MAUSAM, **70**, 3 (July 2019), 533-540

551.501.8 : 551.521.14 (669.1)

Comparison between ground measured and satellite estimates of downward longwave radiation at Ilorin, Nigeria

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(*Received 18 September 2018, Accepted 28 March 2019*)

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सार – पृथ्वी की सतह के कुल ऊर्जा बजट को आकलित करने के उपयोगी कारकों में से एक है डाउनवर्ड लॉगवेव रेडिएशन (DLR)। यद्यपि उपग्रह से प्राप्त डेटा प्रचुर मात्रा में हैं और इनका उपयोग अक्सर वायुमंडलीय अध्ययनों में किया जाता है तथापि दुर्लभ धरातलीय मापन से इसकी संपुष्टि अनिवार्य है। इस शोध पत्र में इलोरीन (8.50° N 4.55° E) नाइजीरिया में सितम्बर 1992 से अगस्त 1994 और जून 1995 से अप्रैल 1998 तक लगभग पाँच वर्षों में धरातल पर मापे गए और उपग्रह से प्राप्त किए गए DLR डेटा की तुलना दो मुख्य सांख्यिकीय सहसंबंध गुणांक और टी-टेस्ट के साथ की गई है। इसके अलावा, माध्य सापेक्षिक प्रतिशत विचलन (E%) का उपयोग दोनों डेटा सेट के बीच मासिक समता को निर्धारित करने के लिए भी किया गया। डेटा के दोनों सेट के मौसमी पैटर्न समान थे, परंतु इसमें मामूली अंतर था और E% में 57 महीनों में एक बार अच्छे मासिक उपयुक्त डटा की उम्मीद थी, जो जून 1996 में हुई थी। शुष्क मौसमों के दौरान सहसंबंध गुणांक मान उच्च थे, लेकिन बरसात के मौसम के दौरान कम और टी-टेस्ट ने कभी-कभी दोनों डेटा सेटों के बीच सांख्यिकीय महत्व को दर्शाया। ज्यादातर बार उपग्रह से प्राप्त किए गए मौसमी पैटर्न के डेटा धरातल से मापे गए डेटा से मेल खाते हैं, कुछ चरम मामलों में सामान्य से उल्लेखनीय विचलन अपवाद हैं। उपग्रह से प्राप्त डेटा के उपयोग की अनुशंसा तब तक की जाती है जब तक कि सटीकता की आवश्यकता न हो और डेटा की छोटी अवधि की कोई समस्या न हो।

ABSTRACT. One of the useful factors for appraising the total energy budget of the earth's surface is downward longwave radiation (DLR). Though satellite-derived data are plenteous and are often used in atmospheric studies, however, its conformity with the rare ground measurements is essential. In this work, ground measured and satellite-derived DLR data for about five years from September 1992 to August 1994 and June 1995 to April 1998 in Ilorin (8.50° N, 4.55° E), Nigeria were compared, using two main statistical measures of correlation coefficient and the *t*-test. Furthermore, the mean relative percentage deviation (*E*%) was also used to determine the monthly parity between both data sets. The seasonal patterns of both sets of data were similar but had inherent slight differences and *E%* produced good monthly fits expect once in 57 months, which was in June 1996. That enormous deviation was also detected graphically. Correlation coefficient values were high during the dry seasons but low during the rainy seasons and the *t*-test sometimes showed statistical significance between both data sets. Most times, the seasonal patterns of satellite-derived data match ground truth except in an extreme case of remarkable deviation from normal in the ground measured data. Using satellite-derived data is recommended unless precision is required and short duration of data is not an issue.

Key words – Downward longwave radiation (DLR), Ground measured data, Satellite-derived data, Parity.

1. Introduction

The energy budget balance of the earth's surface, (E_{net}) can be expressed mathematically as;

$$E_{net} = S_{net} + L_{net} = S_{DR} - S_{UR} + L_{DR} - L_{UR} \quad (1)$$

where, S_{net} is net shortwave radiation, L_{net} is the net longwave radiation, S_{DR} is the shortwave radiation coming down to the earth's surface, S_{UR} is shortwave radiation reflected from the earth's surface back to the sky, L_{DR} is the downward longwave radiation (DLR) coming from the sky to the earth's surface and L_{UR} is longwave radiation reflected upward from the earth's surface to the sky. While net shortwave radiation S_{net} (or algebraic sum of both downward and upward shortwave radiations) comes with the sun's presence and available only during the daytime, however, both longwave radiations are always available. DLR falls within the wavelength interval of 4-100 µm and is obtainable from the sun's total spectrum. The radiation can also be got from the interaction between the constituents of the atmosphere (like, the ozone layer, aerosols, water vapour and other greenhouse gases like CO_2, N_2O, CH_4 etc.) and solar radiations (Sellers, 1965;

Igbal, 1983; Niemela *et al.*, 2001; Ohmura, 2001; Wild *et al.*, 2013; Obot *et al.*, 2018). Hence, DLR is sometimes regarded as atmospheric sky radiation.

Atmospheric processes are driven mostly by the radiant energy received directly from the sun and the absorbed radiation in the atmosphere. For instance, wind flows from one region to another due to the inhomogeneous distribution of solar radiations that heat the air (Offerle *et al.*, 2007). Likewise, DLR influences the hydrological cycle and other atmospheric factors like air temperature, water vapour, cloudiness and rainfall (Obot *et al.*, 2018; Wild and Liepert, 2010). DLR can describe the climatology of a site because it can serve as a substitute for cloudiness and it predicts the climatic features of a region better than other meteorological parameters like temperature, water vapour and humidity (Soares *et al.*, 2004). A major topical issue of the environment is climate change and it is noteworthy to state that DLR can depict the occurrence of climate change. Information on DLR is useful also for the energy balance of buildings, especially for night-time cooling, greenhouses, solar collectors, agriculture and weather forecasting (Dai *et al.*, 1999; L'homme *et al.*, 2007; Wild *et al*., 2008; Wang and Liang, 2009; Eicker and Dalibard, 2011).

Data on DLR are rare due to the complexities of the measuring instrument: pyrgeometer. Some associated complications of the pyrgeometers include the periodic need for calibration in specialised labs and daytime data correction owing to the heating of the dome. Sometimes, the error due to the hotness of the dome could be as high as 30 W/m^2 (Miskolczi *et al.*, 1997; Ji and Si-Chee, 2000; Udo, 2000; Marty *et al.*, 2003). Saddled with the complexities and technicalities involved in ground measurement, equations and remote sensing methods are occasionally deployed to alleviate the paucity of data. While some DLR models use cloud info and screen-level atmospheric parameters like air temperature and water vapour pressure as inputs, others require profiles of air temperature and water vapour pressure (Niemela *et al*., 2001). A major setback of most DLR models is the need for recalibration of their coefficients before using them at other locations. Furthermore, unlike the data for screen-level parameters that are easily available, profiles of air temperature and water vapour pressure are rare to come by (Goody, 1964).

Satellite-derived data have some intriguing advantages over ground measurements. Such edges include long-range and wide-position coverages, cost-effectiveness, low measurement error and not posing much fragility (Diak *et al*., 2000). Satellite measurements are often used as inputs for numerical weather prediction (NWP) methods and their complex natures require the knowledge of several atmospheric gases like CO_2 (Uppala *et al*., 2005). Additionally, the proper trends of atmospheric factors are better understood with long-term data and satellite-derived DLR data have been deployed in studying the climatic mechanisms of the globe (Carlson, 1979; Justice *et al.*, 1985; Sellers *et al.*, 1995; Kaufman *et al.*, 2002; Wang and Christopher, 2003; Obot *et al.*, 2018). Global estimates of DLR have been obtained from soft computing in combination with reanalysis products and satellite inputs (Nussbaumer and Pinker, 2012). Nonetheless, given the wide coverage of satellite data, little is known of the disparities between ground measured and satellite-derived DLR data of an individual station. It has been found that satellite estimates of one type of ground-based solar radiation differ from other radiation in the same location (Marchand *et al.*, 2018).

Using satellite data for some applications may not be suitable because there is no universal benchmark for the diverse methodologies used for deriving data from retrieved images and new techniques are evolving (Ellingson, 1995). At times, two or more satellites are used to acquire data whereby sensor switches and calibration techniques are deployed for the continuation of data. Some operating satellites are orbiting near the equator and a satellite can only complete two revolutions per day, implying that limited daily data can be obtained from satellite images (Posselt *et al.*, 2014). Hence, except in rare cases, diurnal trends of atmospheric factors can only be examined using ground truths but not with satellite-derived data. Apart from ground measurements and satellite methods, reanalysis is another method for data provision. Although reanalysis products use inputs from both satellite and ground truth, yet breaks in satellite readings are corrected using ground data (Uppala *et al*., 2005; Peruchena and Amores, 2017; Urraca *et al.*, 2017; Urraca *et al.*, 2018). Irrespective of the associated problems of satellite methods, as earlier mentioned, long duration studies have been conducted with satellite-derived data. Particularly, Obot *et al.* (2018) used satellite data to study DLR in Nigeria, however, the conformity of satellite data with ground facts is essential to ascertain the accuracy of their findings.

In 1992, the World Meteorological Organisation (WMO) through the Baseline Surface Radiation Network (BSRN) decided to measure meteorological parameters like DLR around the globe with the highest level of accuracy. Presently, there are over 50 ground stations that measure DLR, out of which there are four in Africa, namely De Aar (30.67° S, 23.99° E), Pretoria in South Africa, Namib Desert (23.56° S, 15.04° E) in Namibia, Ilorin (8.53° N, 4.57° E) in Nigeria and Tamanrasset (22.78° N, 5.51° E) in Algeria (Ohmura *et al.*, 1998;

McArthur, 2005; Konig-Langlo and Sieger, 2013). Other purposes of BSRN stations include providing data to serve as a baseline guide for satellite-derived data, studying the trend and mechanism of atmospheric factors like DLR and for promulgating universal models for atmospheric variables. Few organisations like the National Aeronautics and Space Administration (NASA) derive DLR data from satellite images. This study aims to evaluate the conformity between ground measured DLR and satellite-derived data, using BSRN and NASA products for a location in the equatorial region of Africa. The information would provide insights into the closeness between satellite-derived data and ground measurements when the satellite data are deployed.

2. Methodology

The location under consideration in this study is Ilorin (8.50° N, 4.55° E), Nigeria. Details of ground measurement of DLR, the seasons of the site and other information have been previously reported (Miskolczi *et al.*, 1997; Udo & Aro, 1999; Udo, 2000). DRL data from September 1992 to August 1994 and July 1996 to March 1998 were obtained from the BSRN website (https://www. pan gaea. de/PHP/BSRN_Status.php). It should be noted that a majority of the earlier studies used data from September 1992 to August 1994. The measured data were taken every 3 or 2 minutes, which were further reduced to hourly, daily, monthly and yearly values depending on the usage. Daily satellite-derived DLR data from July 1983 to June 2005 downloaded from the website of NASA (https://ecoweb.larc.nasa.gov/sse) were in a unit of KWh/m^2 and were converted to W/m^2. NASA has data on several meteorological and climatic variables (Stackhouse *et al*., 2018; Suarez, 2008). In arriving at the exact months of the dry and rainy seasons, a 30-year rainfall data (1980-2010) obtained from the Nigerian Meteorological Agency (NIMET), Lagos was evaluated. Furthermore, in comparing the two sets of data, two main statistical measures, namely the correlation coefficient, r and the t-test, t_s were used. The correlation coefficient is given as;

$$r = \frac{n(\sum V_c V_m) - (\sum V_c)(\sum V_m)}{\sqrt{[n\sum V_c^2 - (\sum V_c)^2][n\sum V_m^2 - (\sum V_m)^2]}} \quad (2)$$

Moreover, the t-test is given as;

$$t_s = \sqrt{\frac{(n-1)MBE^2}{(RMSE^2 - MBE^2)}} \quad (3)$$

The expressions for the mean bias error (*MBE*) and the root mean square (*RMSE*) in the t-test are given below as:

$$MBE = \frac{\sum(V_c - V_m)}{n} \quad (4)$$

and

$$RMSE = \sqrt{\frac{1}{n}\sum\left(\frac{V_c - V_m}{V_m}\right)^2} \quad (5)$$

where, Vc is the satellite-derived data, V_m is the ground measured data and n is the total number of data points.

Furthermore, to evaluate the extent of conformity or the disparity between both sets of data, the mean relative percentage deviation (*E%*) statistic was used:

$$E\% = \frac{100}{n}\sum\frac{|V_m - V_c|}{V_m} \quad (6)$$

A good fit between the monthly ground measured DLR and its satellite counterpart occurs if *E%* is less than 10.

Since DLR depends on altitude (Iziomon *et al*., 2003) and because it was not stated otherwise, it was assumed that the satellite data were at screen-level, which can be regarded as within 2 metres above ground level, where ground measurements are mostly taken. The appraisal was based on seasonal and non-seasonal considerations and the value of the correlation coefficient, r is excellent at 1.0 (be it positive or negative). Hence, in this study, the targeted correlation coefficient values of the relationships between the satellite and ground data were expected in the range of 0.9 to 1.0, either positive or negative. Furthermore, at a selected confidence level and corresponding (n - 1) degrees of freedom, two models are deemed statistically significant if the calculated t-test value is less than the critical value. At the 95% confidence level, if the calculated t-test in this work was lower than the critical t value, then it was deemed that the satellite-derived data estimated the ground measured DLR with statistical significance.

3. Results and discussion

Because the first phase of ground measurement between August 1992 and September 1994 showed seasonal inclination (Miskolczi *et al*., 1997; Udo and Aro, 1999), so at times only 2-year data from July 1995 to June 1997 were reckoned with (Tables 1&2), to avoid seasonal drift or skewness on the data set for July 1995 to April 1998. The specific months that comprise both the dry and rainy seasons in Ilorin can be seen in Fig. 1, whereby the rainfall diagram has portrayed that the rainy season months are from April to October while the dry season months are from November to March.

TABLE 1

Summary statistics for both the ground measured data and the satellite-derived data of DLR in W/m^2 for Ilorin, Nigeria

Period	Statistics	Ground measured data	Satellite-derived data
Sept 1992 - Aug 1993 (1 year)	Mean (W/m^2)	395	391
	Maximum (W/m^2)	424	431
	Minimum (W/m^2)	334	307
	Std deviation	21.7	30.0
Sept 1993 - Aug 1994 (1 year)	Mean (W/m^2)	400	393
	Maximum (W/m^2)	427	432
	Minimum (W/m^2)	343	318
	Std deviation	15.5	25.1
Sept 1992 - Aug 1994 (2 years)	Mean (W/m^2)	398	394
	Maximum (W/m^2)	427	433
	Minimum (W/m^2)	334	307
	Std deviation	19.0	27.8
July 1995 - June 1996 (1 year)	Mean (W/m^2)	392	403
	Maximum (W/m^2)	419	430
	Minimum (W/m^2)	335	333
	Std deviation	21.4	19.6
July 1996 - June 1997 (1 year)	Mean (W/m^2)	395	393
	Maximum (W/m^2)	421	430
	Minimum (W/m^2)	342	303
	Std deviation	17.9	27.7
July 1995 - June 1997 (2 years)	Mean (W/m^2)	398	393
	Maximum (W/m^2)	430	421
	Minimum (W/m^2)	303	335
	Std deviation	0.90	19.8

Table 1 shows the magnitude of the ground measured DLR at this location and that of the satellite. For the initial two years of September 1992 to August 1994, the average daily DLR was 398 W/m^2 for the ground data while the satellite value was 394 W/m^2. Then again, from July 1995 to June 1997, daily mean DLR was about 398 W/m^2 for ground truth and 392 W/m^2 for satellite output. From the above, it can be concluded that both data sets are quite close. However, there are mixed results from other statistics. For instance, an average error difference of approximately -3.8 W/m^2 was got as the mean bias error (*MBE*) value for the period of September 1992 to August 1994, which implies a slight underestimation by satellite method and is within the acceptable limit of ±5 W/m^2 (Diak *et al.*, 2000). Nonetheless, some *MBE* values were beyond ±5 W/m^2 (Table 2).

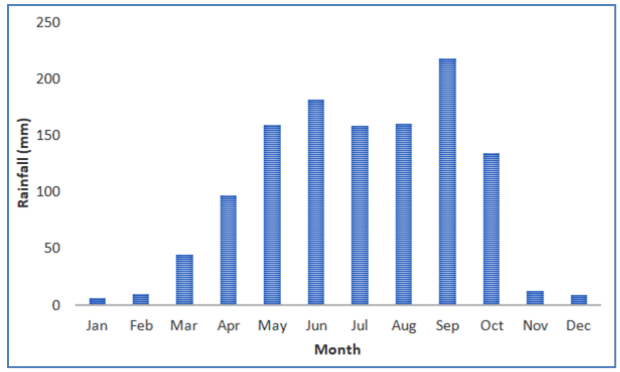


Fig. 1. Average monthly rainfall covering a period of 30 years (1980 - 2010) in Ilorin

The tendency of the satellite-derived DLR data to estimate its ground counterpart is given also in Table 2. At the 95% confidence level and corresponding (n–1) degrees of freedom, the critical t value for two tails is 1.96 and two t-test values were less than 1.96, which comprised: 1.81 for the rainy seasons of September 1992 to August 1994 and 0.97 for the dry seasons of July 1995 to June 1997. Hence, the satellite-derived DLR data occasionally estimated its ground counterpart with statistical significance without showing a seasonal preference. Most times, the rainy seasons had a poor correlation between both data sets: it was 41% during the period between 1992 and 1994 and 17% between 1995 and 1997. However, the correlation coefficients of the dry seasons during the same periods were 82% and 79% respectively. Though the dry seasons consistently had a good statistical correlation between the satellite data and the ground truth, however, that did not always translate to statistical significance between both sets of data.

It can be confirmed by comparing Figs. 2(a&b), that the radiation is seasonal, being high during the rainy seasons and low during the dry seasons, for both the ground measured and satellite-derived DLR. In 1993, the satellite-derived data [Fig. 2(b)] sufficiently captured the ground data [Fig. 2(a)]. Again, in 1997, the seasonal pattern of the ground data [Fig. 2(e)] was like that of the satellite data [Fig. 2(f)], however, in 1996, the enormous fluctuation of the ground data in the middle of the year [Fig. 2(c)] was not adequately captured by the satellite counterpart [Fig. 2(d)]. Furthermore, *E%* (Table 3) indicated that mostly there was a good monthly fit between ground and satellite data except once in 57 months, which was June 1996. Besides, this period coincides with the said enormous fluctuation of ground measured data that was not captured by satellite readings in Figs. 2(c&d). The yearly DLR pattern for approximately 22-year of NASA satellite readings from July 1983 to June 2005 at Ilorin, can be described as an

TABLE 2

Statistical result for comparison between ground measurement and satellite-derived DLR at Ilorin

Periods of observations	Seasons	*n*	*r*	*MBE*	*RMSE*	t_s
Sept 1992 - Aug 1994	All seasons	730	0.85	-3.80	16.03	2.20
	Dry seasons	302	0.82	-11.83	22.40	5.59
	Rainy seasons	428	0.41	1.82	9.24	1.81[a]
July 1995 - June 1997	All Seasons	731	0.67	4.66	18.96	2.28
	Dry seasons	302	0.79	-1.92	17.87	0.97[a]
	Rainy seasons	428	0.17	9.32	19.69	4.84

[a] the satellite data estimated the ground counterpart to statistical significance

TABLE 3

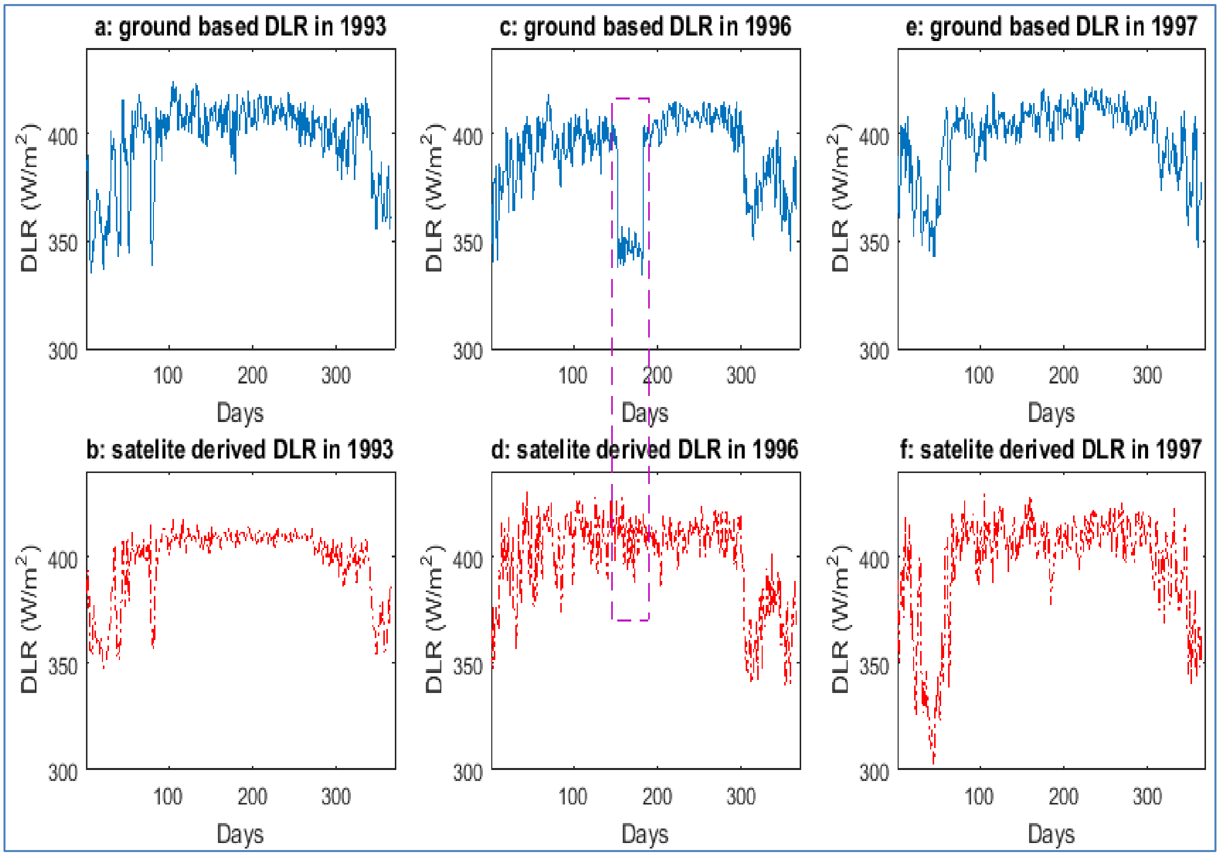
Monthly E% for analysis between ground measurement and satellite-derived DLR at Ilorin (where the value in bold indicates when there was no good fit)

Months	1992	1993	1994	1995	1996	1997	1998
January	-	2.87	2.59	-	4.21	3.12	5.34
February	-	3.35	3.39	-	2.99	9.27	4.69
March	-	1.91	2.44	-	2.99	2.64	4.10
April	-	1.64	1.40	-	3.68	2.36	-
May	-	1.50	2.62	-	3.57	1.77	-
June	-	1.72	1.44	-	**18.37**	1.78	-
July	-	0.97	1.24	1.59	1.79	1.36	-
August	-	0.99	1.15	1.22	1.19	1.17	-
September	1.70	1.59	-	1.54	1.44	1.63	-
October	2.30	1.64	-	1.89	2.19	1.75	-
November	1.71	2.30	-	3.28	2.98	3.09	-
December	6.35	2.45	-	3.08	2.47	3.65	-

irregular curve (Fig. 3). It rises and falls within every three to four years, yet in its totality, the linear trend line is rising (Fig. 3).

Depending on the adopted method, there are varying degrees of deviation in downward longwave fluxes estimated from reanalysis (Gruta *et al.*, 1993; Nussbaumer and Pinker, 2011, Nussbaumer and Pinker, 2012; Stephens *et al.*, 2012). So, the disparity between both sets of satellite and ground data should be expected, possibly due to the unstandardized methods for calculating DRL from satellite images (Ellingson, 1995). Even though some studies (Miskolcki *et al.*, 1997; Jonsson *et al.*, 2006) suggest that the low DLR during the dry season is due to heavy dust particles that obstruct the radiation, however, it could be as a result of the low water vapour concentration in the atmosphere (Obot *et al.*, 2018; Obot *et al.*, 2019). By virtue of the low correlation between satellite and ground data during the rainy seasons, it is possible that the disparity between both sets of data could be due to the inability to precisely interpret the regional water vapour and cloud properties with satellite methodologies (Ellingson, 1995; Lee and Ellingson, 2002; Morcrete, 2002).

Solar activity like sunspot number in the sun's atmosphere varies and sometimes flares erupt from different regions in the sun and travel down to the surface of the earth. Cosmic rays' interaction with the earth depends on the concentration of matter in the earth's atmosphere. Additionally, the gravitational attraction between the sun and the earth is modulated by the



Figs. 2(a-f). Seasonal ground measured and corresponding satellite-derived DLR of Ilorin in 1993 (a, d), 1996 (b, e) and 1997 (c, f). The rectangular dash box across Figs 2(c&d) indicates the region when fluctuations in ground measured data were not captured by satellite-derived data

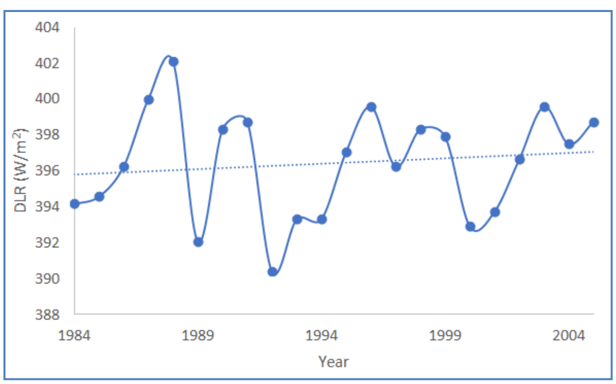


Fig. 3. Annual variation of satellite-derived DLR at Ilorin

strength of the solar disturbance. Equatorial solar radiation is high due to the relatively small sun-earth separation and direct incidence angle. Similarly, the effect of the solar wind is much around the equator (March and Svensmark, 2000; Webb and Allen, 2004). Again, the situation in June 1996 where there is a huge disparity between ground measured and satellite-derived DLR data could be due to the impact of solar magnetic storms not captured in the satellite data retrieval methodology.

4. Conclusions

Satellite-derived downward longwave radiation is also found to have a seasonal effect in line with the measured ground data, however, there are mixed performances in their relationships. The correlation between them is better during the dry seasons and the seasonal deviation error sometimes falls outside the envisaged range of ±5 W/m^2. Statistical significance between both sets of data was sometimes attained. Out of the 57 months from August 1992 to September 1994 and July 1995 to April 1998, it was only in June 1996 that there was a mismatch between ground truth and satellite-derived DLR. The mismatch could be the effect of a solar storm that was not captured by the satellite data method. Possibly, the low correlation during the rainy seasons could be due to the inability of satellite methodologies to infer the regional properties of atmospheric water vapour and cloud. In the absence of any other better technique for data acquisition, using satellite data to study DLR is recommended, since ground measured DLR are rare. However, if need be, satellite-derived data can be used to correct an excessive variation in ground data or *vice versa* (Masiri *et al.*, 2017).

Acknowledgement

The author is grateful to BSRN and NASA, for granting free access to their respective data banks, because without that this work would not have been possible and the anonymous reviewers.

The contents and views expressed in this research paper are the views of the author and do not necessarily reflect the views of his organisation.

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