UPDATE ON THE RE-ESTABLISHMENT OF THE SOUTH AFRICAN WEATHER SERVICES (SAWS) RADIOMETRIC NETWORK IN ALL SIX CLIMATOLOGICAL REGIONS AND THE QUALITY OF THE DATA

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Abstract

The South African Weather Services (SAWS) had a well maintained radiometric network measuring hourly global horizontal irradiation (GHI) and diffuse horizontal irradiance (DIF) data since 1960s. Unfortunately, the network collapsed in the late 80s and early 90s. From 2013, SAWS re-established its solar radiometric network by installing a set of 13 stations capable of measuring GHI, DIF and direct normal irradiance (DNI) in all 6 climatological regions of South Africa. Furthermore, at the De Aar Baseline Surface Radiation Network (BSRN) station there are continuous measurements of the long-wave downward radiation (LWD). The overall percentage performance of SAWS' solar radiation network based on BSRN Quality Control (QC) methodology is 97.79%, 93.64%, 91.6% and 92.23% for LWD, GHI, DIF and DNI respectively. Operational problems dominated the percentage of bad data as follows LWD 2.21%, GHI 1.6%, DIF 3.57% and DNI 3.57%. Overall, the validation results of quality controlled solar radiation at SAWS complemented other solar radiometric networks, satellite data sets, reanalysis archives and literature. The established network has the potential of providing high quality minute solar radiation data sets (GHI, DIF, DNI and LWD) and auxiliary hourly meteorological parameters vital for scientific and practical applications in renewable energy technologies in South Africa.

Keywords: South African Weather Service (SAWS); Radiometric network; Solar radiation; Climatological regions; Baseline Surface Radiation Network (BSRN); Quality Control (QC)

1. Introduction and Theory

1.1. Significance of accurate radiometric measurements

There is a need for knowledge of the amount of solar irradiance received at different sites in South Africa [1]. Historically, SAWS has been the main source of ground solar radiation data, but the network ceased due to technical difficulties and lack of maintenance [2, 3]. The hourly GHI and DIF data from the network that decayed is available in (W/m^2), but the data does not have metadata and some stations have a lot of gaps. According to [4] accurate assessment of solar based renewable energy technologies requires a reliable short-time step database of solar radiation values. With this in mind, SAWS re-established its entire solar network from 2013 with a 13 all-in one solar radiation stations with robust and reliable instruments which according to [5] are suitable for BSRN solar radiation measurements. The 13 SAWS radiometric stations are distributed in all 6 different climatic zones of South Africa as shown in Table 1. Climatic zones are the regions with similar climatic conditions [6] and according to [7] climatic zones were established in order to classify different areas based on their maximum energy demand and maximum energy consumption. Where each radiometric station is located there is an automatic weather station (AWS) measuring hourly temperature, rainfall, pressure, humidity, cloud cover, wind speed and wind direction providing auxiliary meteorological parameters.

1.2. Solar radiometric activities at SAWS

De Aar (DAA) is part of BSRN stations [8], SAWS submit monthly De Aar data sets to BSRN international database, data send to the database had been used in international publications and to validate satellite and models [9, 10, 11, 12]. The other 12 SAWS radiometric stations are not part of BSRN stations but they follow all the protocols set up by World Meteorological Organization (WMO) and BSRN from the site (location), instrumentation, operations, maintenance, data acquisition and archiving, data quality control procedures and calibration methodologies. In this regard, 11 of 13 SAWS radiometric stations namely Prieska, Upington, Irene, Nelspruit, Mafikeng, Mthatha, Bethlehem, George, Durban, Polokwane and Thohoyandou have the same set up. They are all equipped with two secondary standard Kipp & Zonen pyranometers (CMP11) , one CMP11 is unshaded to measure GHI the other CMP11 is shaded with a shadow ball that is mounted on a Kipp & Zonen SOLYS 2 sun-tracker to shield off the direct sun beams measures DIF and a first class Kipp & Zonen pyrheliometer (CHP1) automatically aligned perpendicular to the sun beams by a Kipp & Zonen SOLYS 2 sun-tracker to measure DNI.

De Aar BSRN station have the same set up as the 11 radiometric stations above except that is equipped with high performance CMP21 pyranometers, the sensors have a ventilation unit (CVF4) and have an additional sensor a Kipp & Zonen pyrgeometer (CGR4) to measure LWD. Cape Point radiometric station is equipped with CMP11 and CHP1 but the pyranometers are placed on a 2 meter bench, the DIF measuring CMP 11 is shaded with a metal shadow ring to shield off the direct sun beams instead of a shadow ball and also the CHP1 is mounted on a Kipp & Zonen's two axis 2AP sun tracker, Kipp & Zonen SOLYS 2 sun-tracker was used before but it was replaced in April 2016 after it was blown away by the wind.

Station	Latitude (S, positive)	Longitude (E, positive)	Altitude (m)	Data Coverage	Climatic Zone
		SAWS current			
Prieska	-29.68	22.71	989	2013-09 to 2015-08	Arid
Upington	-28.48	21.12	848	2014-02 to 2017-12	Arid
De Aar	-30.67	23.99	1284	2014-05 to 2017-12	Cold
Irene	-25.91	28.21	1524	2014-08 to 2017-12	Temperature
Nelspruit	-25.39	31.1	870	2014-05 to 2017-12	Hot Interior
Mafikeng	-25.81	25.54	1289	2016-01 to 2017-12	Temperature
Mthatha	-31.55	28.67	744	2014-08 to 2017-12	Subtropical
Bethlehem	-28.25	28.33	1688	2015-01 to 2017-12	Cold Interior
Cape Point	-33.96	18.6	42	2015-02 to 2017-12	Temperature
George	-34.01	22.38	192	2015-01 to 2017-12	Temperature
Durban	-29.61	31.11	91	2016-02 to 2017-12	Subtropical
Polokwane	-23.86	29.45	1233	2015-03 to 2017-12	Temperature
Thohoyandou	-23.08	30.38	614	2015-03 to 2017-10	Hot Interior

Table 1. Description of the new 13 SAWS radiometric station location and climatic zone

1.3. Data acquisition

Data from all 13 SAWS radiometric stations is acquired using a Campbell Scientific CR100 data logger with a sampling rate of 5 seconds. The mean, maximum, minimum and standard deviation of radiation parameters are recorded every minute. The minute values from all 13 stations are send to the central database at SAWS head office in Pretoria remotely via GPRS signals where it is achieved in monthly files per station, during the achieving process basic quality control checks like filling in the data gaps with a standard code **(-999)** takes place and metadata is created.

1.4. Station maintenance and calibration

Station maintenance, inspection and cleaning activities are conducted on a bi-weekly basis. This involves dusting of the sensor dome using a soft lint-free cloth and distilled water to remove any dust on the domes and optical windows, checking on the alignment of the shadow ball (or the shadow ring) and the CHP1 if the sun spot is still pointing to the sun, check if the spirit in the CMP11 and CMP21 is still level horizontally, check if all the cables are still intact and no damages. Desiccants are replaced within 6 months. Cleaning and inspection times are recorded (metadata). SAWS have central radiation monitoring screen at the head office, where battery voltage levels, radiation data transmission (using GPRS), suspicion of the sun-tracker alignment and unusual parameter curves shape are monitored in real time, if there is something suspicious people from station are contacted immediately to double check and take an action to fix the problem as soon as possible.

All operational sensors CMP11, CMP21, CHP1 and CGR4 were calibrated by the manufacturer and they are traceable to the World Radiometric Reference (WRR) based on International Pyrheliometer Comparison **(IPC-XI, 2010)** factors, this means that SAWS measurements meet the international criteria for accurate and scientifically valid radiometric data. Calibration certificates for each of the 40 operational sensors in network are readily available (metadata). SAWS have two primary standards reference calibrating instruments a Physikalisch-Meteorologisch-Observatorium **(PMO6 850404)** Standard cavity pyrheliometer and an EPPLEY Absolute Cavity Radiometer **(AHF 31109)** and three secondary standard reference calibrating instruments a Linke-Feussner pyrheliometer **(LINKE 700198)** and two pyrheliometers **(CHP1 170481, CHP1 170482)** all these 5 calibrating instruments are traceable to the WRR through **(IPC-XII, 2015)** factors, they will be used as standard references to re-calibrate the network in 2018 . SAWS also have a Kipp & Zonen Calibration Facility for Radiometers (CFR Facility) which will be used as an artificial sunlight source for indoor calibration.

2. Data and Analysis method

Minute solar radiation data GHI, DIF, DNI and LWD from all 13 SAWS solar radiometric stations as shown on Table 1 above is subjected to quality check procedures based on BSRN QC standards [9, 13]. These are physically possible limits, extremely rare limits and comparison test before any analysis, only the data that passes the first two quality check tests (physically possible limits and extremely rare limits) is used in the analysis. Missing data and the data that did not pass the first two BSRN QC tests is discarded (replaced by NaN) and will not be part of the analysis methodology applied by [9, 11, 14, 15]. After quality check, months that have less than 10 % of missing data plus data that failed the first two quality checks is used (only a month with 90% or more of available data plus the data that passed first two quality check tests is used). After quality checks, the minute values are averaged to 15 minutes and then 4 slots of 15 minute averages are averaged to get hourly mean values, see e.g. [9, 11, 15]. Further, all night values, values between sunset (20:00) and sunrise (05:00) based on South African standard time (SAST), i.e., when the solar zenith angle is less than 90 degrees (SZA < 90 degrees) are replaced by 0. Hourly mean values are then averaged to get daily mean values and monthly mean values were calculated from daily mean values.

Additionally, Satellite Application Facility (SAF) on Climate Monitoring (CM), CMSAF [17], Environmental Data Records (EDR) monthly mean Surface incoming shortwave radiation (SIS) data with a spatial resolution of (0.05°x 0.05°) from Meteosat Second Generation (MSG) was used to validate concurrent quality checked monthly average GHI values calculated from minute GHI values measured from 13 SAWS solar radiometric network. According to [18], the EDR products are accurate enough to be used for solar energy applications and to support meteorological organization with diurnal, sub-seasonal and seasonal solar radiation data sets. The validation metrics mean bias error (MBE), mean absolute bias error (MABE), root mean square error (RMSE), square of correlation coefficient (r^2) from all the months with 90% or more good data. Diffuse Fraction (DHI/GHI), hereafter DF, was also calculated from all 13 stations from the months with 90% or more of both GHI and DIF good data. Annual average temperature and humidity of each station from 2013 to 2017 were calculated for each radiometric station using hourly data from AWS.

NASA Surface meteorology and Solar Energy (NASA SSE) annual averaged GHI values for a 22-year period (July 1983 - June 2005) with a spatial resolution of 1°x 1° [19] was also used in the validation of quality controlled data from 13 SAWS radiometric station monthly mean GHI data .Validation results from [20, 21] were also used to validate the performance of new SAWS radiometric network, Durban STARlab 2017 [22] (annual GHI mean, temperature, humidity, diffuse fraction) were also used to compare a nearby station Durban. SAWS historical long term annual mean GHI and DIF data from 1962 to 1982 [23] was also compared to the nearby stations.

3. Results and Discussion

3.1. BSRN QC results

After subjecting all the minute solar radiation data measured at a newly established SAWS radiometric network to all three BSRN quality check procedures reported in [9], the monthly percentage per station quality code for each radiation parameter was calculated from monthly percentages weighted yearly averages were calculated and then from weighted yearly averages overall station performance per station for each parameter was calculated. The results are shown in Table 2 (LWD), Table 3 (GHI), Table 4 (DIF) and Table 5 (DNI). Only data represented by code 0 is regarded as the data that passed all the three BSRN QC tests, code 5 represent missing data or data that was not recorded, code 8 and 10 represent data that failed first and second BSRN QC tests respectively, code 16 and 32 represent data that failed the third BSRN QC test, code 40 represent data that failed both the second and third BSRN QC test and 42 represent data that failed all three BSRN QC tests. When doing analysis only data coded 0, 16 and 32 was used regarded as good data, data coded 5, 8, 10, 40 and 42 was discarded and replaced by NaNs as they were regarded as bad data. In general, only the data with more than (90 % sum of the data coded 0, 16, 32) was used in the analysis.

Parameter	**Long-Wave Downward Iradiance (LWD)**							
Code/Station	**0**	**5**	**8**	**10**	**16**	**32**	**40**	**42**
De Aar	97.79	2.21	0	0	0	0	0	0
Overall	**97.79**	**2.21**	**0**	**0**	**0**	**0**	**0**	**0**

Table 2. Weighted averages of all BSRN QC codes for LWD at De Aar from when the station started recording a full month of data to end of December 2017

Parameter	Global Horizontal Irradiance (GHI)							
Code/Station	**0**	**5**	**8**	**10**	**16**	**32**	**40**	**42**
Prieska	96.91	2.79	0	0	0	0.3	0	0
Upington	97.29	1.61	0	0	0.7	0.4	0	0
De Aar	97.02	2.13	0	0	0	0.8	0	0
Irene	96.89	0.02	0.1	1.2	0.8	0.5	0.14	0
Nelspruit	93.45	0.01	0.1	0.8	0.1	5.6	0.02	0
Mafikeng	94.86	0.04	0.2	0.8	0.4	3.6	0.05	0
Mthatha	99.16	0.01	0	0	0.2	0.6	0.02	0
Bethlehem	94.7	0.12	0.1	0.9	0.7	3.3	0.14	0
Cape Point	92.37	3.13	0	0	0.3	4.2	0.03	0
George	84.07	2.85	0.1	0	2.5	11	0.04	0
Durban	95.59	0.01	0	0	1.5	2.9	0	0
Polokwane	84.12	2.32	0	0.2	0.5	7.3	0.1	0
Thohoyandou	90.84	5.61	0	0	4.9	1.2	0	0
Overall	**93.64**	**1.59**	**0**	**0.3**	**1**	**3**	**0**	**0**

Table 3. Weighted averages of all BSRN QC codes for GHI per station from when the station started recording a full month of data to end of December 2017

Parameter	Diffuse Horizontal Irradiance (DIF)							
Code/Station	**0**	**5**	**8**	**10**	**16**	**32**	**40**	**42**
Prieska	96.77	2.79	0.2	0	0.2	0	0.01	0
Upington	97.2	1.61	0.1	0.1	0.4	0.7	0.01	0
De Aar	97.02	2.24	0.2	0	0.8	0.1	0.01	0
Irene	96.93	0.02	0.2	1	0.9	0.8	0	0
Nelspruit	93.42	0.01	0.1	1.2	5.1	0.1	0	0
Mafikeng	94.8	0.04	0.3	0.8	3.7	0.4	0	0
Mthatha	99.16	0.06	0	0	0.6	0.2	0	0
Bethlehem	92.12	2.12	1.5	1.1	3.5	0.7	0.07	0
Cape Point	90.56	3.13	1.8	0	4.2	0.3	0.02	0
George	83.81	5.47	0.4	0	12	1.2	1.12	0
Durban	74.98	20.64	0.1	0	2.9	1.5	0	0
Polokwane	83.64	2.32	0.7	0.1	7.4	0.5	0	0
Thohoyandou	90.41	6	0	0	1.6	4.5	0	0
Overall	**91.6**	**3.57**	**0**	**0.3**	**3.3**	**1**	**0.1**	**0**

Table 4. Weighted averages of all BSRN QC codes for each DIF per station from when the station started recording a full month of data to end of December 2017

Parameter	Direct Normal Irradiance (DNI)							
Code/Station	**0**	**5**	**8**	**10**	**16**	**32**	**40**	**42**
Prieska	96.85	2.79	0.1	0	0.3	0	0	0
Upington	97.23	1.57	0.2	0	0.3	0.5	0	0
De Aar	96.79	2.13	0.2	0	0.8	0.1	0	0
Irene	96.86	0.02	1.4	0	0.9	0.8	0	0
Nelspruit	93.64	0.01	0.7	0	5.6	0.1	0	0
Mafikeng	95.1	0.04	0.8	0	3.7	0.4	0	0
Mthatha	99.15	0	0	0	0.6	0.2	0	0
Bethlehem	94.74	0.12	1	0	3.5	0.7	0	0
Cape Point	92.38	3.13	0	0	3.6	0.3	0	0
George	84	5.63	0.1	0	11	2.4	0	0
Durban	75.7	20.01	0	0	2.9	1.4	0	0
Polokwane	84.06	2.32	0.3	0	7.4	2.3	0	0
Thohoyandou	92.7	6	0	0	1.2	1.6	0	0
Overall	**92.23**	**3.37**	**0**	**0**	**3.2**	**1**	**0**	**0**

Table 5. Weighted averages of all BSRN QC codes for DNI per station from when the station started recording a full month of data to end of December 2017

3.2. Validation and Comparisons results

Months with 90% or more of minute good data were used to calculate monthly mean GHI and DHI. Tables 6, 7 and 8 provide information on the number of months (for each station) that were used for validation analysis From Table 7, almost all the sites had a negative MBE (observation minus satellite) values meaning CMSAF EDF SIS consistently overestimated ground measurements. According [12], the validation accuracy threshold MABE of monthly mean GHI against CMSAF monthly SIS ought to be 15 W/m^2, target accuracy threshold is 10 W/m^2 and optimal accuracy threshold is 8 W/m^2.The comparison between concurrent CMSAF EDR SIS against SAWS GHI monthly means showed a great similarity with MABE of less than 15 W/m^2 in 11 of 13 stations. Only Cape Point (temperature coastal) and Durban (subtropical coastal) stations had an MABE greater than a validation threshold accuracy 15 W/m^2 i.e., 18.9 W/m^2 and 19.0 W/m^2 respectively.

Prieska, Upington, De Aar, Irene, Mafikeng, Bethlehem, Polokwane (stations located in the arid climatic regions, cold interior and temperature interior) reached an optimal threshold with a MABE of less than 8 W/m^2 when compared to CMSAF EDR SIS, Nelspruit (hot interior) reached a target accuracy threshold with MABE less than 10 W/m^2 while Thohoyandou (hot interior), George (temperature coastal) and Mthatha (subtropical coastal) meet the validation threshold with MABE less than 15 W/m^2.

Station	Latitude	Longitude	Altitude	N	GHI_OBS	GHI_CMS	NASA_SEE
	(S, positiv	(E, positiv	(m)	(Months)	(W/m^2)	(W/m^2)	(W/m^2)
SAWS current							
Prieska	-29.68	22.71	989	21	241.8	246.0	243.3
Upington	-28.48	21.12	848	44	261.1	260.2	244.6
De Aar	-30.67	23.99	1284	40	258.1	258.9	240.8
Irene	-25.91	28.21	1524	41	236.8	243.7	235.4
Nelspruit	-25.39	31.1	870	42	203.9	212.9	203.8
Mafikeng	-25.81	25.54	1289	23	246.9	251.1	238.3
Mthatha	-31.55	28.67	744	41	193.1	203.1	201.3
Bethlehem	-28.25	28.33	1688	30	227.7	232.9	229.2
Cape Point	-33.96	18.6	42	17	180.9	215.4	226.3
George	-34.01	22.38	192	36	194.9	207.4	208.8
Durban	-29.61	31.11	91	23	181.0	200.1	181.3
Polokwane	-23.86	29.45	1233	29	230.0	238.0	230.0
Thohoyandou	-23.08	30.38	619	30	199.7	210.0	211.7
Spain							
Almeria	36.85	-2.39		12	205.4	199.9	210.8
Malaga	36.72	-4.48		12	206.5	200.6	199.5
Bilbao	43.17	-2.91		12	144.6	151.1	162.9
Sweden							
Visby	57.67	18.35		212	122.8	127.5	131.3
Lund	55.71	13.21		222	114.0	113.1	120.8
Karlstand	59.36	13.47		214	113.8	117.2	112.5
Finland							
Helski-Kump	60.2	24.96		35	117.3	122.8	113.8
Uto	59.78	21.37		97	121.5	129.6	127.5
SAWS Historical							
Upington	-28.4	21.27	836	156	259.8		244.6
Pretoria	-25.73	28.18	1330	156	229.8		235.4
Cape Town	-33.97	18.6	44	156	221.1		226.3
Durban	-29.96	30.95	8	156	186.9		196.3
Port Elizabeth	-33.98	25.6	60	156	208.2		201.7
Bloemfontein	-29.1	26.3	1351	156	246.6		236.3
STARLab Du	-29.97	30.92	105.5	12	185.4		196.3

Table 6. Validation results of SAWS GHI, CMSAF SIS, NASA SSE, Spanish National radiometric network, Sweden radiometric network and Finland radiometric network, SAWS historical network and STARlab Durban

Station	Latitude	Longitude	Altitude	N	MBE	MABE	RMSE	(r^2)
	(S, positi	(E, positive	(m)	(Months)	(W/m^2)	(W/m^2)	(W/m^2)	
SAWS current								
Prieska	-29.68	22.71	989	21	-4.2	4.2	5.4	0.998
Upington	-28.48	21.12	848	44	0.9	3.8	5.2	0.995
De Aar	-30.67	23.99	1284	40	-0.8	3.6	4.6	0.997
Irene	-25.91	28.21	1524	41	-6.9	7.8	10.0	0.981
Nelspruit	-25.39	31.1	870	42	-8.9	9.0	11.4	0.958
Mafikeng	-25.81	25.54	1289	23	-4.1	5.1	6.9	0.989
Mthatha	-31.55	28.67	744	41	-10.3	10.3	12.1	0.982
Bethlehem	-28.25	28.33	1688	30	-5.2	5.6	7.7	0.989
Cape Point	-33.96	18.6	42	17	-18.9	18.9	21.5	0.991
George	-34.01	22.38	192	36	-12.5	12.5	13.5	0.997
Durban	-29.61	31.11	91	23	-19.0	19.0	20.1	0.981
Polokwane	-23.86	29.45	1233	29	-7.4	7.6	11.6	0.964
Thohoyandou	-23.08	30.38	619	30	-10.3	10.4	13.2	0.964
Spain								
Almeria	36.85	-2.39		12	-5.4	7.5	9.8	0.990
Malaga	36.72	-4.48		12	-5.9	7.6	9.7	0.990
Bilbao	43.17	-2.91		12	6.5	10.2	13.9	0.980
Sweden								
Visby	57.67	18.35		212	-4.7	5.8	7.7	0.890
Lund	55.71	13.21		222	0.8	5.0	7.1	0.900
Karlstand	59.36	13.47		214	-3.3	4.9	7.0	0.900
Finland								
Helski-Kum	60.2	24.96		35	-5.5	6.4	8.0	0.900
Uto	59.78	21.37		97	-8.1	8.2	10.1	0.920

Table 7. Validation statistics results of SAWS GHI, CMSAF SIS, Spanish National radiometric network, Sweden radiometric network and Finland radiometric network

Stations	Latitude	Longitude	Altitude	N	DHI_OBS	Diffuse	Humidity	Temp
	(S, positive	(E, positive)	(m)	(Months)	(W/m^2)	Fraction	(%)	(°C)
SAWS current								
Prieska	-29.68	22.71	989	21	42.6	0.18	38.0	20.2
Upington	-28.48	21.12	848	44	46.5	0.18	35.4	20.9
De Aar	-30.67	23.99	1284	40	50.0	0.20	44.5	17.5
Irene	-25.91	28.21	1524	41	72.0	0.30	54.9	18.2
Nelspruit	-25.39	31.1	870	42	74.9	0.40	62.0	19.5
Mafikeng	-25.81	25.54	1289	23	61.4	0.24	43.9	19.9
Mthatha	-31.55	28.67	744	41	69.5	0.33	68.1	17.4
Bethlehem	-28.25	28.33	1688	30	72.9	0.31	59.1	14.7
Cape Point	-33.96	18.6	42	17	66.8	0.34	77.2	16.1
George	-34.01	22.38	192	36	69.5	0.36	79.2	15.9
Durban	-29.61	31.11	91	23	71.9	0.39	72.8	20.5
Polokwane	-23.86	29.45	1233	29	73.2	0.31	58.2	18.0
Thohoyandou	-23.08	30.38	619	30	68.3	0.34	60.8	21.1
SAWS Historical								
Upington	-28.4	21.27	836	156	50.2	0.19		
Pretoria	-25.73	28.18	1330	156	68.1	0.30		
Cape Town	-33.97	18.6	44	156	61.4	0.28		
Durban	-29.96	30.95	8	156	69.9	0.37		
Port Elizabeth	-33.98	25.6	60	156	68.6	0.33		
Bloemfontein	-29.1	26.3	1351	156	59.6	0.24		
STARlab Durb	-29.97	30.92	105.5	12	70.5	0.38	74.9	21.8

Table 8. Validation results of SAWS DHI, SAWS DF, annual humidity and annual temperature, SAWS historical DHI, SAWS historical DF and STARlab DHI observed, DF, humidity and temperature

The DF and humidity are two important parameters that impact on the performance of some solar energy systems [22]. In the analysis of these two parameters, it was observed that De Aar, Upington, Prieska and Mafikeng have annual DF (DIF/GHI) of less than 0.3 while the humidity was less than 50 %. Nelspruit, George, Durban and Cape Point have an annual DF greater than 0.34 while Cape Point, George and Durban had annual humidity of more than 70 %. Cape Point and Durban have both higher humidity and higher DF which could be attributed to high aerosol load, and hence higher MABE values at these coastal stations. Stations located at a very low altitude showed a large MABE, Cape Point and Durban included, station altitude might be one of the factors that contribute to overestimation of ground solar radiation by satellites.

De Aar BSRN was the only station from Southern Africa that was used to validate CMSAF satellite [24] stations with the same climatology as De Aar (inland, west side of the country towards the interior) showed a very good similarity while stations with different climatology to De Aar (coastal, east side of the country) Durban and Cape point included did not show a very good similarity. According to [25] the difference can be due to underestimation of aerosol effect when SIS CMSAF product was derived, sensitivity changes of the radiometers can also be a factor. The stations will be further investigated and calibration to monitor the change in sensitivity of the sensors will be done.

The square correlation coefficient (r^2) of SAWS radiometric network was greater than 0.950 in all the stations, which shows a good linear relationship between the SAWS observation and CMSAF satellite data, as shown in Table 7.

The overall statistical metrics results are in line with the results obtained by other international institutions measuring ground radiation and maintaining the network well [14, 20, 21] using CMSAF monthly data sets as shown in Table 7. Durban annual average monthly data from SAWS current radiometric network was compared to a nearby station Durban STARlab 2017 [22] annual average GHI, DF, humidity and temperature and the results were all comparable as shown in Table 8. SAWS historical station annual average GHI, DHI, DF from 1969-1982 [23] were all comparable to SAWS current radiometric and NASA SSE 22 year annual average [19] were also comparable to all 13 SAWS radiometric stations, as shown in Table 6, 7 and 8.

4. Conclusions

The utility of solar radiation measurements in South Africa is highly dependent on; a) the assessment of uncertainties in the measured data, b) expansion and continuous monitoring of the health status of the radiometric network, c) status of the solar radiation resource database, and d) model development. In this contribution, these pertinent operational tenets of SAWS radiometric network monitoring, quality control procedures and the validation results have been elucidated. . Our results show that notwithstanding the most dominant source of bias being operational in nature i.e., the missing data due to power and vandalism, the overall quality of measured data is good. The available minute quality controlled dataset will be useful for variable renewable energy research, design of energy systems, building photovoltaic (PV) stations, evaluation of thermal environment within buildings, building energy models and agricultural crop models and implementation of energy policies and programmes in the country. We posit that the national collective of all the solar resource archives will have an immense contribution to the renewable energy research in support of addressing key aspects of renewable energy technology development in South Africa.

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