and 60-minute averages were calculated from the one-minute values, also similarly to the solar averages; note, however, that for solar position averages all the minutes within each interval were included.

2.3. Data Quality Checks

The BSRN set of tests were applied to the one-minute measurements. The BSRN tests check whether the values are: within physically possible limits, within extremely rare but physically possible limits, under a maximum diffuse ratio (Gd/G), and consistent among each other (measured G is not very different from a G calculated from Gb and Gd), see (Long and Dutton, 2002). Using the calculated zenith angle and extraterrestrial radiation from each method, SP and NO, the QC equations and limits for each test were obtained and the checks were applied to all daytime entries, which were then flagged according to whether they passed or failed each test from each claculation method, separately. Note that day and night are defined by the sun crossing the local horizon and in this case a zenith angle of 90 degrees was used for both locations; therefore, daytime length depends on the calculated solar position; for NO and SP this meant differences of at most two minutes in daytime length (from sunrise to sunset) in some days of the year. Entries that failed the physically possible, diffuse ratio and consistency checks were removed from the averaging calculations to obtain the aggregated values listed in Table 1. All nighttime entries were considered as 'good quality' and included in the averagings with an irradiance value of zero.

2.4. Comparison Parameters

Comparisons between the methods were quantified through the mean bias error (MBE), mean absolute error (MAE), root-mean-square error (RMSE) and their corresponding relative quantities rMBE, rMAE, rRMSE (in %). Error in this context means the difference between the values derived using the NO method with respect to the ones derived using the SP method, that is, quantities derived from SP calculations were taken as 'reference', since SP provides higher precision.

3. Results and Discussion

3.1. Solar Position Variables

Table 2 presents the differences in the calculated solar variables studied, for all daytime minutes of the year; as previously stated, daytime entries are defined here as those with solar zenith angle (Θz) less than 90 degrees. Since sunrise and sunset may occur at slightly different minutes for each solar calculator, the results in this table only include minutes in which Θz is less than 90 degrees in both sets at the same time. The zenith and azimuth angles are in degrees; I_0 and I_{0b} in W/m^2; the air mass (AM) and fpr (factor used to obtain the modified clearness index proposed by R. Perez) are dimensionless. In general, differences appear smaller than 1% in most cases, but some larger values can be observed. The largest differences are seen for air mass and happen, as shown in Figure 1, at the lowest solar elevations, that is, near sunrise and sunset, when the zenith angle approaches 90 degrees, and the same is found for the fpr factor, which has behaviour similar to that of air mass; this is mainly attributed to the fact that SP includes a correction for atmospheric refraction, which was not included in the NO calculator, and this correction is larger at low solar elevations; however, since solar radiation is low at these elevations, these differences may not have a big effect.

Tab. 2: Comparison of solar calculations for all daytime minutes in each year; 'errors' refer to the difference in NO values with respect to the SP values

	MBE	rMBE(%)	MAE	rMAE(%)	RMSE	rRMSE(%)
DOH14						
Θz	0.043	0.082	0.156	0.295	0.190	0.359
azimuth	0.004	0.002	0.277	0.154	0.352	0.196
I_0	-0.957	-0.126	3.669	0.482	4.440	0.583
I_{0b}	-0.072	-0.005	1.913	0.140	2.222	0.163
AM	0.111	3.367	0.117	3.559	0.570	17.339
fpr	0.003	0.276	0.004	0.324	0.013	1.078
DOH15						
Θz	0.043	0.082	0.123	0.233	0.153	0.289
azimuth	0.006	0.003	0.208	0.116	0.271	0.151
I_0	-0.955	-0.125	3.137	0.412	3.824	0.502
I_{0b}	-0.072	-0.005	1.913	0.140	2.222	0.163
AM	0.111	3.381	0.115	3.498	0.563	17.109
fpr	0.003	0.276	0.004	0.307	0.012	1.046
DES15						
Θz	0.031	0.065	0.092	0.189	0.118	0.241
azimuth	0.005	0.003	0.298	0.166	2.786	1.548
I_0	-0.802	-0.097	2.001	0.241	2.664	0.321
I_{0b}	-0.065	-0.005	1.977	0.145	2.303	0.168
AM	0.101	3.313	0.103	3.385	0.533	17.472
fpr	0.003	0.252	0.003	0.270	0.012	0.988

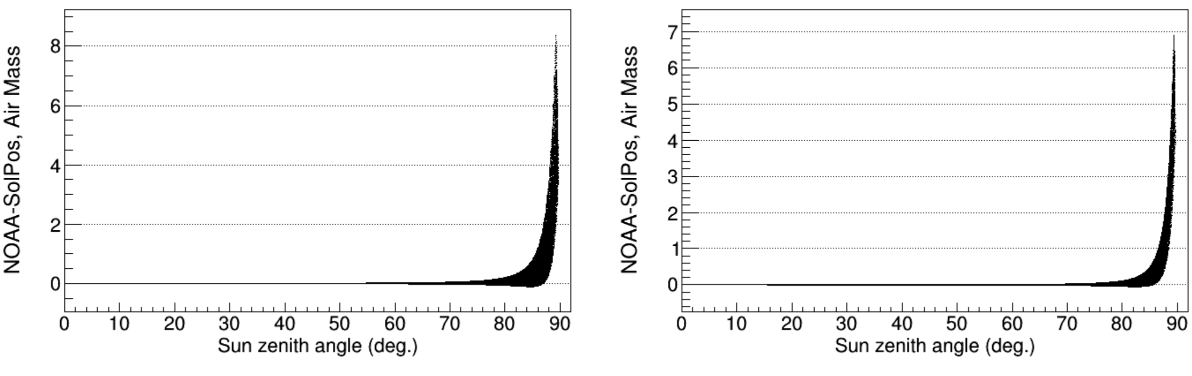

Fig. 1: Difference in air mass as calculated with NO with respect to SP, as function of solar zenith angle, for DOH14 (left) and DES15 (right).

3.2. Quality Check Filtering

The percentages of daytime entries, per dataset (year), that failed to pass the quality checks using the NO and SP methods are listed in Table 3, together with the total number of daytime minutes (only excluding non-available entries) according to each method.

Tab. 3: Percentages of one-minute daytime entries that failed QC in each year, from the SP and NO methods. N_{SP} and N_{NO} are the total number of daytime minutes, according to each method; unavailable entries are not counted.

	%SP	%NO	N_{SP}	N_{NO}
DOH14				
Gb	0.072	0.095	265389	263880
G	0.237	0.158	265389	263880
Gd	0.595	0.338	265389	263880
DOH15				
Gb	3.051	3.033	265717	264218
G	3.247	3.117	265717	264218
Gd	3.555	3.283	265717	264218
DES15				
Gb	15.365	14.814	265435	264082
G	15.382	14.830	265435	264082
Gd	15.389	14.837	265435	264082

To identify where the QC are producing the highest differences, Figure 2 presents the difference (NO with respect to SP) in percentage of failed entries within each hour and day of the year, for the three datasets. Most differences are negative, indicating that the NO-based checks find lower amounts of bad entries. No seasonal trends can be seen, but it is noted that the quality evaluation of G and Gb data from the DOH station presents higher differences at the lowest elevations, mainly during summer, and all through days with large amounts of bad quality data (e.g., around day 280 in DES15, as mentioned in Section 2.1).

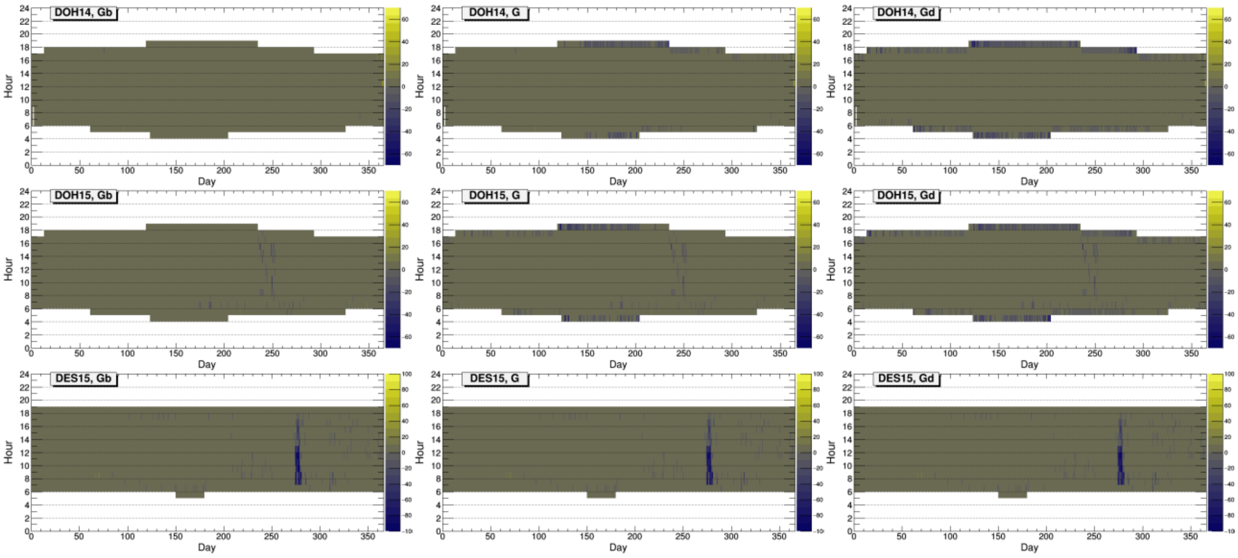

Fig. 2: Differences in the percentage of daytime entries that failed QC for each solar irradiance component, within each hour of each day. The colour scales represent the differences of NO with respect to SP. Note that for DES15 the scales go up to +/-100%.

Looking from another perspective, the percentages of failure, from each method separately, are depicted in Figure 3 as a function of irradiance, in bins of 100 W/m^2. The graphs show that the lowest G and Gd values have failure rates around 2-3% at the DOH station, with the NO-based tests finding less bad-quality entries than SP. Otherwise, the difference between both methods does not indicate a noticeable dependency on irradiance. Notice also that for DES15 the large Gd values, which are clearly erroneous, are always identified in the most extreme cases (~1000 W/m^2 and above), but between 500 and 1000 W/m^2 the tests are less likely to find all the (possibly) wrong data.

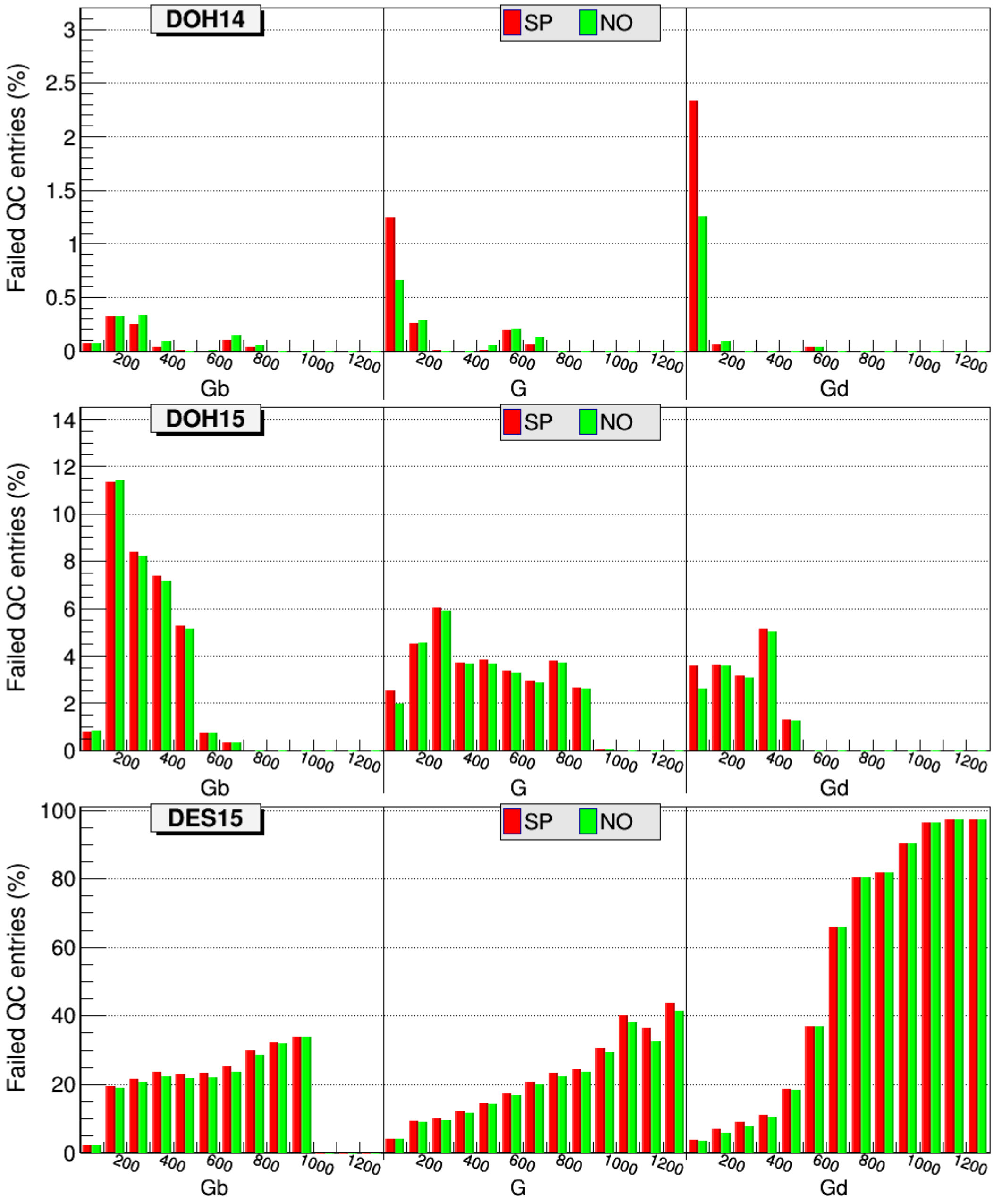

Fig. 3: Percentage of entries that failed QC for each solar irradiance component, as a function of irradiance.

3.3 Aggregated Solar Radiation

After removing the entries that fail QC, different averages were calculated. As general overview, the total annual irradiations (in kWh/m^2) are given in Table 4. For reference, the table also includes the annual totals obtained without any quality filtering, that is, by including all the available measurements. For DES15 the required the number of days with valid data had to be reduced in order to obtain a yearly value. It is evident that at this level the solar calculation method does not make any difference.

Tab. 4 :Total annual irradiations (in kWh/m^2) for the three datasets by using all available data (RAW columns), and after QC filtering based on SP and NO calculations.

		Gb			G			Gd	
	RAW	**SP**	**NO**	**RAW**	**SP**	**NO**	**RAW**	**SP**	**NO**
DOH14	2073	2068	2069	2203	2205	2206	777	778	778
DOH15	1785	1800	1799	2130	2134	2133	879	876	875
DES15	1389	1266	1266	1910	1798	1798	1159	902	902

Also at the level of monthly and daily irradiations (not shown) both solar calculation methods produce the same results. At higher temporal resolution, but looking for possible temporal dependencies, Figure 4 illustrates the monthly averages of the differences in *hourly* irradiance, for each daytime hour of the day. No seasonal dependences are seen, but it is noted that, in general, the differences are slightly larger in two cases: the more common is in the hours that include sunrise and sunset, mainly due to the smaller values of measurements and calculations, which result in comparatively larger sensitivities in the tests; and relatively larger differences (although still small, under +/-4 W/m^2) are found in periods with large percentages of low-quality data, as seen in August-September for DOH15 and February-March for DES15.

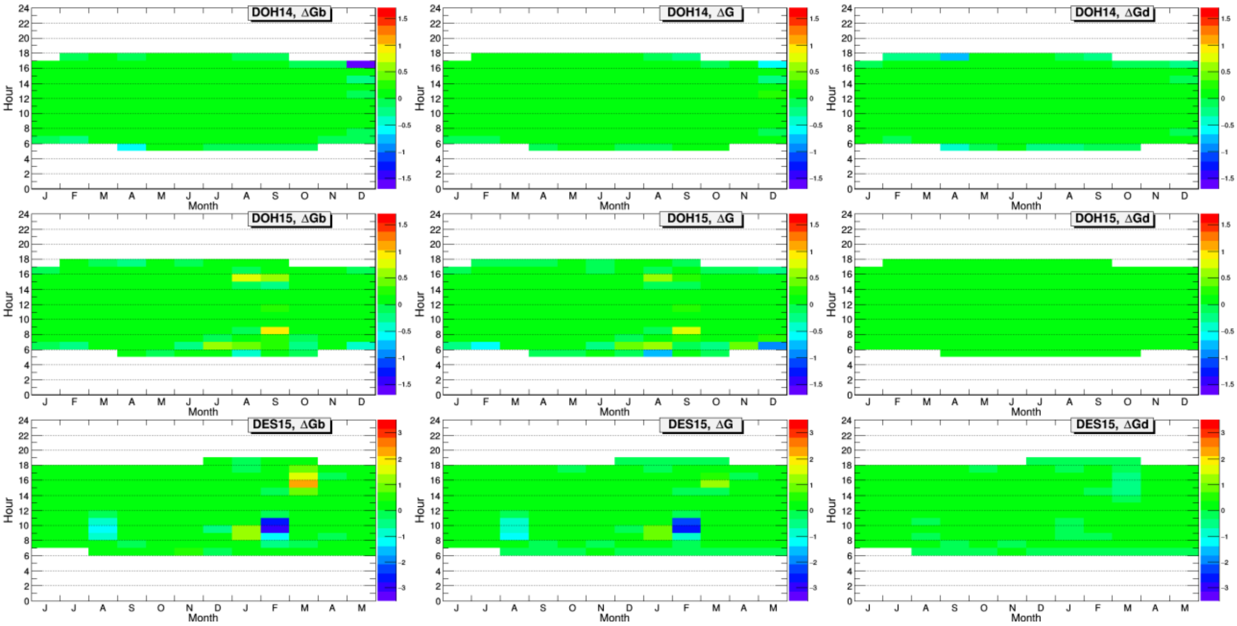

Fig. 4: Monthly averages of the difference (NO – SP) in hourly irradiances are shown in colour scales, in W/m^2.

3.4 Clearness Indices

The atmospheric clearness indices are normalised forms of the irradiances that remove the seasonal changes in Iob and I_0, and are commonly used in many applications, from charaterising solar climate to modelling and forecasting solar radiation. Given their widespread use, two indices were also studied here: the beam clearness index Kn = Gb / I_{0b}, and the global clearness index Kt = G / I_0; their values range from 0 to 1, but in some cases can be slightly above 1 due to reflections from clouds. Figure 5 shows the relative differences, in %, between the hourly clearness indices, averaged over each month in the periods under study; as before, the SP-based values were taken as reference. The hourly Kt and Kn were obtained using the corresponding hourly averages of the measured and extraterrestrial irradiances. As in the previous cases, no clear seasonal dependencies can be seen (the change in shade of green from June to July corresponds to a change of less than 0.2%), and the larger differences are seen in the sunrise/sunset hours, reaching as much as 8%, but the rest of the time the differences are well within +/-2%.

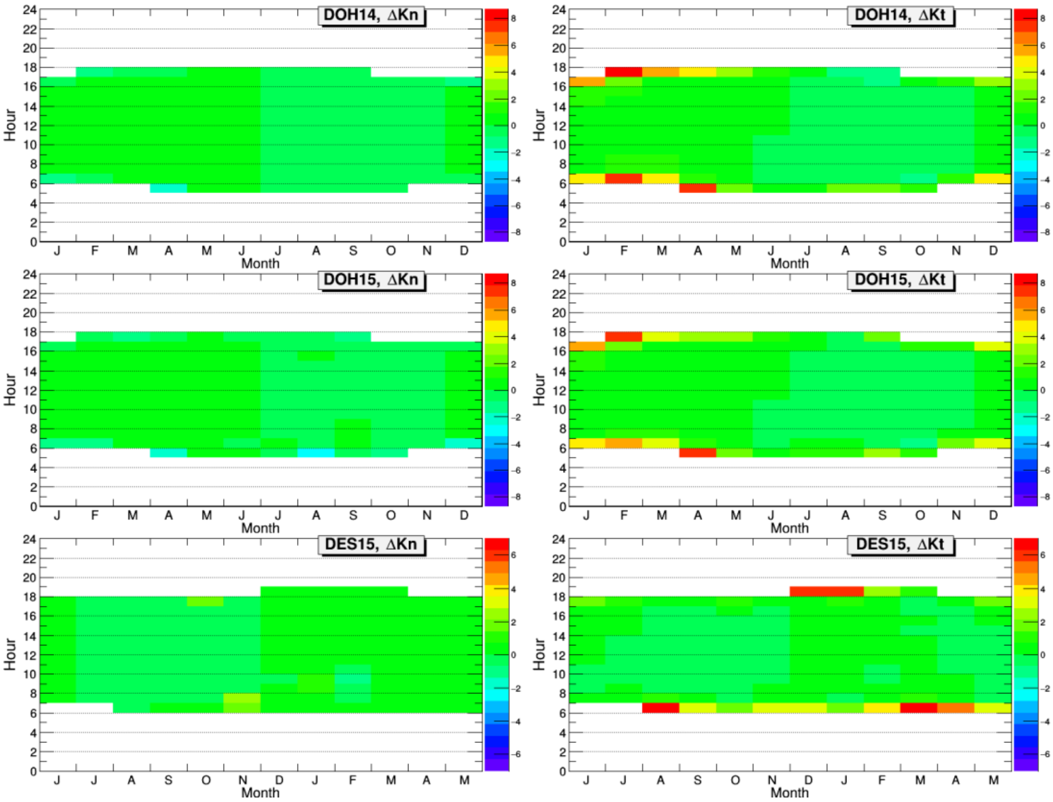

Fig. 5: Monthly averages of the relative difference (No – SP) in the hourly values of the beam and global clearness indices, Kn and Kt respectively, shown in the colour scales in %.

4. Conclusion

To assess the quality of measured solar radiation, a number of tests are applied in order to flag data so that erroneous measurements can be excluded from the analysis. Many commonly used tests are based on the position of the sun in the local sky at the time of each measurement, and since it is not practical to measure this position continuously, it is normally determined through calculations, for which a wide spectrum of choice exists. Calculation methods differ in precision and temporal coverage, varying in complexity, with some of them even requiring external (measured) inputs. For solar applications, currently there is no recommended standard methodology for the calculation of solar position, so the selection is in each case a matter of convenience, chance, or speed, although the highest precisions are frequently sought for, without knowing whether the highest accuracies are really necessary for studying solar resources, that is, whether they actually make a difference in a practical sense. The study presented here used two different solar calculation methods to derive the BSRN quality checks applied to a total of three years of data from two different locations. After filtering the measured data at one minute resolution, averages of the direct, global and diffuse irradiances were made at different time scales, namely, 15, 30 and 60 minutes, daily, monthly and annual, and results from both methods were compared to look for differences. The results indicate that through the year there is no noticeable change in derived quantities by using either of the two solar position calculation methods, although some (yet still small) differences can be noticed at low solar elevations and during periods with large amounts of bad-quality data.

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