Estimation of Global Solar Radiation from SAURAN stations using air temperature-based models Hargreaves & Samani and Clemence models.

BY

CHARLOTTE BEAUTY SHABANGU

(11605955)

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SUPERVISOR: DR. N.E MALUTA (UNIVEN)

Co- SUPERVISOR: DR T.S MULAUDZI (UNIVEN)

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DECLARATION

I, Charlotte Beauty Shabangu declare that this research dissertation is my original work and has not been submitted for any degree at any other university or institution. The dissertation does not contain other persons' writing unless specifically acknowledged and referenced accordingly.

Signed student……………………………………… Date: ……………………… 07/01/2021

DEDICATION

I would like to dedicate this work to my grandmother, Elesia Maganyane, who raised me, believed in me and has always seen the best in me. I would like to appreciate her support and being my pillar through prayers.

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I would first like to give all the glory to the Almighty God, who strengthened and guided me in wisdom throughout this research work.

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ABSTRACT

Knowledge of the amount of solar radiation available in a location is important for solar energy systems, architectural designs, agronomy, and installation of pyranometers. Some developing countries do not have good quality meteorological stations that can directly measure global solar radiation. Thus, several empirical methods were developed to estimate global solar radiation. This study uses two temperature-based models which are Hargreaves - Samani and Clemence models. Four selected stations from the Southern African Universities Radiometric Network (SAURAN) for this study are University of KwaZulu–Natal, Howard college (KZH), University of Stellenbosch (SUN), Nelson Mandela University (NMU) and University of Venda (UNV). A three-year (2014-2016) temperature data for each station were sourced from SAURAN. The performance of the two models was validated using statistical analysis that is, Mean Percentage Error (MPE), Mean Bias Error (MBE), Root Mean Square (RMSE), Coefficient of Determination (R^2) and t-statistical value (t). Both models obtained acceptable values of MBE, MPE, RMSE, R^2 and t in KZH, NMU and UNV stations. Both models achieved the best values of MBE from 2014 to 2016, ranging from -0.0099 to 0.0147 in KZH station, followed by NMU with MBE values ranging from - 0.0293 to -0.0014, -0.0104 to 0.0330 for SUN station, 0.0241 to 0.0245 for UNV station. The models achieved MPE values between ± 10 % in all the stations. The R^2 values for both models are close to 1, while the t-statistic values of one, which is less than critical value, was achieved by the models from all selected stations. This suggests that both models have got capacity to estimate global solar radiation in all the selected areas of study. However, the higher values of MBE and RMSE also revealed high level of overestimation by the models in SUN station. Therefore, this study has found evidence that both Hargreaves - Samani & Clemence models can be best recommended for estimating global solar radiation in KZH, NMU and UNV stations and areas with similar climatic and meteorological conditions.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

NOMENCLATURE

i. SAURAN – Southern African Universities Radiometric Networks

ii. ARC – Agricultural Research Council

iii. SAWS – South African Weather Service

iv. DNI - Direct Normal Irradiance

v. DHI – Diffuse horizontal irradiance

vi. GHI – Global horizontal irradiance

vii. S– Actual sunshine hours

viii. S_0 – Maximum possible sunshine duration

ix. ΔT – Change in temperature

x. H – Average daily global solar radiation

xi. H_0– Extraterrestrial solar radiation

xii. d_n – Number of day

xiii. T_{min} – Minimum air temperature

xiv. T_{max} – Maximum air temperature

xv. RH– Relative Humidity

xvi. a, b and c - Regression coefficients

xvii. K_r– Empirical coefficient

xviii. I_{sc} – Solar constant

xix. ω_s – Sunset/sunrise hour angle

xx. δ – Solar declination

xxi. MPE– Mean percentage error

xxii. MBE– Mean bias error

xxiii. $RMSE$– Root mean square error

xxiv. R^2 –Coefficient of determination

xxv. t – t - statistics

xxvi. KZH – University of KwaZulu Natal Howard college station

xxvii. SUN – University of Stellenbosch station

xxviii. NMU – Nelson Mandela University station

xxix. UNV-Vuwani Science Resource Centre station (is owned by University of Venda)

CHAPTER 1: INTRODUCTION

1.1 Background

It is known that global economy is influenced by the amount of oil from developed countries and other non-renewable sources of energy. Many lives can be improved when economy is well established. There is no doubt that energy contributes a lot to the country's economic growth since most of the activities are driven by energy [1,2,3].

There are two types of primary sources of energy, non - renewable energy and renewable energy sources. Scientists discovered renewable energy sources, which are environmentally friendly, sustainable, inexhaustible, clean, and less expensive. Examples of such sources are solar energy, wind energy, solar thermal, hydro power, and biomass. Renewable energy is the energy that is generated from resources of the natural environment and seasonal resources [1 - 7].

Countries do have strategic plans for introducing alternate energy systems in the form of renewable energy. For example, the African Development Bank has planned to provide 23.4 million people with access to electricity. In 2020 renewable energy is expected to contribute 15% of the electricity supply in South Africa [6]. The country is so fortunate that a good number of renewable energy production plants have already been built such as solar energy, wind power, and biomass [3]. Using non-renewable energy is a common practice in the world, especially in developing countries, such as South Africa. Non -renewable energy is defined as the energy that cannot be replenished once it has been used, like energy from fossil fuels which are finite. Examples of fossil fuels are coal, oil, natural gas, and nuclear energy. More than 90% of coal accounts for the electricity generation in South Africa which as a developing country will depend on coal for economic growth and industrialization for quite a while [1,2,3,6,7].

One of the disadvantages of coal powered stations is that they are very costly to build and take a long process. Coal has huge waste problems of all variety of energy sources and pollutes the environment, thus it puts living organisms in high-risk conditions. In the process of burning, coal releases polluting products like sulfur, iron, uranium, thorium, and other impurities which cause climate change that affects the natural environment. So far South Africa has been assessed to be amongst the world's top 15 largest emitters of carbon dioxide because of its high dependency on coal [6].

The method of using fossil fuels for electricity generation to support economic growth has not been sufficient in solving unemployment issues and thus putting the country at the disadvantage of the shortage of energy. This has resulted in slow economic growth, unemployment, and poverty [1-5].

Solar energy is the best choice of all renewable energy sources especially if it can be used in a cost-effective manner and converted into electrical energy through photovoltaic systems [3,4]. When solar radiation travels through the Earth's atmosphere, some of it is scattered because of some atmospheric particles like clouds, only some of it directly from the Sun reach the Earth's surface. Global solar radiation is the total amount of direct and scattered solar radiation. Proper knowledge of global solar radiation data in different areas is useful for the design and installation of renewable energy technologies based on solar energy. Inaccurate measurements of solar radiation may result in the poor-quality design of devices. South Africa as a developing country finds it expensive to install equipment such as pyrheliometer and pyranometers for measuring direct solar radiation. Thus, some alternative ways of estimating the global solar radiation using empirical models are useful [4-6]. These models use meteorological inputs such as sunshine, cloud -cover, precipitation, air temperature, relative humidity, etc. [6]. However, sunshine and cloud data are not always available at most meteorological stations [7]

This research focuses on estimating global solar radiation using the maximum and minimum temperature data from the selected Southern African Universities Radiometric Network (SAURAN) stations around Southern Africa as inputs. Hargreaves – Samani and Clemence models have been used to estimate the global solar radiation at the stations under study.

1.2 Significance of the study

The amount of solar radiation reaching the surface of the Earth varies from one location to another. It is important to know the amount of global solar radiation falling on each site. Due to the scarcity of radiometer devices in the developing areas, several empirical methods are established to estimate global solar radiation. The global solar radiation data estimated at any particular area informs the solar system designers about the state of solar energy in that area. The estimated data can also be used in many applications like architectural designs, meteorological forecasting, solar heating agronomy, and power generation. Since the two models have been employed in this study, the better model inaccuracy is recommended for estimating global solar radiation in the areas where meteorological stations are not available but with the same climate conditions and geographical coordinates as the selected study areas.

1.3 Research problem

South Africa just like any developing country, experiences financial challenges as it addresses the rolling out of new renewable energy technologies. So, though the knowledge of in-situ solar radiation is vital, it is not feasible to install solar radiometry instruments in every site to get solar radiation measurements. Solar radiation is the main source of renewable energy and is usually an input parameter to solar-based renewable energy technologies. Thus, access to solar radiation data is very crucial. The ground measurements of global solar radiation data require the installation of pyranometers in specific locations and day to day maintenance. In-situ measurements of global solar radiation become very costly and sometimes there is inaccuracy and unreliable data due to lack of knowledge of the personnel and calibration processes, thus not every country can afford this. Considering available weather stations and institutions within South Africa, the measurement of global solar radiation data is only possible at a few institutions outside the public domain, so this hampers the development of renewable technologies. The cost of establishing a measuring station is too high and this has led to the establishment of different empirical models which also need to be tested in South African climatic conditions [8].

1.4 Research focus

There is a dire need for solar radiation data to inform solar designers as well as building architects. Alternatively, the global solar radiation can be correlated with meteorological data available in a particular region. This work is based on two of the selected empirical solar models that were developed by the researchers to cab the difficulty of accessing and or unavailability of solar radiation data through the estimation method. [8].

This study focuses on estimating global solar radiation using two air temperature - based models which are Hargreaves - Samani and Clemence models. Air temperature data from four SAURAN stations in South Africa have been used as input. The models were validated by comparing the estimated global solar radiation with the observed global solar radiation.

1.5 Purpose of the study

1.5.1 Overall aim

The aim of the study is to estimate global solar radiation data using the air temperature data from the four SAURAN stations in South Africa as inputs.

1.5.2 Objectives of the study

1.5.2.1 To compute global solar radiation from Hargreaves – Samani and Clemence model using the data from four SAURAN stations.

1.5.2.2 To determine the performance of the models.

1.5.2.3 To validate the reliability of the models.

1.5.2.4 To identify the most accurate air temperature model suitable for estimating global solar radiation at the selected study areas.

1.6 Hypotheses

A good agreement between the estimated and the observed global solar radiation using the selected models provides a measure of the accuracy of the observed data and models. The level of accuracy enables us to determine the best suitable model for estimating global solar radiation in the selected study areas. The estimated and observed global solar radiation data from the chosen models must be in reasonable agreement.

1.7 Chapter Summary

This chapter outlines the introduction of the thesis. It gives clarity on what this study is all about. We started by taking a look at the advantages of using renewable energy and also solar radiation as its main source. We have stated the problem, which led to the aim of the study, which will have more significance, in trying to bring a solution to the problem. So, this study stands on the hypothesis stated above, which cannot just be proven in words but scientifically, or experimentally. If the hypothesis is proven true, then this study will evidently be relevant to society and the market as well. One of the objectives of this study as stated above is to validate the temperature-based models. By the end of this study, we should be able to know whether both the selected models, i.e. Hargreaves - Samani and Clemence models are suitable for estimating global solar radiation at the selected areas.

CHAPTER 2: LITERATURE REVIEW

2.1 Solar energy

Solar energy constitutes a huge source of heat on the Earth‘s surface and it is the driving force for weather activities and climate. Thus, it is the main important source of renewable energy. Solar energy is the energy from the Sun in the form of radiant energy to the Earth's surface. The amount of solar radiation data and weather measurement parameters are useful in assisting solar engineers and architectures to understand the amount of energy falling at a particular area. It is also used in agriculture for crop drying and electricity generation [7, 8]. The solar radiation reaching the surface of the Earth varies from one place to another due to the different climatic conditions, it is thus necessary to have the knowledge of solar radiation data. The amount of solar radiation passing through the atmosphere to the Earth's surface decreases because of scattering, reflection, and absorption by atmospheric factors such as water vapour, air molecules, clouds, etc. Thus, all these take us to the discussion of different types of solar radiation namely: global solar radiation, diffuse solar radiation, and direct solar radiation [8,9].

2.1.1 Global solar radiation

As we know solar radiation is released from the Sun, some of it comes directly to the surface while some are scattered in different directions [10]. Global solar radiation is the total amount of diffuse and direct solar radiation [11]. It is measured using a pyranometer [11]. Knowledge of global solar radiation is important to solar engineers since it assists in designing suitable solar devices like photovoltaic cells and solar energy systems. Global solar radiation is important for designing a suitable solar energy system. See Figures 2.1 and 2.2. Figure 2.1 illustrates the effects of the atmosphere on solar radiation, while Figure 2.2 illustrates different types of solar radiations as a result of contact with different atmospheric particles.

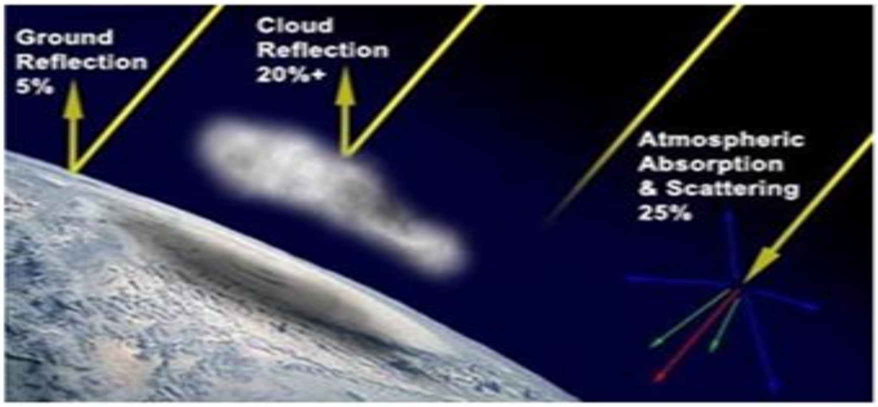

Figure 2.1: Effects of the atmosphere on solar radiation [12].

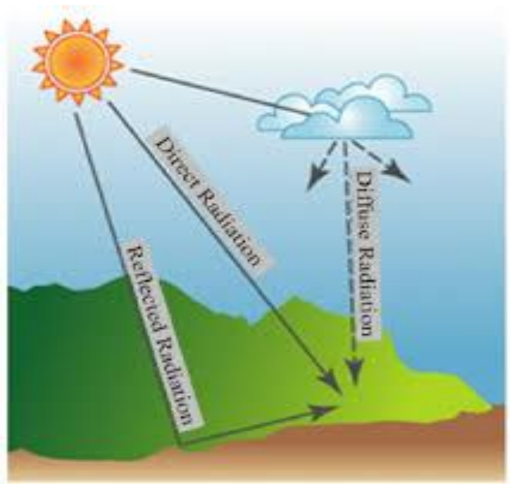

Figure 2.2: Components of global solar radiation: Direct, diffuse, and reflected solar radiation [13].

2.1.2 Diffuse solar radiation

Diffuse solar radiation is the amount of solar radiation scattered and coming in different directions [11]. The scattering is due to air molecules and other objects components such as clouds, ozone layer, aerosols and water vapour in the atmosphere, causing only a small portion of the scattered radiation to reach the Earth's surface as diffuse solar radiation (see Figure 2.1) whereby 5% portion of the radiation goes back to space while 20% of solar radiation reaches the Earth surface. The scattering is usually more during cloudy days, mostly during winter. When the sky is clear the amount of diffuse solar radiation is about 15%. A pyranometer with a shadow band is used to measure the diffuse solar radiation [11,14].

2.1.3 Direct solar radiation

Direct solar radiation is radiation that comes directly from the Sun to the Earth’s surface [11]. It is also called beam radiation and can be measured using a pyrheliometer which is normally installed on a solar tracker. Direct solar radiation travels in straight lines and it is usually more intense than diffuse solar radiation [14]. During clear days the amount of direct solar radiation is in excess at about 85 % and it travels in one direction [5,14].

2.1.4 Reflected solar radiation

This is the type of radiation that is reflected from the ground to the sky and it depends on the ground reflectivity. The percentage of the reflected solar radiation is very high in snow places. Snow reflects about 80 to 90 % solar radiation [5,14].

2.1.5 Extra-terrestrial solar radiation

Extra-terrestrial solar radiation is the radiation from outside the Earth’s atmosphere or on the upper atmosphere. It is the main source of terrestrial solar components and it is not affected by atmospheric conditions. Knowledge of extraterrestrial solar radiation is essential in solar applications like solar tracking [5], combined heat power systems, which use concentrated solar power (CSP), biomass, and hydropower [15].

2.2 Advantages of using solar radiation technologies

Electricity generated from the Sun could be of good use in places where national electric grid lines are not available. Energy generated from solar technologies is clean and sustainable. Solar technologies do not release CO_2 and other waste products during operation. Thus, solar radiation technologies reduce the emission of greenhouse gases that play a role in climate change. Solar technologies also create job opportunities through the manufacturing and installation of the various solar system technologies. So, solar technologies are starting to be important features of our economy. Solar technologies can be used to improve the quality of water resources and are cost-effective [6,7,16].

2.3 Solar energy technologies

2.3.1 Photovoltaic systems

Photovoltaic cell or solar cell is a device that converts sunlight into electrical energy. The photovoltaic devices depend on the amount of sunshine available. These devices have the capacity to produce power throughout the year, with the amount depending on time and season [17,16]. Usually, during summer, the photovoltaic devices produce more electrical energy. Photovoltaic systems are capable of converting 1 kW/m^2 solar energy into 100 watts of electricity, which can cater for appliances like television, lamp, etc [17,18]. Photovoltaic Voltaic (PV) cells are the building block of solar panels.

2.3.2 Solar thermal systems

A solar thermal device uses energy from the Sun directly for heating, drying, evaporation, and cooling. Solar water heaters, solar water drying, etc are some of the products that use solar thermal systems [17,18].

2.4 Factors that affect solar radiation.

2.4.1 Heavy cloud cover

The clouds contain huge amount of water drops and ice crystals, which scatter radiation passing through them to move in different directions, so that only a small amount of solar radiation makes it to the Earth's surface. There are also different types of clouds and they play important roles. Optically thin clouds allow a small portion of radiation to pass through to the ground, whereas optically thick clouds stop the radiation from reaching the ground surface. Solar radiation can be reflected by the ground surface into the atmosphere and be reflected to the ground (see Figure 2.1 and Figure 2.2) [19].

2.4.2 Ozone

Ozone is a form of oxygen which is blue in colour and is contained in an ozone layer, in the upper atmosphere. The ozone is beneficial in the upper atmosphere since it protects the Earth from ultraviolet radiation which can damage plants and can also be harmful to humans causing sicknesses like cancer. Atmospheric components like oxygen, ozone and nitrogen oxide are responsible for absorbing solar radiation in the upper atmosphere, meanwhile water vapour, carbon dioxide and aerosols absorb solar radiation in the lower atmosphere [19].

2.4.3 Seasons

Seasons are caused by $23\frac{1}{2}$ (degree) tilt of the Earth's equator to the ecliptic plane. On the 21 June, which is the longest day of the year, and having the highest temperature of the year, as the Earth rotates around the Sun, its northern tip tilt about 90 degrees directly to the Sun by $23\frac{1}{2}$ (degree) N latitude. This day is called summer solstice and it is equivalent to the summer season in the Northern Hemisphere, while it is equivalent to the winter season in Southern Hemisphere. The Earth continues to rotate until 21 September, when the dark hours are equal to daytime hours, which is the equinox and it is astronomic spring season. This takes place from September 21 - 22. The Earth takes another turn and continues until 21 December which is the winter solstice with the longest number of dark hours in the Northern hemisphere. During this time summer solstice takes place in the Southern hemisphere, with the longest number of light hours. Which means that during this time the Northern Hemisphere and Southern Hemisphere receive different quantities of solar radiation (see Figure 2.3). Daylight and sunshine duration affect the amount of solar radiation falling on the Earth's surface. As the sunshine hours become longer in an area, the amount of solar radiation increases [19,20]

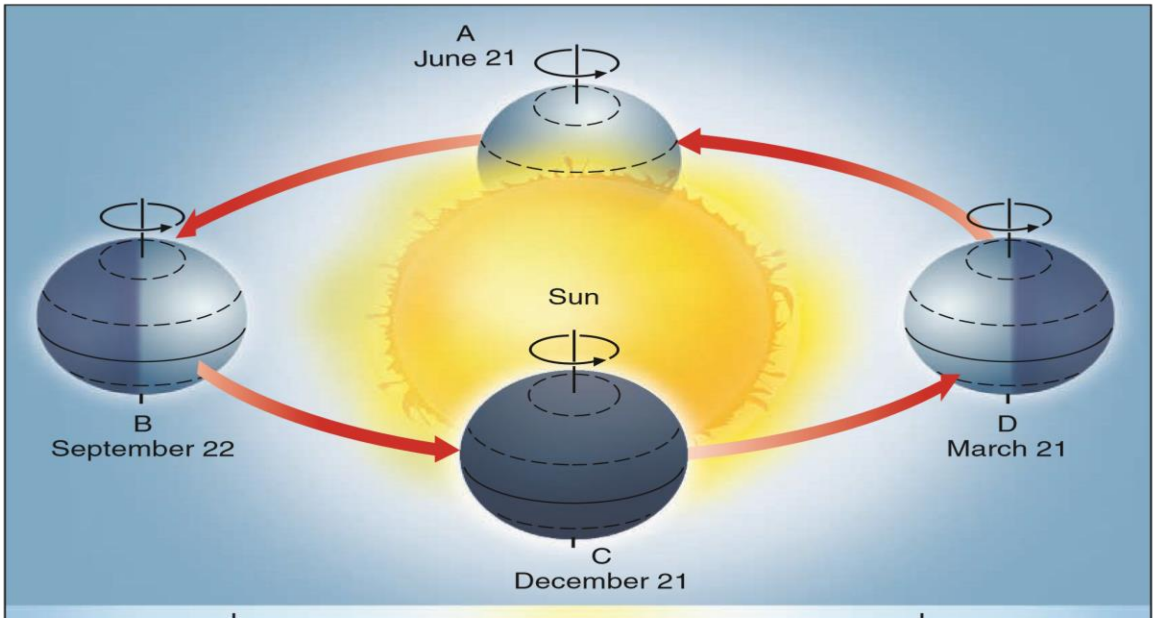

Figure 2.3: Geometric relationship between the Earth and the Sun during June and December solstices [19,20].

2.4.4 Latitude

Latitude can be defined as angular distance north or south of the equator. Places close to the equator tend to have high temperature. The ones far from the equator have cool temperatures. The smaller the value of the latitude, the higher the temperature whereas, the higher the value of latitude the cooler the temperature [19, 20]. The amount of the temperature controls the amount of solar radiation received in a particular area.

2.4.5 Altitude

As the solar radiation passes through the atmosphere to the Earth's surface, some of it is depleted due to contact with the atmospheric constituents. Some of the solar radiation is absorbed by greenhouse gases like water vapour and carbon dioxide, thus increasing the temperature. These gases absorb long-wave radiation and emit it to the Earth, thus keeping the atmosphere warm. Places with high altitude contain less water vapour and carbon dioxide, hence such places have low temperature. Temperatures decrease as the altitude increases. The greenhouse gases also absorb the solar radiation, and emit it to the ground, which will also reflect it back to space [19,20,21].

2.5 Measurement of solar radiation

2.5.1 Diffuse solar radiation

Diffuse solar radiation, which is shaded from direct Sun can be measured using a pyranometer [22,23]. Diffuse solar radiation is the amount that reaches the Earth 's surface indirectly. On clear sky, 8% of energy is from diffuse energy. The amount of diffuse solar radiation can also be attributed to air pollution and Earth configuration, and it amounts to 22%. Diffuse radiation is very little when the sky is clear, meanwhile it can be largely expected on cloudy days [24].

2.5.2 Direct solar radiation

Direct solar radiation is measured using pyrheliometer, which can be continuously pointed at the centre of the Sun through sun tracker. In order to measure direct solar radiation correctly, the surface must be positioned to be normal to the solar direction. Sunlight usually enters through a window and is directed onto a thermopile which is a device that converts heat to an electrical signal that can be recorded [23,25].

2.5.3 Global solar radiation

Pyranometer is used to measure global solar radiation, which is the sum of diffuse and direct solar radiation [22,23]. In order to obtain good quality data of global solar radiation, pyranometer must be calibrated at regular intervals and a good maintenance is also required [22,23]. Knowledge of global solar radiation is important for modelling and designs of solar technology devices like the photovoltaics.

2.6 Meteorological parameter measurements in South Africa

Measurements of the solar radiation reaching the surface of the Earth is essential for research based on solar energy, agriculture land reform, climate change etc. Establishing a weather station and its maintenance is a major problem in the developing countries like South Africa due to the cost implications. Currently there are meteorological stations in South Africa which are controlled and monitored by the following institutions: Agricultural Research Council (ARC), South African Weather Service (SAWS), Southern African Universities Radiometric Network (SAURAN) and ESKOM.

2.6.1 South African Weather Service (SAWS)

SAWS was established with the aim of capturing meteorological data in Southern Africa in 1914 and it has been the main source of ground irradiation data [26]. One of the objectives of SAWS is to improve the quality of meteorological service benefits in South Africa. It is also one of the tools that are used for free weather and climate reports to the public funded by grants from the government [26]. SAWS hosts an impressive database of global and diffuse solar radiation, which is not freely available to the public [27]. SAWS provide weather and climate information to the Aviation industry on a cost recovery through regulation tariffs and to the commercial clients like mining, telecommunications and municipalities [28].

2.6.2 Agricultural Research Council (ARC)

The Agricultural Research Council Institute for Soil, Climate and Weather (ARC -ISCW) has established agrometeorological programme that has developed and installed Agromet weather stations network since 1940. The Agromet stations consist of 100 mechanically controlled and 530 automatic weather stations that measure global solar radiation, air temperature, wind speed, relative humidity, evaporation, sunshine duration and rainfall at ground level. These stations were developed to enable farmers in South Africa to obtain some data which will help them in their activities for optimum yields [29].

2.6.3 Southern African Universities Radiometric Network (SAURAN)

SAURAN was initiated by the University of Stellenbosch and the University of KwaZulu Natal. Its goal is to come up with a network that provides quality and long-term record of solar radiation data. The stations under SAURAN measure parameters such as direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI). Meteorological data is also provided by stations under this network [30]. Some of the SAURAN stations have additional radiometers that measure ultraviolet radiation and mereological data such as wind, temperature, pressure, rainfall and relative humidity. The SAURAN station data is accessible to public from the SAURAN website, and it is open to the public [30,31].

2.6.4 Eskom

Eskom is a South African electricity power utility for public use and oversees stations powered by coal–fire, nuclear, and wind; they also run the hydroelectric generators as well as plants based on gas turbines. Some of the power stations are base-load while others are peak load. Based-load stations are the cheapest to run while the peak-load are the most expensive power stations to run. This is due to the fact that electricity demand is high in the morning as well as in the evening since most of the people use electrical appliances such as geysers, irons and stoves. Eskom came up with home flux tariff, which is a time-of-use tariff, meaning that energy charges are based on time of the day when electricity is used. Eskom also introduced advanced meter infrastructure technology, designed to measure electricity consumption on a time-of-use basis. Hence the cost of electricity varies depending on the type of power station run during the time of demand [32]. Eskom manages renewable energy projects like photovoltaics systems, concentrating solar thermal power stations and non-renewable installation such as Lethabo power station, etc [33,37]. Eskom has installed solar irradiance measuring instruments at different sites in the Northern Cape since 2006.

2.7 Climatic conditions of selected sites under study

2.7.1 Stellenbosch site

Stellenbosch is a coastal area in the western Cape province on the outskirts of Cape Town. Stellenbosch is the area where the University of Stellenbosch is situated. It usually experiences rainy/wet and extreme cold weather during winter, dry and warm summer, with latitude of 33.9281 ˚S, it has annual average temperatures of 17 degrees. During summer, Western Cape coastal regions experience a temperature range from 15 ˚ C to 27 ˚C. A cold front season was recorded in 2014-2015 resulting in severely cold weather in the coastal regions of the Western Cape.[34].

2.7.2 University of Venda site - (Vuwani Science Resource Centre)

Vuwani Science Resource Centre is one of the community projects owned and overseed by University of Venda [58]. It is located in a rural area in Vuwani, Venda in Limpopo. Limpopo has more sunshine hours during summer seasons. As we know, UNIVEN is situated in Limpopo province in Thohoyandou which is one of the low veld regions of Limpopo. Thohoyandou experiences temperatures ranging between 25 and 40 ˚ C. Latitude for University of Venda is

23.13100 ° **(S).** The rainy season usually occurs between October and March with an average rainfall of 800 mm [34,35].

2.7.3 KwaZulu Natal site

University of kwazulu Natal Howard college is situated in Kwazulu -Natal province, in a coastal city called Durban, whose latitude is 29.87098 ˚ (S). University of Kwazulu Natal Howard College is one of the four selected study areas, which are installed with SAURAN stations in South Africa. This area usually experiences very hot summers, with temperatures ranging from 23 to 33 ˚C. Durban has an average of 320 days of sunshine a year but January is Durban's hottest month. Severe storms and hail weather were recorded in January 2015[34] in this area.

2.7.4 Nelson Mandela University site

Nelson Mandela University is located in Eastern Cape, Port Elizabeth. Eastern Cape experiences a higher level of humidity and rainfall. Port Elizabeth, the coastal city of the Eastern Cape, experiences temperatures ranging from 7 to 20 ˚ C, especially during the winter seasons from April to August. During summer, temperature ranges from 16 to 26 ˚ C. Nelson Mandela University has a latitude of 34,0122 ° **(S)**. Port Elizabeth's sunshine hours range from 6 hours and 54 minutes daily in June to 8 hours and 54 minutes daily in December Port Elizabeth has a latitude of [35].

2.8 Models used for estimating Global Solar Radiation

There are various weather institutions and stations in South Africa, as discussed above which fall under SAURAN, ESKOM, SAWS, and ARC. These weather stations are unable to cover the whole of South Africa as a country and there is a lack of weather data in many rural areas. One of the solutions to this problem is the use of theoretical models to estimate the global solar radiation data needed for the introduction of renewable energy technologies in those rural areas.

Different theoretical models have been used to estimate global solar radiation using parameters like evapotranspiration, relative humidity, temperature, sunshine hours, cloud cover, and precipitation variables [36].

Ogolo 2010 [9] determined sunshine duration and temperature data for four different sites in Sahelian, Savannah, Midland, and Coastal sites in Nigeria. The authors used the Angstrom-

Prescott type, Hargreaves - Samani and Garcia models. The expression for the Hargreaves – Samani model used is linear regression between clearness index and square root of ΔT, which is a change in maximum and minimum temperature values, while a and b are regression constants. Specifically, a is measure of the overall atmospheric transmission for totally cloudy condition, while b is the rate of increase of $\frac{H}{H_0}$ with $\frac{S}{S_0}$, H, H_0, S and S_0 denotes monthly average daily global solar radiation, extraterrestrial solar radiation, monthly average daily actual sunshine hours and monthly average daily predicted sunshine hours respectively. Garcia model is the air temperature-based model adapted from Angstrom-Prescott model. The two models were tested using different statistical analysis for the four different locations and the temperature-based models were recommended suitable for estimating global solar radiation in all four regions [9].

In their research studies, Ugwu *et al*, 2011 did a performance assessment of Hargreaves - Samani model for estimating global solar radiation in Savanna region. They used average daily air temperature data as the inputs. Their results showed that there is a correlation between the observed and the estimated values of the monthly average global solar radiation [38].

Maluta *et al*,2018 carried out a performance assessment of the Hargreaves -Samani and Clemence models for estimating global solar radiation in Pretoria, Gauteng province. They used temperature data from three ARC stations, which are: Arcadia, Botanical, and Wonder boom stations. Through statistical validations, their results proved that Hargreaves -Samani and Clemence models are suitable for estimating global solar radiation [39].

Mulaudzi *et al*, 2015 [40] investigated the performance of three different models for estimating global solar radiation in Vhembe District, Limpopo. These were Angstrom-Prescott linear model that uses actual sunshine hours (S), maximum possible sunshine hours (S_0), regression constants (a) and (b), Hargreaves - Samani models and Garcia model which are the air temperature-based models. The authors used four stations in different areas of Limpopo Province. Their results suggested that Angstrom - Prescott and Hargreaves - Samani models are suitable for these areas [40].

Mulaudzi *et al*, 2015[41], in their research compared the performance of three empirical models for estimating global solar radiation in the North West Province, South Africa. The authors used a five-year daily sunshine hours, minimum and maximum air temperature and global solar radiation data from ARC and SAWS stations at North West province. The models compared were Angstrom Prescott -linear (that uses actual sunshine hours (S), maximum possible sunshine hours (S_0), regression constants (a) and (b), Hargreaves-Samani and Glover & McCulloch models. Their study showed that the Angstrom- Prescott linear and Hargreaves - Samani models were suitable [41].

In general, solar energy conversion systems are essentially sensitive to sunlight and ambient temperature. However, one of the advantages of using temperature-based models is that the temperature data can be easily measured in most places including remote rural area.

2.9 Description of models

2.9.1 Angstrom - Prescott model

This is a model based on sunshine duration. It was first proposed and designed by Angstrom for the estimation of global solar radiation. He derived a ratio of correlation between the average daily global solar radiation to clear days and the ratio of average daily sunshine hours to maximum possible sunshine duration [40]. However, Prescott [42,54] later improved the method by replacing clear days with extraterrestrial solar radiation. The equation for the model finally became the following relation:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right), \tag{1}$$

where H, H_0, a , b , S and S_0 represent the monthly average daily global solar radiation, extraterrestrial solar radiation, the measure of overall atmospheric transmission for an overcast sky condition, the rate of increase of $\frac{H}{H_0}$ with $\frac{S}{S_0}$, actual or observed sunshine duration and maximum possible sunshine duration, respectively. The model has been successfully used by many researchers [40,41].

2.9.2 Garcia model

The Garcia model originates from Angstrom - Prescott and has some modifications. It can be expressed using the following equation [41]:

$$\frac{H}{H_0} = a + b * \frac{\Delta T}{S_0} \ , \tag{2}$$

where a , b , ΔT , S_0 , H and H_0 represent measure of overall atmospheric transmission for overcast sky condition, the rate of increase of $H/_{H_0}$ with $\Delta T/_{S_0}$ the change in temperature, maximum daily sunshine duration, mean daily global solar radiation and extraterrestrial solar radiation, respectively [41,42].

2.9.3 Swartman and Ogunlade model

This model uses sunshine duration and relative humidity. It was developed by Swartman and Ogunlade for estimating global solar radiation and can be expressed using the following equation [42]:

$$H = a\left(\frac{S}{S_0}\right)^b RH^c \tag{3}$$

where H denotes the mean daily global solar radiation, a the measure of overall atmospheric transmission for totally cloudy condition, RH is the relative humidity, while b and c control the rate at which atmospheric transmission is affected as the temperature difference increases [42].

2.9.4 Bristow and Campbell model

Bristow and Campbell model is an empirical temperature model designed by Bristow and Campbell for estimating global solar radiation. The following is the model's relation [42,43]:

$$\frac{H}{H_0} = a[1 - \exp(-b\Delta T^c)] \tag{4}$$

where ΔT is a temperature difference, H is the daily global solar radiation, H_0 represents extraterrestrial solar radiation. The regression coefficients, a, b and c are such that a denotes the maximum value of atmospheric transmission coefficient, which is the maximum radiation that can be expected on a clear day and it depends on the amount of pollution on air and elevation, while b and c control the rate at which atmospheric transmission is affected as the temperature difference increases, and it differs from humid to arid environment [42,43].

2.9.5 Hargreaves - Samani model

Hargreaves - Samani model is the empirical model for estimating global solar radiation. The model uses daily minimum and maximum air temperature data as inputs. The minimum and maximum air temperature depend on the amount of cloud cover, humidity and solar radiation, which can be used to determine cooling loads for buildings and predict local air temperature [43]. While comparing to clear skies, cloud cover usually decreases the maximum air temperature due to lower solar radiation measurements and increases minimum air temperature due to increased downward emission and reflection of longwave radiation by clouds at night [44]. This model is commonly applied to estimate monthly global solar radiation based on the weekly or monthly averages of daily temperature ranges [45]. The advantage of estimating global solar radiation using the model is greater because temperature data are available for wider areas and over longer periods in most of the areas under study. The model is expressed using the following equation [43]:

$$H = K_r H_0 \sqrt{T_{max} - T_{min}} \tag{5}$$

where H (units of MJ/m^2/day), T_{min}, T_{min}, H_0 and K_r represent the average daily global solar radiation, minimum air temperature, maximum air temperature, extraterrestrial solar radiation, and empirical coefficient respectively. Annandale et al, 2002 [46] set the empirical coefficient (K_r) in this model, to 0.16 for inland regions and 0.19 for coastal regions. This is one of the models applied in this study to determine global solar radiation data. The extra-terrestrial solar radiation, H_0 is defined as solar radiation outside the Earth's atmosphere [38,43,47].

2.9.6 Clemence model

The Clemence model was established by Clemence in 1992 [48] for estimating solar radiation in the Southern African sites which record air temperature only.. The model was tested for estimating global solar radiation at about 30 Southern African weather stations from agrometeorological data bank of the Soil and Irrigation Research Institute (SIRI). Statistical tests i.e., index of agreement and coefficient of determination (R^2) suggested that the model was positive and accurate in estimating global solar radiation, especially for the summer rainfall zone [40]. The model's relation is as follows [48]:

$$H = (1.233 * H_0 * \Delta T + 10.593 * T_{max} - 0.713 * T_{max} * \Delta T + 16.548) * 0.04184 \tag{6}$$

where ΔT represents a change in temperature, i.e. $T_{max} - T_{min}$, T_{min} minimum air temperature and T_{max} maximum air temperature [48].

2.10 Chapter summary

In this chapter, a detailed background for the study was done, in terms of solar radiation, its components and measurements. A brief review of literature around estimation of global solar radiation was done.

Hargreaves - Samani and Clemence models were selected because they only use air temperature data as input, which is always universally available in contrast with sunshine duration and relative humidity. Measurement of air temperature can be done even at primary and secondary schools using a simple maximum and minimum thermometer. In this chapter different models were discussed. Two models were then selected, which are Hargreaves – Samani and Clemence models.

CHAPTER 3: STUDY AREA AND METHODOLOGY

3.1 Introduction:

Knowledge of solar radiation is of good necessity in a particular area for the design and installation of solar radiometers such as pyranometers, pyrheliometers, etc., for agricultural purposes, architectures and climate change mitigations. Some developing countries find it hard to afford good quality data from their meteorological stations [49]. There have been several empirical models designed to estimate global solar radiation, some of which are discussed in chapter 2. This Chapter focuses on estimating global solar radiation from four SAURAN stations across South Africa using Hargreaves -Samani and Clemence models.

3.2 Study area

This research study is based on the selected areas in South Africa where the SAURAN weather stations are recording meteorological parameters such as wind speed, air temperature and humidity are available. The climate trends in South Africa were observed during the previous five decades, i.e., 1960 – 2010, it was found that the annual mean temperatures have increased by at least 1.5 times the average global temperatures that showed 0.65 % increase in the same period [47]. The annual rainfall has shown a decrease, at the present time, SA is experiencing drought in some provinces like the Northern Cape [39]. There are eleven active SAURAN stations installed in the Southern Africa out of which four stations have been selected for this research. These stations' geographical coordinates are tabulated in Table 1.

3.3 South African Universities Radiometric Network (SAURAN)

Eleven working SAURAN stations have been installed in Southern Africa. In the current study the stations were selected such that some of them are in the coastal areas while some are in the inland areas. Seven weather stations were installed in the University campuses as follows: Stellenbosch University (SUN), University of Pretoria (UPR), University of Free State (UFS), University of KwaZulu – Natal Howard college (KZH), University of KwaZulu – Natal Westville (KZW), Nelson Mandela University (NMU) and University of Venda (UNV), Vuwani Science Resource Centre [30,31].

Some of the stations are located in four rural areas which are Vanrhynsdorp (VAN), Vryheid (VRY), Graaff-Reneit (GRT) and in the Richtersveld region (RVD) [30,31].

The four selected SAURAN stations (coastal and inland) with their geographical coordinates are given on Table 1.

Table1: Geographical coordinates of the research study area

Station	**Code**	**Latitude ° (S)**	**Longitude ° (E)**	**Altitude (m)**
University of Venda	UNV	23.13100	25.9761	628
University of Stellenbosch	SUN	33.9281	18.8654	119
Nelson Mandela University	NMU	34,0122	25.6652	35
University of KwaZulu-Natal Howard college	KZH	29.87098	30.97695	150

An inland station that was used in the study is University of Venda, situated in Thohoyandou, Limpopo Province, while coastal stations under study are University of Stellenbosch (in Western Cape), Nelson Mandela University (in Eastern Cape) and University of KwaZulu-Natal Howard (in KwaZulu Natal: KZN) [30,31,37]. South Africa has different climatic zones. Stellenbosch falls under warm-summer Mediterranean climate, KZN is in a humid subtropical climatic zone, UNV is in a tropical humid climate and NMU in Port Elizabeth is an oceanic climate [50].

Different latitude receives different amount of solar radiation. Accordingly, NMU is the furthest from the equator followed by SUN. The temperature decreases as the latitude increases, so, we expect the UNV station to have measured high temperatures as compared to the other three stations under study. UNV's altitude is higher than the SUN, NMU and KZH. The temperature changes with altitude. For every 100 m rise in altitude, the temperature decreases by approximately one degree Celsius [57]. At high altitudes, the air molecules are far much apart hence less air pressure, this reduces the air temperature since the kinetic energy of the molecules is less. The heating air is less dense due to buoyancy.

3.4 Methodology

In order to accomplish the main aim of this research, several steps were undertaken. Four of the SAURAN weather stations which measured air temperature, wind speed, wind direction, humidity, rainfall and solar radiation (direct, diffuse and global) were selected for this research study. The Hargreaves - Samani and Clemence temperature-based models described in the previous chapter and represented by equations, (5) and (6) were respectively selected from a pool of solar empirical models to estimate the daily average global solar radiation. The temperature data was sourced from the SAURAN website for the stations located in South Africa.

3.4.1 Selection of the stations and models

The daily minimum and maximum air temperature data for period of three years from 2014 - 2016 were sourced from SAURAN website for all the stations. The temperature data were analyzed to check whether there was any missing data from all the stations. It was discovered that 85 % of data was missing from some stations hence only those stations with 100 % data were selected. For the University of Venda site only the data for 2016 was found to be complete, and consequently, four stations were selected as per criteria stated. The stations are located at the following institutions: University of Stellenbosch (SUN), Nelson Mandela University (NMU), University of KwaZulu Natal Howard College (KZH), University of Venda (UNV), as illustrated in Table 1, with their geographical coordinates. These stations represent different climatic zones in the Southern Africa.

Estimation of the daily global solar radiation on the horizontal surface from the daily ranges of air temperature offers an alternative method in the absence of actual sunshine duration data. Most of the researchers have estimated the global solar radiation through the sunshine models and had high coefficients of regressions. Due to lack of actual or observed sunshine duration data for this research study, the Hargreaves - Samani and Clemence temperature models were selected since they only use air temperature data as input and is always available. SAURAN stations do not measure the actual sunshine hours.

3.4.2 Determination of the extra-terrestrial solar radiation

Each of the selected model needs the extra-terrestrial solar radiation data. So, the daily extra-terrestrial solar radiation (H_o) was calculated with the help of MATLAB software using the following relation [41]:

$$H_o = \frac{24*I_{sc}}{\pi}\left[1 + 0.033\cos\left(360 * \frac{d_n}{365}\right)\right]\left[\frac{2\pi\omega_s}{360}\sin\phi\sin\delta - \cos\delta\cos\phi\sin\omega_s\right], \quad (7)$$

where I_{sc} d_n and ω_s represent solar constant, the serial order of a given day from 1 January to 31 December and the hour angle respectively. Solar constant can also be expressed in $MJm^{-2}day^{-1}$ as follows [42]:

$$I_{sc} = \frac{1367*3600}{1000000} = 4.9212 \ . \quad (8)$$

The hour angle was calculated using MATLAB software in the following equation [47]:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \ , \quad (9)$$

where ϕ denotes the latitude of a site, δ denotes a solar declination and can be defined as the angle between Sun's ray when extended to the center of the Earth and the equatorial plane and can be calculated using the following formula [41,42]:

$$\delta = -23.45 \ \sin\left(\frac{360*24*d_n}{365}\right) \ . \quad (10)$$

Maximum possible sunshine duration (hours) was calculated using MATLAB software in the following equation:

$$S_0 = \frac{2\omega}{15} \ , \quad (11)$$

where S_0 , ω denotes maximum possible sunshine hours and hour angle respectively [42].

3.4.3 Comparison of the results.

After computing the estimates of the daily global solar radiation data per selected station, the results were compared graphically using MATLAB software, where a comparison was between the observed and the estimated global solar radiation for both Hargreaves - Samani and Clemence models. The performance and accuracy of the two models were assessed statistically using the same software.

3.4.4 Statistical analysis

In pursuance of the objectives of this study, the performance and accuracy of the two models were assessed statistically using the computational MATLAB software. The statistical analysis used were mean bias error (MBE), root mean square error (RMSE), Mean Percentage Error (MPE), Coefficient of Determination (R^2) and t-statistic test *(t)*. Lower values of MBE, MPE and RMSE imply good performance of a model. A positive value of MBE implies overestimation while its negative value shows underestimation. R^2 is used to assess the performance of the model and is best at the value of 1 while the smaller t-statistic value implies good performance of the model [43, 47,51]. The following equations were used for our statistical analysis [43,47]:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_{im} - H_{ie})^2\right]^{\frac{1}{2}}, \quad (12)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_{im} - H_{ie}) \quad , \quad (13)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{im}-H_{ie}}{H_{im}}\right) \times 100\% \ , \quad (14)$$

$$R^2 = \left[1 - \sum_{i=1}^{n}\frac{(H_{im}-H_{ie})^2}{(H_{im}-\overline{H}_{im})^2}\right] . \quad (15)$$

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2-(MBE)^2}\right]^{1/2}, \quad (16)$$

where, H_{im} and H_{ie} represents the i^{th} observed global solar radiation values and estimated global solar radiation values respectively n denotes the total number of observations, $\overline{H}_{im}$ denotes the mean observed global solar radiation and $n-1$ represents the degrees of freedom [43,47,52].

3.5 Chapter summary

In this chapter, we have given detailed geographical and climatic information of the selected study area. We also critically explained all necessary methods carried out in estimating global solar radiation. The chapter is basically about the application of Hargreaves-Samani and Clemence models in this study and the methodology applied. This chapter also outlined important equations of statistical analysis which were used to validate selected models.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction.

Estimation of global solar radiation for the selected stations was done using Hargreaves & Samani and Clemence models. There is a specific amount of solar radiation in each area. Therefore, this chapter gives account for all the results by representing results graphically and in Tables. The graphs and Tables were critically discussed. This chapter is the most important one since it reveals whether the hypothesis stated in chapter 1 is valid or not. The validity of the two models has been examined in this chapter as one of the objectives of the study, where the models were analysed through statistic equations. The errors from the estimation of global solar radiation and observed ones were outlined in discussion of results. The results shown indicate whether the models were successful in estimating global solar radiation for selected models, which further exhibits the significance of this work, and is a solution to the problem stated in chapter 1.

4.2 Extra-terrestrial solar radiation.

Table 2 shows the comparison of monthly mean daily extraterrestrial solar radiation data for the stations under study, which were calculated from equation (7) using MATLAB software. We know that extra-terrestrial solar radiation depends on the latitude, day number of the year, solar declination, and sunshine hour angle. The magnitude of the extraterrestrial solar radiation is always higher than global solar radiation on the Earth's surface, which is scattered and absorbed by the atmosphere, gas molecules, and clouds [17,18]. It can be observed from Table 2 that the UNV station obtained the highest values of H_0 from February to October. UNV station has the lowest latitude, that is, 23.13100 ° **(S)**, KZH (29.87098 ° **(S)**), NMU (34.00859 ° **(S)**), and SUN (33.92810 ° **(S)**).

Table 2: Extraterrestrial solar radiation for different stations. Units are in MJ/m^2

Months	H_0 -KZH	H_0-SUN	H_0-NMU	H_0 -UNV
1	31.50	43.10	43.15	42.30
2	39.70	39.20	39.19	40.00
3	34.10	32.80	32.79	35.80
4	27.20	25.30	25.28	30.10
5	21.50	19.20	19.28	25.00
6	18.80	16.40	16.39	22.50
7	19.90	17.60	17.60	23.60
8	24.70	22.60	22.58	27.80
9	31.30	29.80	29.73	33.40
10	37.60	36.90	36.85	38.40
11	42.00	42.00	42.98	41.50
12	43.80	44.20	44.15	42.70

Figure 4.1 shows the monthly mean daily extraterrestrial solar radiation for 12 months for each station (for each year from 2014-2016) for different stations. Monthly mean extraterrestrial solar radiation for KZH station can be identified by red dot marks, for SUN station by green star marks, NMU station by blue diamond marks, and UNV station by purple square mark. The amount of extraterrestrial solar radiation also depends on the time of the year. The extraterrestrial solar radiation for the four selected study areas was calculated for January to December (it's the same in each year). The results from the graph show that the amount of extraterrestrial solar radiation is high during summer, especially from January, February, March, September, October, November, and December, while it is very low during April, May, June, July, and August. The variation can be attributed to different temperatures.

The temperature is usually high during summer and low during winter. It could also be due to different seasons. From 21 June to September, Southern Hemisphere experiences a winter solstice, where the amount of solar radiation received is very small. It can be observed from the graph that the UNV station has the highest amount of extraterrestrial solar radiation amongst the four stations. One may take into consideration the effect of the station's latitude which is the lowest value compared to the other three stations under study, that is to say, 23.13100 ° **(S)** and shows that the angular equatorial distance from the Sun to the Earth is close to the equator, while for SUN it is 33.92810 ° **(S)**, NMU -34.0085 ° **(S)**, and KZH 29.87098 ° **(S).** Hence the lower the latitude the higher the temperature and conversely the higher the latitude the lower the temperature [19,20], which has contributed to variation in extraterrestrial solar radiation for the stations.

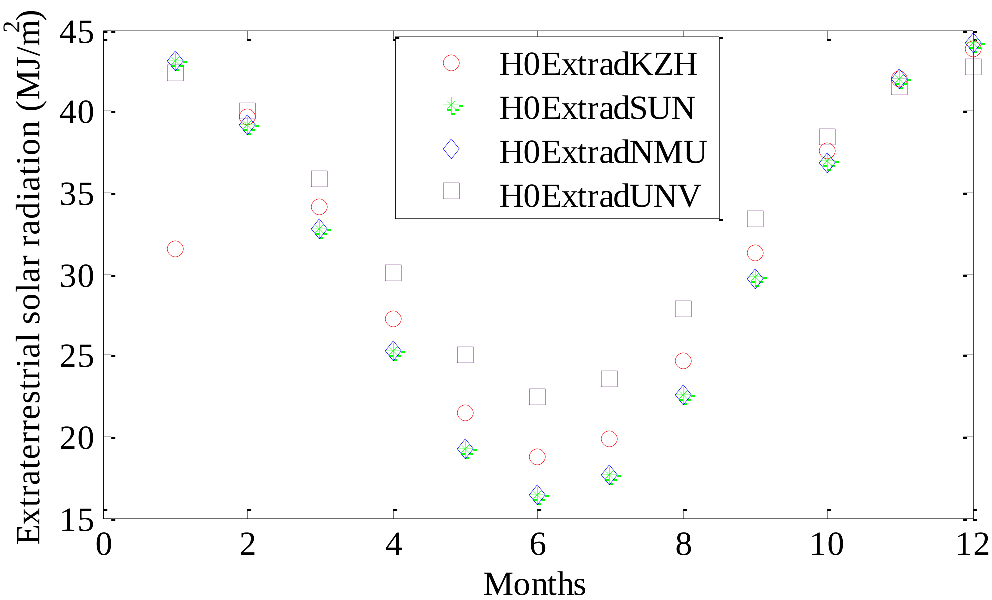

Figure 4. 1: Comparison of monthly mean daily extraterrestrial solar radiation and months for different stations.

Table 3: Monthly mean daily maximum possible sunshine hours for different stations

Months	SUN	NMU	KZH	UNV
1	13.981	13.987	13.686	13.249
2	13.226	13.230	13.045	12.776
3	12.215	12.216	12.184	12.137
4	11.136	11.133	11.262	11.452
5	10.231	10.225	10.493	10.883
6	9.779	9.772	10.111	10.602
7	9.992	9.986	10.291	10.734
8	10.776	10.772	10.956	11.225
9	11.820	11.820	11.847	11.886
10	12.898	12.901	12.766	12.569
11	13.794	13.800	13.528	13.133
12	14.223	14.230	13.890	13.400

From Table 3 above the monthly mean maximum possible sunshine hours was calculated using equation (11), it can be observed that the SUN station has the lowest mean values of sunshine hours amongst all the selected stations. This is due to the fact that Western Cape experiences wet and cold weather during the winter season. The highest temperature measurements occurred during November, December, January, and February, simply because Western Cape experiences dry and hot weather during summer. UNV station seems to be having the lowest amount of sunshine in Springs, summer, and Autumn amongst all selected study areas. This is because Limpopo usually faces higher rainfall during summer

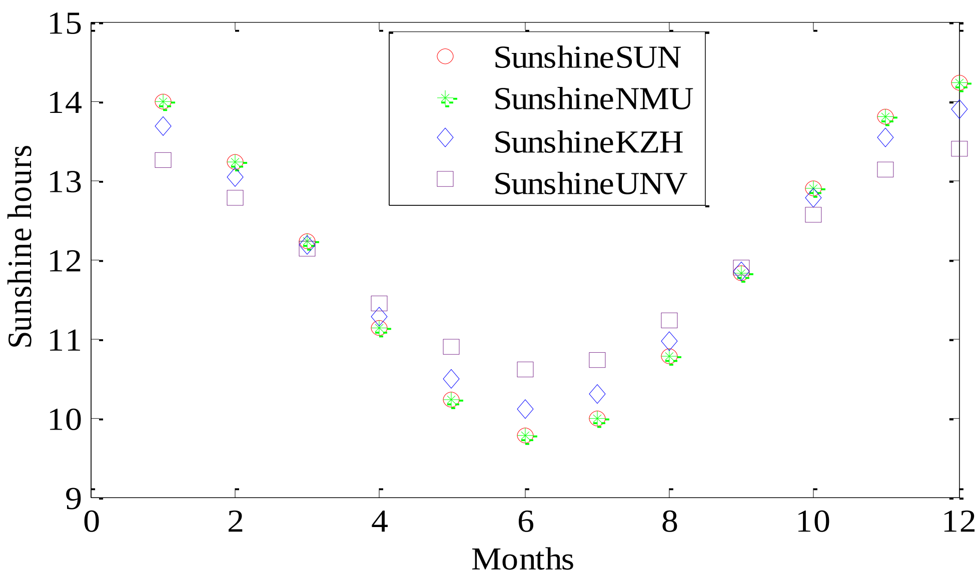

Figure 4.2: Monthly mean daily maximum possible sunshine hours for different SAURAN stations.

Figure 4.2 shows a comparison between montly mean daily maximum possible sunshine hours and the month of the year (Sunshine hour is expressed as average value over several years,hence the graph represents the mean value of sunshine hours for all the years, i.e 2014-2016 in all the selected stations) for different stations. Sunshine hours for SUN station can be identified by red dots scattered plots, NMU green star scattered plots, KZH blue diamond scattered plots, and UNV purple square scattered plots. The first factor to be noted is that sunshine hours depend on the seasons. The observations from the Figure show that there is a decline in the number of sunshine hours during winter for all the stations. The variation of sunshine hours amongst the stations under study might be due to climatic conditions and factors such as air pollution, fog, rime, etc per site [35]. During summer the occurrence of high clouds and convection clouds contributes a lot towards sunshine hours than in winter [35]. There is also an increase during summer. UNV station is having the lowest sunshine hours amongst all the stations during summer, particularly in January, February, October, November, and December. This can be attributed to variations in daytime hours. Limpopo Province has daytime hours of 10.09 less than other selected study areas in Summer while it has more daytime hours of about 10.44 in winter than all other stations [35], as a result, UNV has the highest sunshine hours in winter as compared to other stations. Western Cape experiences more rainfall from June To August. Another contributing factor is that the UNV station has the highest value of altitude amongst all the selected stations as indicated in section 3.3. Table 1 from the previous chapter, as results Venda, where the UNV station is situated experiences early sunset hours than the other selected study areas [35], hence the UNV station has the lowest number of sunshine hours. The latitude of both SUN and NMU stations are close to each other, that is, SUN latitude is 33.92810 ° **(S)** while NMU has a latitude of 34.00859° **(S)** (In section 2.4.4. Latitude was listed as one of the factors that affect solar radiation. The places that have lower values of latitude are close to the equator, with higher temperatures, while the places with higher latitude are further from the equator, hence they have lower temperatures . SUN and NMU stations have higher latitudes amongst all the selected stations, as results they have cooler temperatures than other stations, this explains why SUN and NMU stations obtained lower values of estimated global solar radiation than UNV and KZH stations, see section 4.2 and 4.4). SUN station has an altitude of 35 while NMU has an altitude of 119 and it can also be observed from Table 1 that NMU has the lowest altitude.(In section 2.4.5. it was explained that place with lower altitudes have lower temperatures,resulting in lower amount of solar radiation falling in a location).

As one of the Earth's poles tilt towards the Sun, the summer solstice occurs. During this time the Earth is tilted 23.45 degrees towards the Sun in the Southern hemisphere. This takes place on December 21-22 in the Southern Hemisphere [20]. The Earth has also tilted away from the Sun at 23.45 degrees. This is called the winter solstice and it occurs on June 21-22 in the Southern Hemisphere [20]. During astronomical autumn, 21-22 March, where there is the equinox, solar declination is zero and during astronomical spring, on the 21-22 September, at the occurrence of the equinox, the solar declination is zero. The Solar declination (δ) for all the stations understudy was calculated for each day using equation (10) in Section 3.3.2. The calculated solar declination values range between 23.45 to -23.45 degrees from January to June, and it shows a decrease during these months. Solar declination also ranges between -23.45 degrees to 23.45 degrees from June to December, showing more increase during these months. At the winter solstice, the declination of the Sun reaches its minimum. At the summer solstice, the declination of the Sun reaches its maximum. At the vernal equinox or autumnal equinox, the declination of the Sun is zero.

4.3 Air temperature

The air temperatures are subject to many influences such as latitude, ocean currents, cloudiness, daylength whereby the shorter the number of daylight hours the less the time the Earth is subject to heating, etc. The Southern hemisphere experiences its winter season in June. The observed air temperatures as per station under study are tabulated below. The diurnal range of the temperature increases with the distance from the sea and the areas where solar radiation is the strongest. For the KZH station, the difference between the day's highest and lowest temperature in January is around 6 ℃ for the period under study while in June, the temperatures vary from 7 ℃ to 11 ℃.

Table 4: Monthly mean daily maximum and minimum air temperature for KZH station.

Year	2014		2015		2016	
Months	T_{max} (℃)	T_{min} (℃)	T_{max} (℃)	T_{min} (℃)	T_{max} (℃)	T_{min} (℃)
1	27.877	21.510	27.203	20.925	27.647	21.347
2	28.498	21.500	26.835	20.020	27.650	21.089
3	27.261	20.544	27.012	20.395	27.642	20.772
4	25.222	17.872	24.643	17.887	26.253	19.119
5	24.138	16.201	25.203	17.734	24.053	16.189
6	23.275	14.100	23.622	15.287	22.519	15.164
7	21.917	13.884	21.909	14.341	21.188	13.314
8	23.315	15.738	22.792	15.860	23.092	14.890
9	23.479	16.573	22.381	16.436	22.775	15.862
10	22.658	16.047	25.239	18.241	23.722	18.246
11	24.071	17.803	24.732	17.771	26.793	19.999
12	26.127	19.738	26.637	20.526	26.623	20.865

Table 4 shows that the minimum temperature occurred in July in 2014, 2015, and 2016 at 13.884 ℃, 14.341 ℃, and 13.314 ℃ respectively. The maximum temperatures occurred in the month of February and were 24.498 ℃, 26.835 ℃ , and 27.650 ℃. Accordingly, during the summer season, temperatures are expected to be high since the humidity could be low and water levels too. (Other stations are explained under Table 5, Table 6 and Table 7).It shows that for the period of three years, there is small variation of temperature at KZH station. So, KZH is one of the provinces that receives its rainfall during summer but due to climate change, rainfall is scarce. Therefore, the maximum temperatures usually experienced from December to February the following year. KwaZulu-Natal experiences cold weather in winter and the temperature is likely to be low.

Table 5: Monthly mean daily maximum and minimum air temperature for SUN station.

Year	2014		2015		2016	
Month	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)
1	28.383	16.207	28.414	14.952	31.431	19.387
2	30.161	17.483	28.411	14.228	28.575	16.688
3	25.168	14.257	26.602	13.717	26.368	14.385
4	26.495	13.111	23.131	10.453	24.291	12.227
5	21.159	10.757	17.978	7.750	21.519	10.071
6	17.775	8.613	16.907	6.658	19.109	7.819
7	17.882	6.784	19.903	8.647	17.906	7.256
8	21.494	8.751	21.483	10.399	20.897	7.890
9	21.884	9.524	26.136	13.700	19.514	.882
10	25.335	13.495	27.151	13.994	23.187	10.549
11	27.116	12.838	28.282	15.138	24.480	13.016
12	27.560	16.272	29.060	14.863	27.645	14.611

According to Table 5, the SUN station seems to be having the lowest temperatures amongst all the stations. SUN station experienced a low temperature range roughly from 21℃ to -8℃, in winter, during the months of June, July, and August from 2014 to 2016, since it experiences more rainy and extreme weather during winter seasons. It can also be noted that the SUN station also exceeded the KZH station by an average maximum temperature of 30℃ during summer. Western Cape experiences dry, and hot weather during summer. SUN station temperature range in most of the summer seasons and was surpassing NMU station from 2014 to 2016.

Table 6: Monthly mean daily maximum and minimum air temperature for NMU station.

Year	2014		2015		2016	
Month	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)
1	27.023	18.836	27.468	18.063	28.658	19.534
2	26.250	16.760	26.314	17.418	27.224	17.712
3	22.588	14.711	26.244	17.086	26.075	16.932
4	22.147	10.505	23.244	14.180	25.934	15.615
5	22.082	9.788	22.866	13.123	24.660	12.465
6	23.283	12.062	20.776	10.014	23.547	10.554
7	22.465	11.666	19.174	10.159	22.117	9.408
8	22.776	13.324	21.233	11.319	23.081	10.905
9	22.762	14.360	22.303	12.343	24.460	12.414
10	24.757	15.362	23.780	14.260	25.290	14.087
11	27.022	17.541	23.712	13.903	26.684	15.255
12	26.350	17.899	27.468	17.503	27.457	14.393

In Table 6, the only season in which NMU surpasses SUN station in temperature is during winter. The average maximum temperature can be seen from Table 6 reaching ± 22 °C in winter. Port Elizabeth has a higher level of humidity and rains throughout the year, yet without snow or frost. It is in a subtropical region, where the warmth of waters from the Indian ocean spreads over the shore, which could have been the cause of some slight rise in temperatures.

Table 7: Monthly mean daily maximum and minimum air temperature for UNV station.

Year	2016	
Month	T_{max} (°C)	T_{min} (°C)
1	32.887	20.805
2	34.201	21.519
3	31.507	20.008
4	30.900	16.974
5	26.941	12.825
6	25.769	11.372
7	25.067	10.701
8	27.992	11.170
9	30.786	15.087
10	31.669	17.405
11	31.803	19.987
12	31.711	20.512

Table 7 illustrates the monthly mean daily minimum and maximum air temperatures for UNV station for 2016. It can be observed that during summer the temperatures at UNV station are the highest amongst all the selected stations. This is due to the fact that UNV has the lowest latitude coordinate, which is closer to the Earth's equator than all the other selected stations.

Comparison between the monthly mean daily minimum and maximum air temperatures is also illustrated through scattered plots from Figure 4.4 – 4.7. Where monthly mean daily minimum air temperatures for KZH, SUN, and NMU stations from 2014 -2016 can be identified in the figure through red square marks, black positive marks and green triangle marks scattered plots respectively. The monthly mean maximum air temperature for 2014 -2016 can be identified by blue diamond marks, maroon star marks and purple circles marks scattered plots respectively. For UNV station, monthly mean daily minimum air temperature can be identified with blue diamond marks scattered plots for 2016, while monthly mean daily air temperature can be identified with maroon marks scattered plots for 2016.

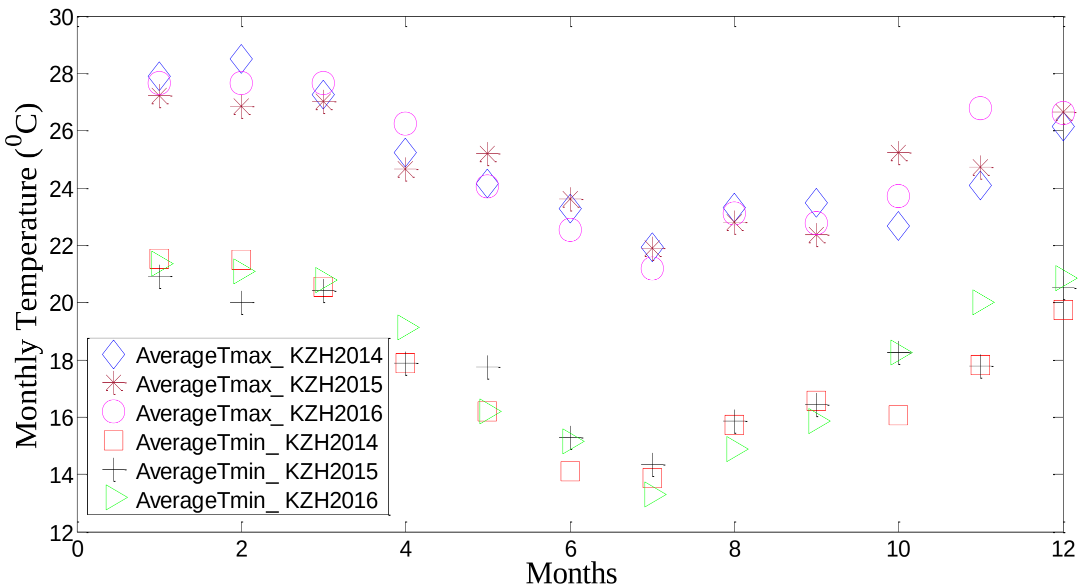

Figure 4.3: Monthly mean daily minimum and maximum air temperature for KZH station.

Figure 4.3 shows the monthly mean daily minimum and maximum air temperature data from 2014 -2016 for the KZH station. The 2014 red square marks scattered plots suggest that there was some decline in monthly mean daily minimum air temperature during winter and high in summer. In winter there were fewer day hours than night hours. So, the temperature is low during long night hours. Usually, the minimum temperatures are experienced before sunrise [20,21]. According to the graph, the lowest minimum average temperature was 14 ℃ in July and the highest was close to 22℃ in January.

It can be observed in Figure 4.3 that in 2014 (represented by blue diamond) there was some decline in temperature during the months of March, April, May, June, and July. The highest maximum temperature was above 28 ℃ while the lowest was 22 ℃. Though there was a peak in temperature in the months of August and September, there is some decline again in October.

From Figure 4.3 it is observed that in 2015 (see black +) there were fluctuations of monthly mean daily minimum air temperature. There was a drop during the months of May, June, and July. The winter season is cold, there was too much cold, hence the temperatures were very low. Reports of severe storms were made for the month of January 2015 [53]. For February, there were heavy rains and thunderstorms in KwaZulu Natal which might have led to fluctuations [53,55,56]. In 2015 (see maroon asterisk) too many fluctuations of monthly mean daily maximum air temperature were observed (There was a rise and fall in temperature, causing some inconsistency in temperature data trend during the season. Example, the data trend in temperature is expected to go down during winter, but we can observe a rise in temperature in May. Hence, we also observed inconsistency in the months of September, October and November. There is a sideways trend in temperature data. Hence the graph is uneven. This can be attributed to variation in weather.

In 2016, (see green marks in Figure 4.3) the temperature was high in summer. The lowest temperature was in July. There was an increase in monthly mean daily minimum air temperature in the month of August through December. During the months of May, June, and July is winter season in the Southern Hemisphere [20]. South Africa experiences severe colds during winter, hence the temperatures are low during this season. According to weather observations, there was a drop in temperature in April, May, June, and July. The lowest temperature was 21 ℃ in July, while the highest mean monthly maximum temperature occurred in Summer with 28 ℃. The figure also shows low temperatures in May, June, and July. In 2016, there is a good trend of monthly mean daily maximum air temperature.

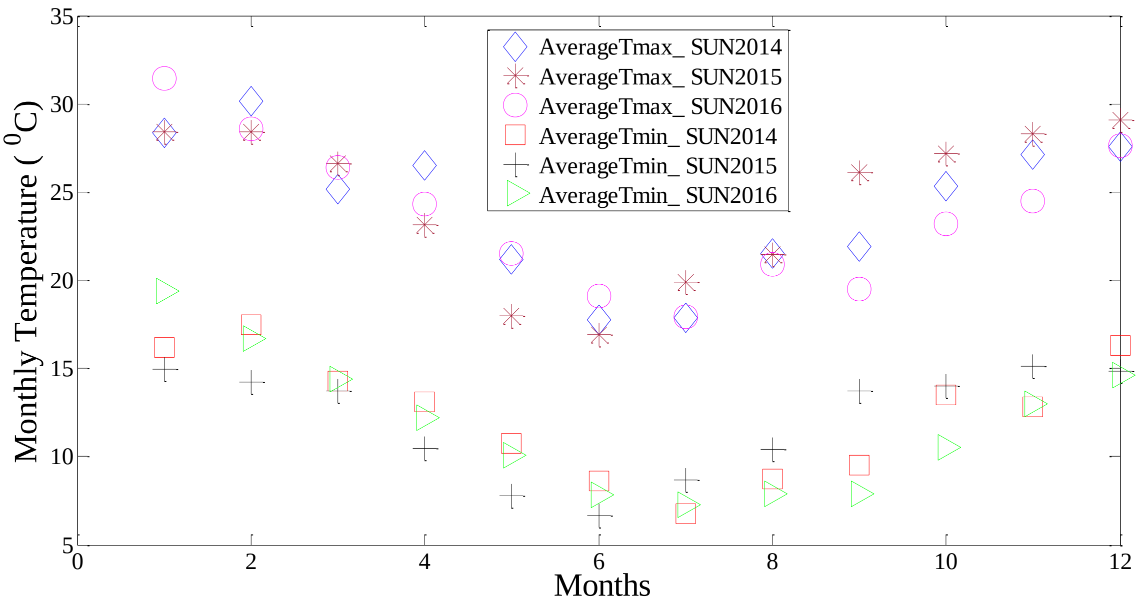

Figure 4.4: Monthly mean daily minimum and maximum air temperature for SUN station.

In 2014 it can be seen that the graph starts with a low monthly mean daily minimum air temperature in January and increase again in February (see red square marks scattered plots in Figure 4.4). Even though one might expect the temperatures to be high, since it's summer season, but possibility of heavy rains could have contributed to low temperature. According to the figure, there is too much decline in temperature in June, July, and August, with July having the lowest temperature. The number of sunshine hours is less during winter. Western Cape Province where SUN station is situated experiences more rainy and severe cold weather during this season [35].

In Figure 4.4 it is shown that (blue diamond marks) there was a decline in monthly mean daily maximum air temperature during the month of January in 2014. Western Cape experiences dry summer weather during this season. There was more decline in temperature during winter, i.e. in May, June, and July. In 2014, the winter season coastal regions like Western Cape, KwaZulu Natal, and Eastern Cape were affected by cold front weather, resulting in heavy snowfalls, rains, and extreme cold weather [55].

In 2015 (see black positive marks in Figure 4.4) there was a peak in monthly mean daily minimum air temperature during summer and more decline in winter. The lowest temperatures are in winter. However, there were not too many fluctuations in monthly mean daily maximum air temperatures (see maroon marks). The plots show the peak in monthly mean daily air temperature from the month of July to December. Also shown is more decline in monthly mean daily minimum air temperature from January to July (see black positive marks), while it obtained the highest values of monthly mean daily minimum air temperature amongst in the months of July, August, September and November as compared to 2014 and 2016. In 2015 there are only a few days where disastrous weather was reported. It may also be observed that 2016 did not start with a decline in monthly mean daily maximum air temperatures in the month of January (purple marks). though it shows some fluctuation in August and September. Green scattered plots show the lowest values in monthly mean daily minimum air temperatures from August to December. It is also observed that low temperatures occur in winter. Western Cape experiences rainy and cold weather in the winter season [35]. The fluctuations were very less in 2016 as compared to previous years, i.e., in 2014 and 2015. In 2016, monthly mean daily minimum and maximum air temperatures show more weather stability from January to June. Fluctuations start occurring from July until December.

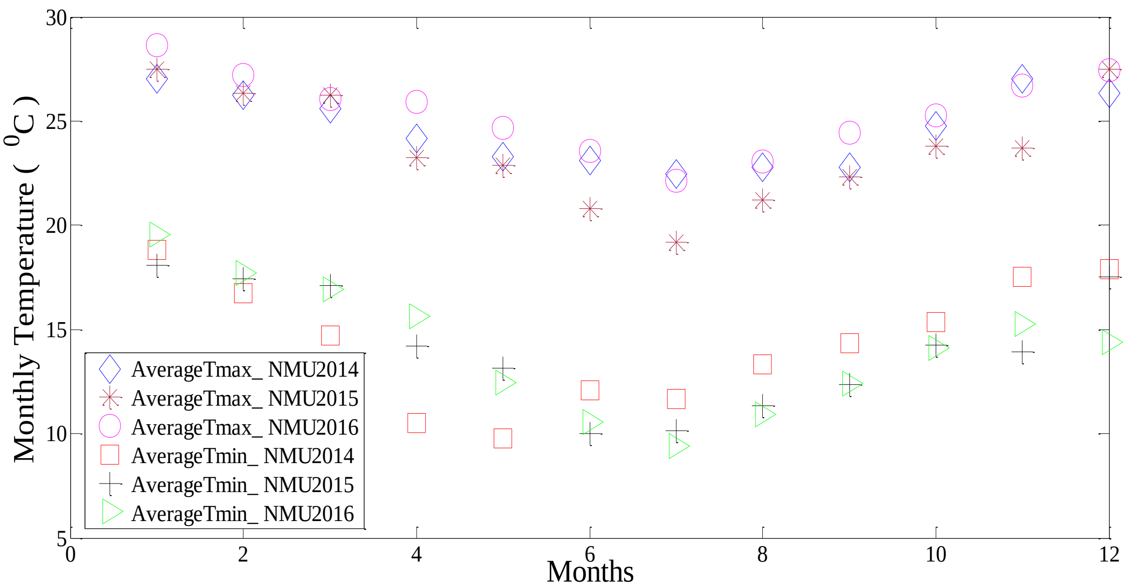

Figure 4.5: Monthly mean daily minimum and maximum air temperature for NMU station.

According to Figure 4.5, NMU shows good trend in monthly mean daily air temperature while showing slight fluctuation in December 2014. This follows a report of a cold front in 2014 during the winter season that affected coastal areas, i.e., KwaZulu Natal, Eastern Cape, and Western Cape. There was also an occurrence of severe colds, floods that caused disturbance of weather in those regions, from April to September in 2014 [55]. The monthly mean daily maximum air temperature in 2014 has no fluctuations, rather there is evidence of temperature changing at a constant rate.

In 2015, there was a huge decline in monthly mean daily minimum air temperatures in April and May. The temperature started to decline more during April, due to change in season. Even the sunrise time and sunset time changes. April and May's temperatures were very close since it is autumn season. The temperatures were very low starting in June, and there was an increase in August.

Both monthly mean daily minimum and maximum air temperatures in 2015 show too much instability in weather due to variation in seasons. The Highest temperature occurred during summer in December and January, where the mean maximum air temperature approaches 28 ℃. In 2016 monthly mean daily maximum air temperature it can be seen that the temperature declined very low during winter, there was also a peak from September through December. NMU has the highest latitude amongst all the selected study areas. It has the lowest temperatures in Summer, Springs, and Autumn. From 2014-2016, NMU station had lower values temperatures than SUN station except during winter because Western Cape where SUN station is situated experiences more rainy and severe cold in winter [35].

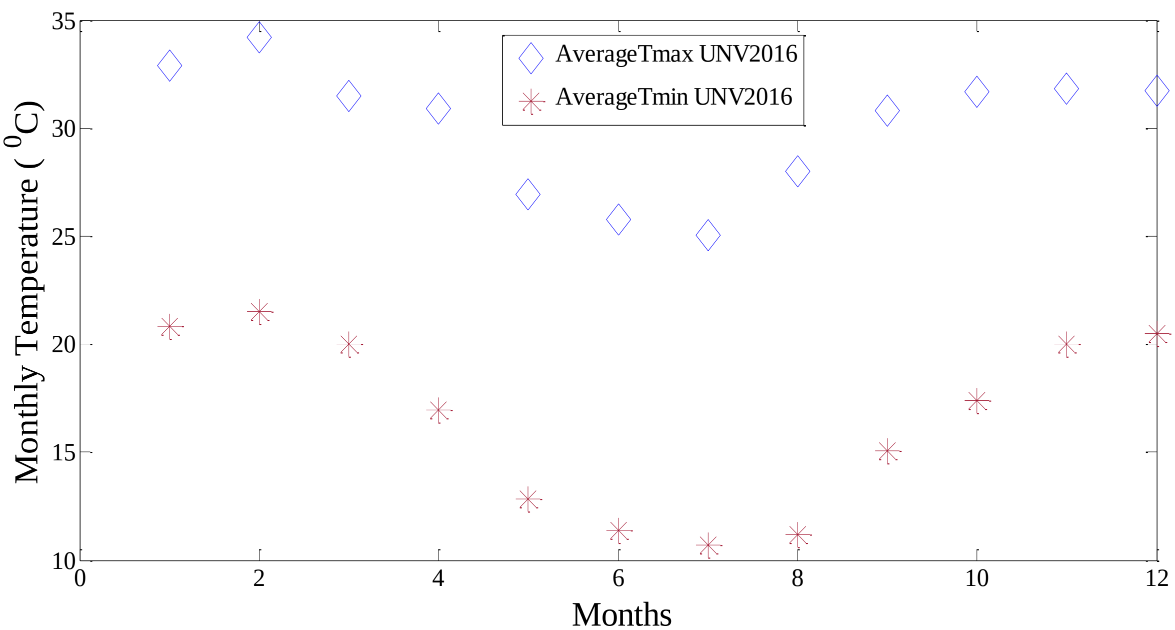

Figure 4.6: Monthly mean daily minimum and maximum air temperature for UNV station.

Figure 4.6 shows comparison of both monthly mean daily minimum and maximum air temperature and months for UNV station from the year 2016. Figure 4.6 depicts that the UNV station has the highest values of monthly mean daily minimum and maximum air temperatures amongst all the selected study areas. UNIVEN has the lowest latitude. It gets very hot, as a result Venda has high temperatures. Thohoyandou is one of the lowveld regions of Limpopo [35]. It can be observed that UNV is leading with the highest values of monthly mean daily minimum and maximum air temperatures in all seasons amongst all the stations. During the months of May to July, UNV had monthly mean daily air maximum temperatures ranging from 25 ℃ to 27 ℃. During summer the maximum temperature ranged from 33 ℃ to 34 ℃. In Figure 4.6, the UNV station had monthly mean daily temperatures ranging from 11 ℃ to 13 ℃ during winter. Monthly daily minimum air temperature ranged from 20℃ to 21 ℃ during summer. Thohoyandou experiences temperatures ranging between 25 ˚ C and 40 ˚ C [35].

4.4 Daily temperature comparison

Figures 4.7 - 4.17 illustrate daily minimum and maximum air temperature for different stations, from the months of January to December from the period of 2014 to 2016. Minimum air temperature can be identified by green asterisk scattered plots, while maximum air temperature can be identified by red circles scattered plots. The Figures show that the temperature was usually high during summer and spring, it was very low in winter.

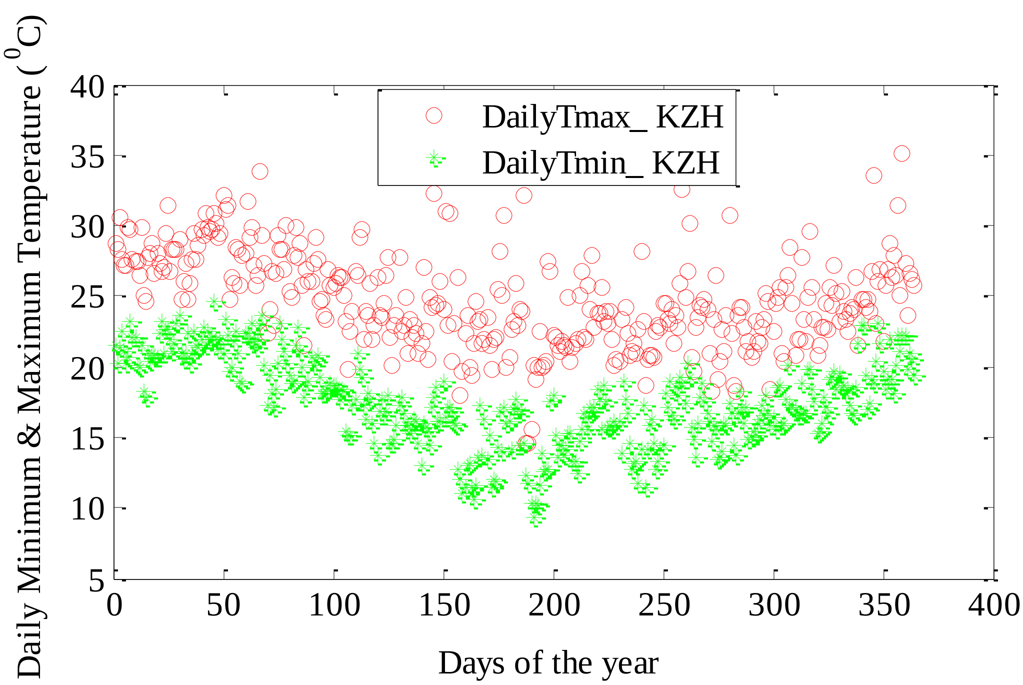

Figure 4.7: Daily minimum and maximum air temperature for KZH station in 2014

Figure 4.7 shows the daily minimum and maximum air temperature for the KZH station in 2014. In Figure 4.7, the temperature is very low during winter due to cold weather, in both minimum and minimum air temperature plots. Coastal regions like Eastern Cape, Western Cape, and Kwazulu-Natal were hugely affected by cold front systems, which caused severe colds, floods, snowfalls particularly from April to September [55]. This also resulted in low temperatures. It can also be observed in Figure 4.8 that the lowest temperature in a maximum plot is below 20℃ , while the lowest temperature in a minimum plot is below 10 ℃ (see Figure 4.7).

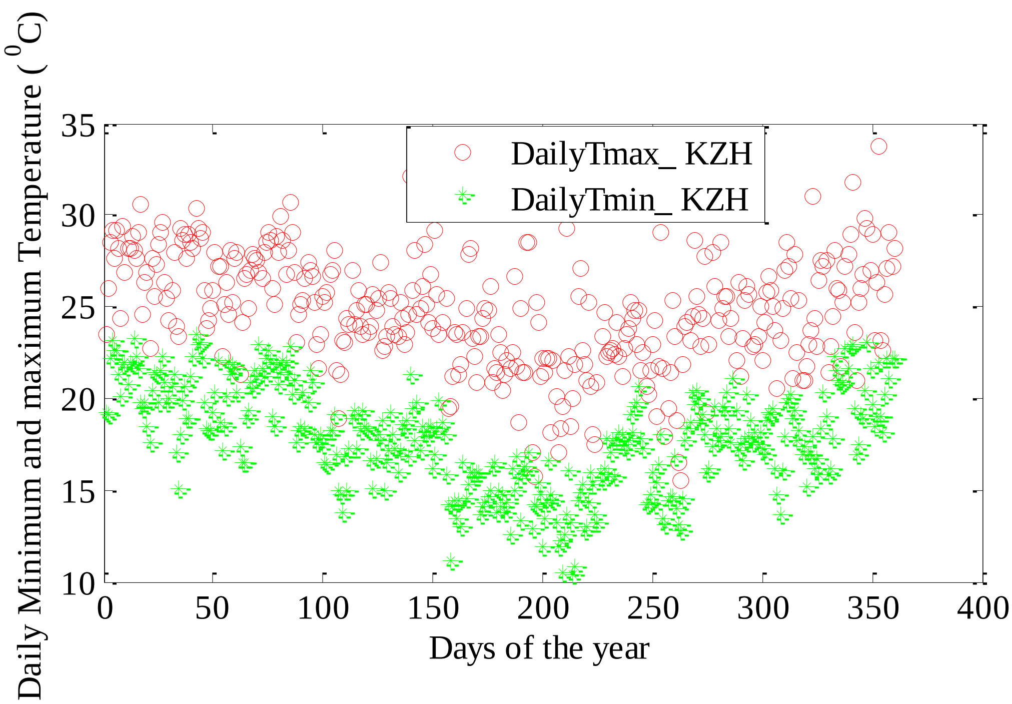

Figure 4.8: Daily minimum and maximum air temperature for KZH station in 2015.

In Figure 4.8 both the minimum and maximum air temperature were low during winter. But the temperatures were not as low as in 2014. The daily minimum air temperature data is not showing any fluctuations. But during this season we also know that KwaZulu Natal also has more sunshine hours, due to long hours of daylight [53]. As a result, we find KZH having high minimum air temperatures during summer. Daily maximum air temperature data showed good up and down trend. High temperatures can be observed during summer between 0 to 90 day of the year on the graph, which is January, February and March, and December, which is day 335 to 365.

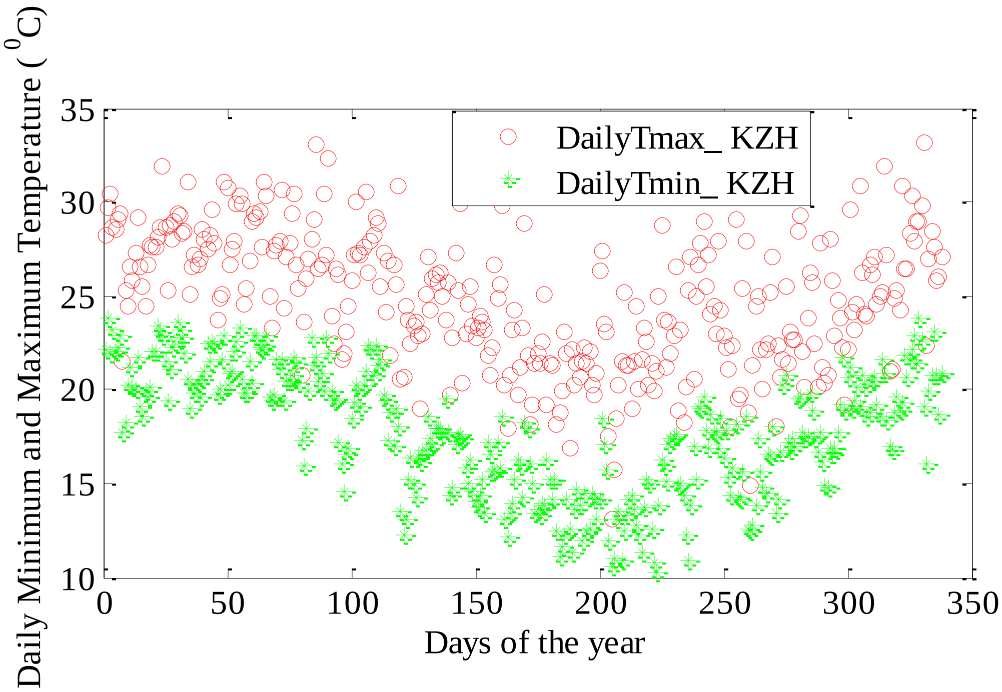

Figure 4.9: Daily minimum and maximum air temperature for KZH station in 2016.

Comparing Figure 4.9 to that of 4.7 and 4.8 it can be seen that 2016 has higher minimum and maximum daily air temperature . During summer KwaZulu Natal experiences a high rate of rains and sunshine hours. But KwaZulu-Natal was also affected by heavy rains from 24-27 July 2016 [53,55,56], resulting in severe colds and low temperatures. Well, some fluctuations can also be observed on the maximum air temperature plot during July, i.e., from 182 to 212 day of the year.

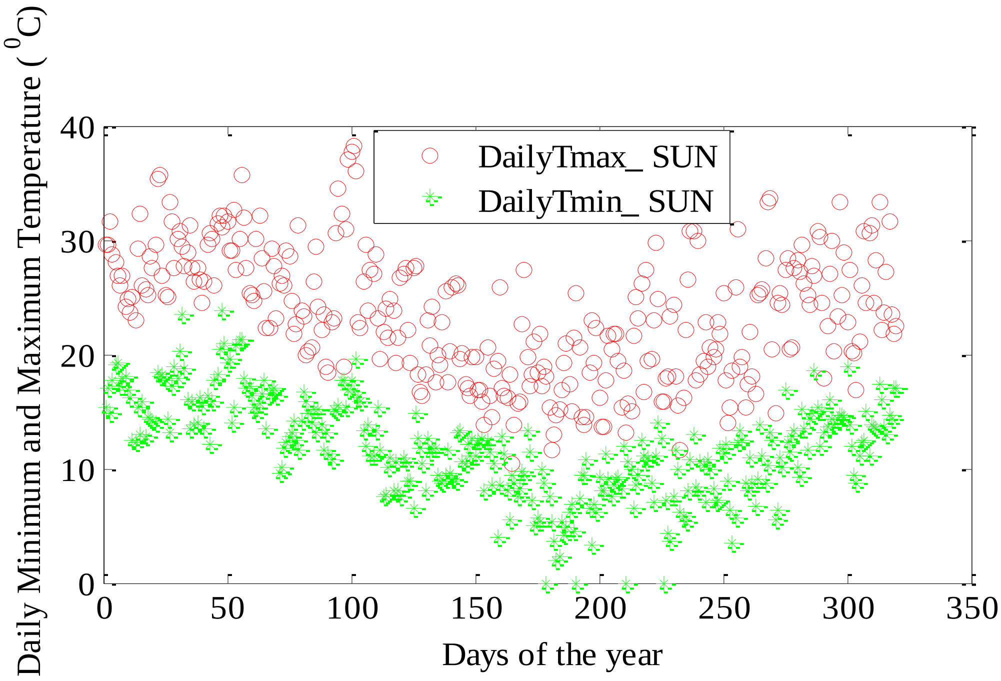

Figure 4.10: Daily minimum and maximum air temperature for SUN station in 2014.

Figure 4.10 illustrates relationship between daily minimum and maximum air temperature and days of the year. From figure 4.10 the lowest daily minimum air temperature value of 0 ℃ can be observed in winter, particularly from day 182 to 243, which is June to August. Western Cape province, where SUN station is situated is one of the coastal regions that were affected by long-term change of weather, which included serious cold front systems from April - September. Well Western Cape also experiences rains and cold weather in winter [35,51]. Daily maximum air temperature can be observed to be below 40 ℃ from the graph. Daily maximum air temperature was high in summer, from day 0 to 90, which is January to March, and day 334 to 365, which is December.

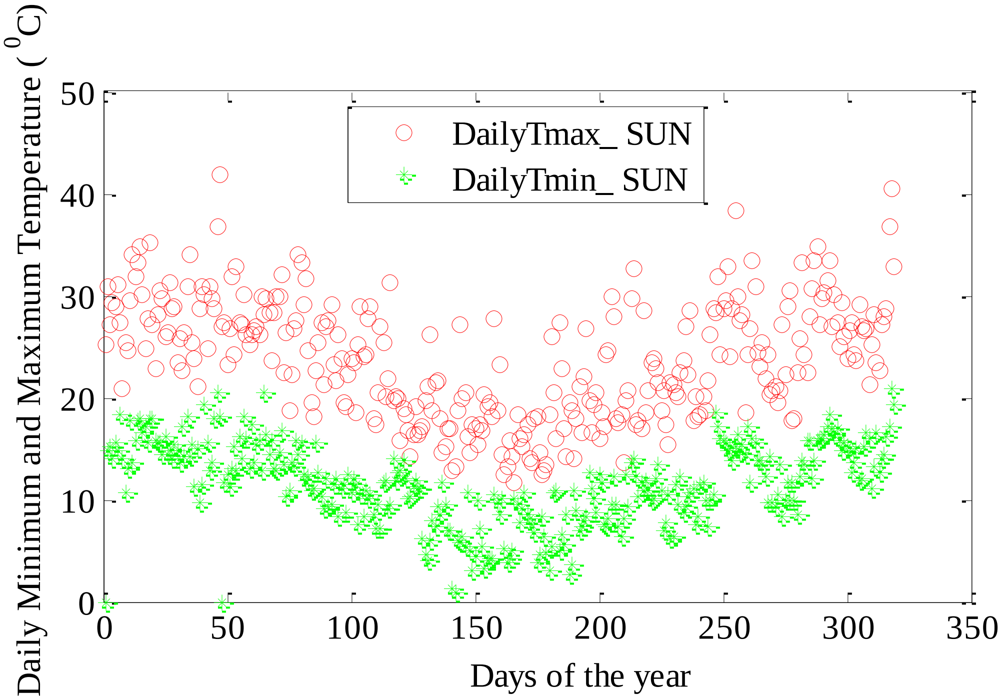

Figure 4.11: Daily minimum and maximum air temperature for SUN station in 2015.

In Figure 4.11 there seem to be some two outliers. This is because, on day 1 and day 48, SUN experienced temperatures of 0 °C. It can also be observed that during winter the temperatures are very low in both minimum and maximum plots, while in summer the temperatures are high. It should be noted that Western Cape experiences cold and wet weather in winter, contributing to extremely low temperatures, while it has hot and dry weather during summer. Western Cape experiences small sunshine hours during winter, which is why even the minimum air temperatures are very low in winter as observed in Figure 4.11 [35].

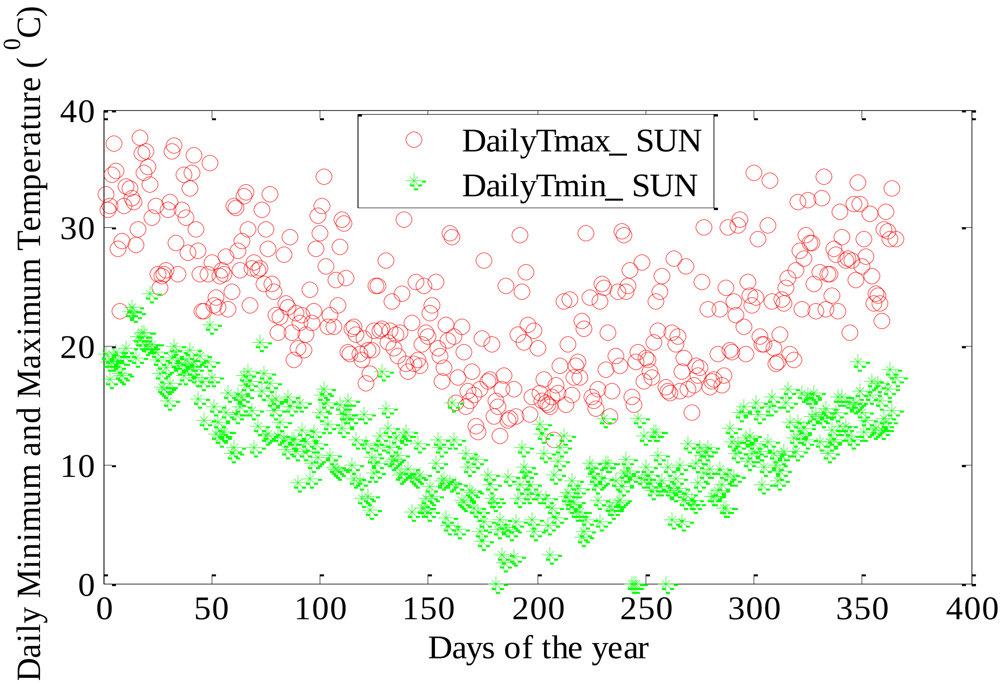

Figure 4.12: Daily minimum and maximum air temperature for SUN station in 2016.

Figure 4.12 illustrates variations in daily minimum and maximum air temperatures for during the year of 2016. In Figure 4.12 the lowest minimum air temperatures were 0 ℃ during winter, i.e., between day 182 to 243 (June to August) and also in springs September between day 244 to 273. Western Cape usually experiences more cloud cover September [31]. Western Cape experiences rain and cold weather during winter, resulting in low temperatures [31]. Extreme colds and heavy occurred from 24 July onwards [49], resulting in low temperatures. The daily maximum air temperature was high in summer, between 30℃ to 40 ℃ . This can be observed from day 1 t 90 (January to March) and day 335 to 365 (December). The daily maximum air temperature ranged between 10℃ $<$ Temp $\leq$ 30 ℃ in winter, from day 181 to 243 (May to August).

Figure 4.13 shows variations of daily minimum and maximum air temperature for 365 days for NMU station in 2014.NMU station in Figure 4.13 below also illustrates some fluctuations in minimum air temperature plot from day 121 to 151, which is May. Eastern Cape is one of the coastal provinces that were affected by severe cold fronts from April to September 2014 [53]. Eastern Cape experienced lower temperature in winter due to rains and severe colds [35]. It can be observed from figure 4.13 that daily maximum air temperature ranges between 10 ℃ $<$ Temp $\leq$ 35 ℃.

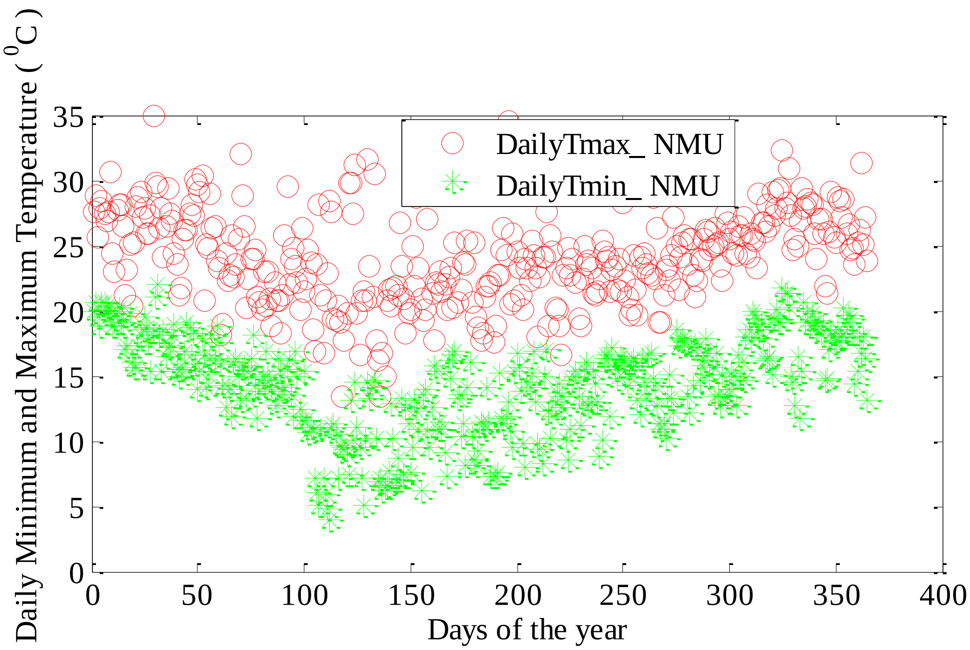

Figure 4.13: Daily minimum and maximum air temperature for NMU station in 2014.

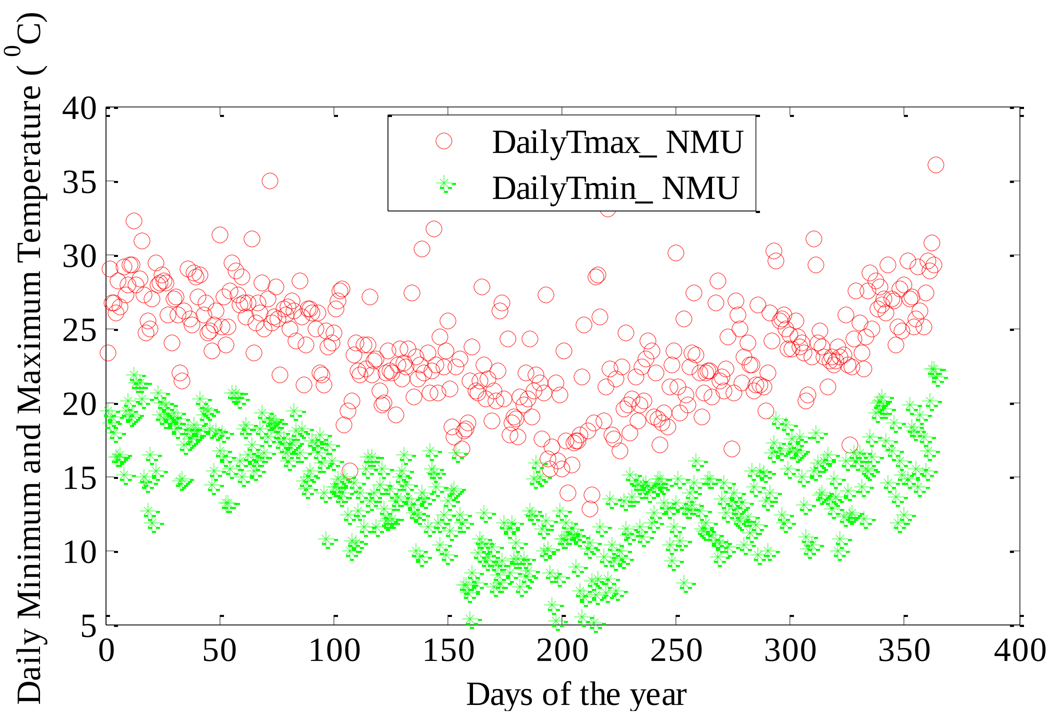

Figure 4.14: Daily maximum and minimum air temperature for NMU station in 2015.

Figure 4.14 illustrates relationship between daily minimum and maximum air temperature and days of the year for NMU station in 2015. In Figure 4.14 there are not many fluctuations in minimum air temperature. Daily minimum air temperature ranged between 0℃ < Temp < 25 ℃

.In winter NMU station obtained lower minimum air temperature, from day 121 to 251(May to August) in 2015. It can also be observed from the Figure 4.14 that there was a leap of minimum and maximum air temperature from spring (from day 273) in both scattered plots. Daily maximum air temperature ranged from 15℃ < Temp < 40 ℃ .

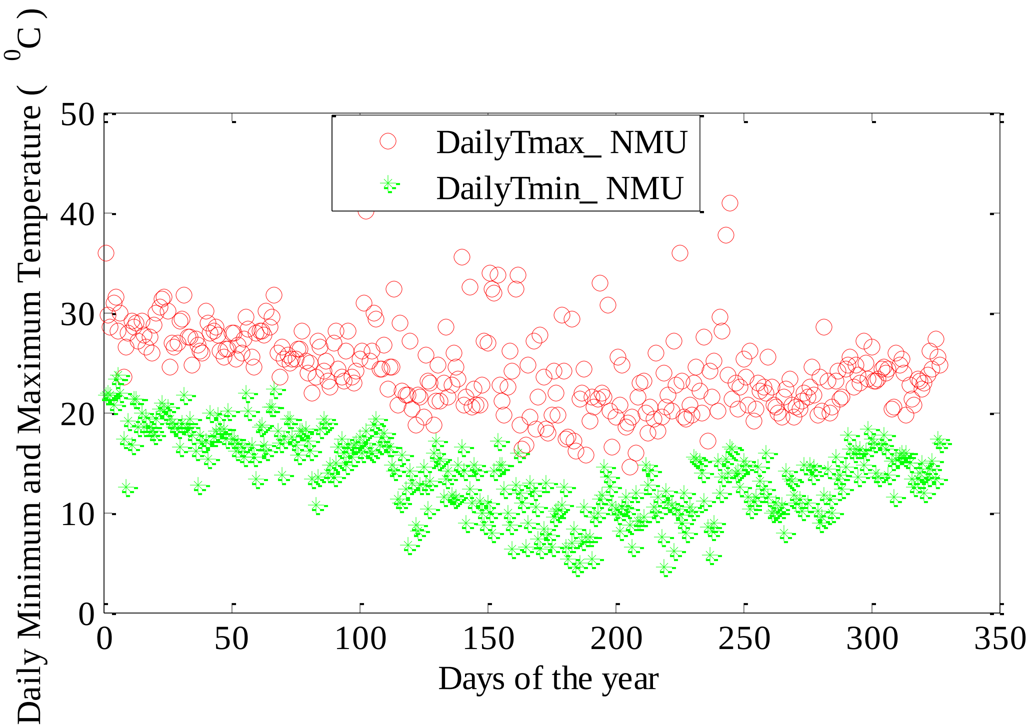

Figure 4.15: Daily minimum and maximum air temperature for NMU station in 2016.

Figure 4.15 illustration of variation in daily maximum and minimum air temperature for different days in 2016.Heavy rains and floods were experienced by Eastern Cape Province from 24-27 July in 2016 [53,56]. The graph shows that the temperature data ranged between 0 ℃ and 41 ℃. It should be noted that usually temperatures are expected to be low in winter, in most parts of South Africa. Port Elizabeth, where NMU station is situated can experience light rains in winter. According to Figure 4.15, the maximum air temperature is above 30℃ in winter. Lower values of minimum air temperature can be observed from day 121 to day 243 (May to August) in Figure 4.15.NMU has the highest value of latitude amongst the selected study areas, hence the temperatures are lower than other stations.

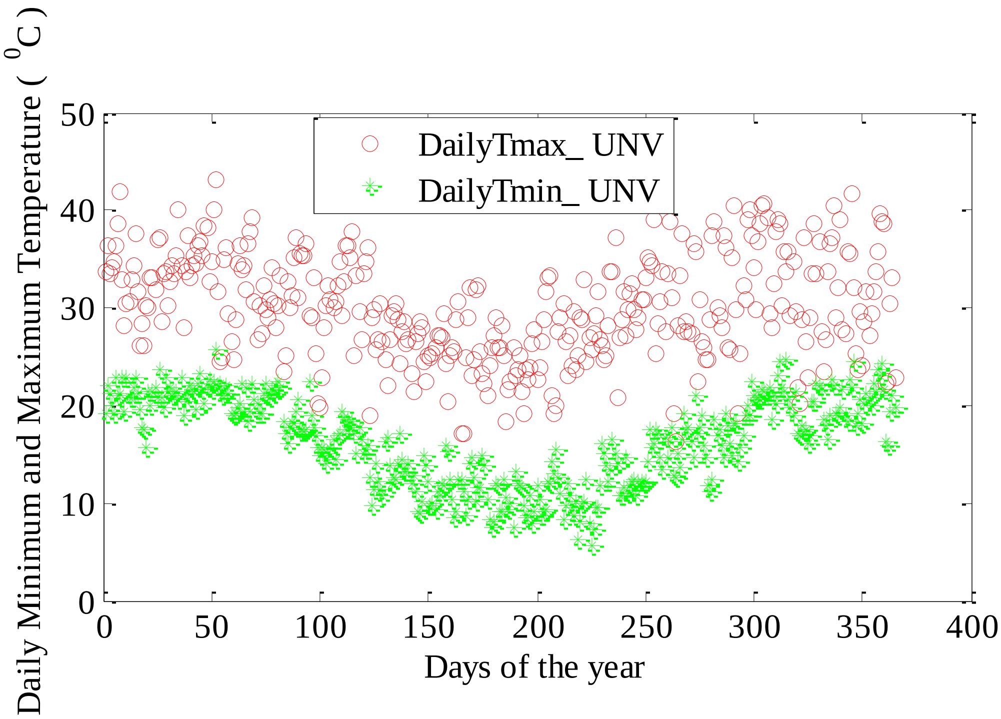

Figure 4.16: Daily minimum and maximum air temperature for UNV station in 2016.

Limpopo Province has the lowest latitude amongst all selected study areas. Limpopo province also experiences long sunshine hours. In Figure 4.16 UNV station has a higher minimum and maximum temperatures during summer, while there is more decline during winter. UNV station in Figure 4.16 shows no fluctuations. The peak in temperatures occurred from September until December. It is evident from the graph that temperature is very high during summer and low during winter.

4.5. Daily Comparison

The results of estimated global solar radiation were then compared with the observed global solar radiation by plotting scattered plots using MATLAB software. The amount of global solar radiation depends on the season, location, sunshine hours, day of the year, etc. It should also be noted that one model may be good for estimating global solar radiation in a particular area, at the same time it could be bad for another area, depending on the climatic conditions of the area. Ten (10) scattered plots from the year 2014 to 2016 for different stations are presented below, labelled Figures 4.17 - 4.26. Figures 4.17 – 4.26 show the comparison between daily estimated and observed daily global solar radiation for University of Kwazulu-Natal Howard College station, University of Venda, Vuwani science resource centre station, Stellenbosch station and Nelson

Mandela University station respectively. Hargreaves - Samani model is indicated by red circles, Clemence model is indicated by green asterisk , and observed global solar radiation is indicated by blue diamond marks.

Figures 4.17 - 4.19 show a good relationship between the daily estimated global solar radiation and the observed global solar radiation for KZH from 2014-2016, resulting in a good estimation by both models. In Figures 4.20 – 4.22 it can be observed that Hargreaves – Samani and Clemence models overestimated global solar radiation for Stellenbosch University station for all the years (2014– 2016). Figure 4.24 and 4.25 show a good estimation by both models since there is a good correlation between estimated and observed global solar radiation. The graphs in Figures 4.17 to 4.26 show a high level of global solar radiation during summer, then dropped because of rainy and cold days.

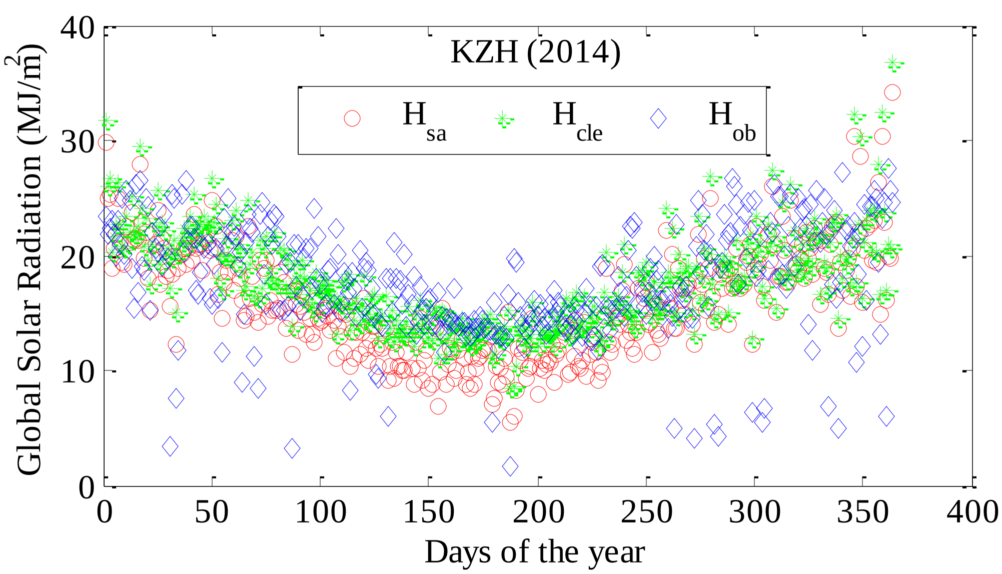

Figure 4.17: Comparison of estimated and observed daily global solar radiation for KZH station in 2014.

In Figure 4.17 it can be observed that the Hargreaves - Samani model slightly underestimated observations from the months of May, June, July, and August (Day 121 to 243) only, which is acceptable. During these months the estimated global solar radiation from Hargreaves-Samani model started below 10 MJ/m^2, while very few observed values of global solar radiation can be seen below 10 MJ/m^2 (The underestimations are minor since the model correlated well with the observed global solar radiation in other months). Clemence model shows a good correlation between daily estimated and observed global solar radiation well throughout the year, hence it performed very well. From the observation, we can see that both models have a capacity to estimate global solar radiation in this area.

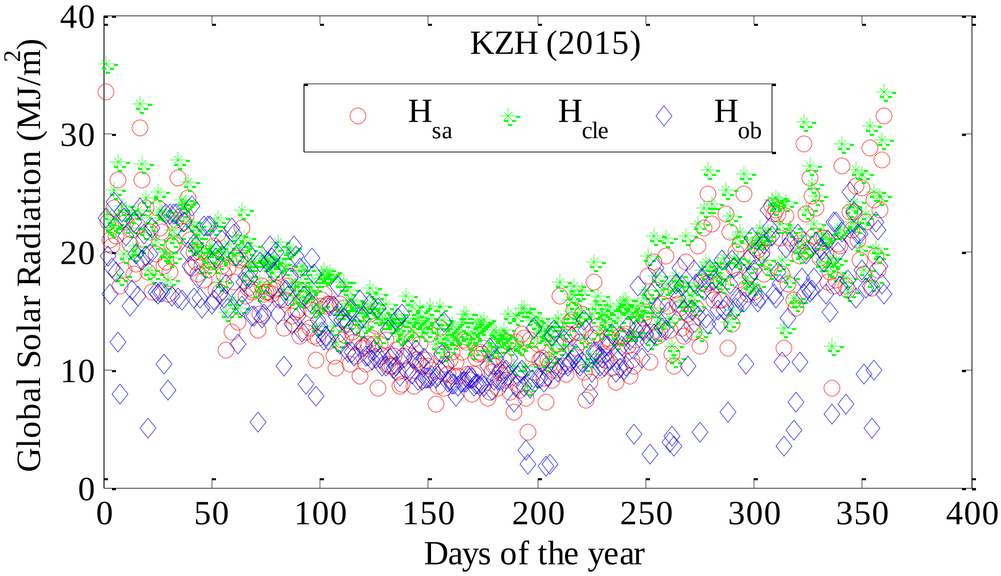

Figure 4.18: Comparison of estimated and observed daily global solar radiation for KZH station in 2015.

In Figure 4.18 it is evident that Hargreaves – Samani performed very well in 2015, we can see a good agreement between daily estimated and observed global solar radiation. As for the Clemence model, there was some slight overestimation in April and May only, which is still acceptable. Well from the graph it is evident that Hargreaves - Samani model exceeded the Clemence model in performance. Both models are seen as having suitability to estimate global solar radiation in this area.

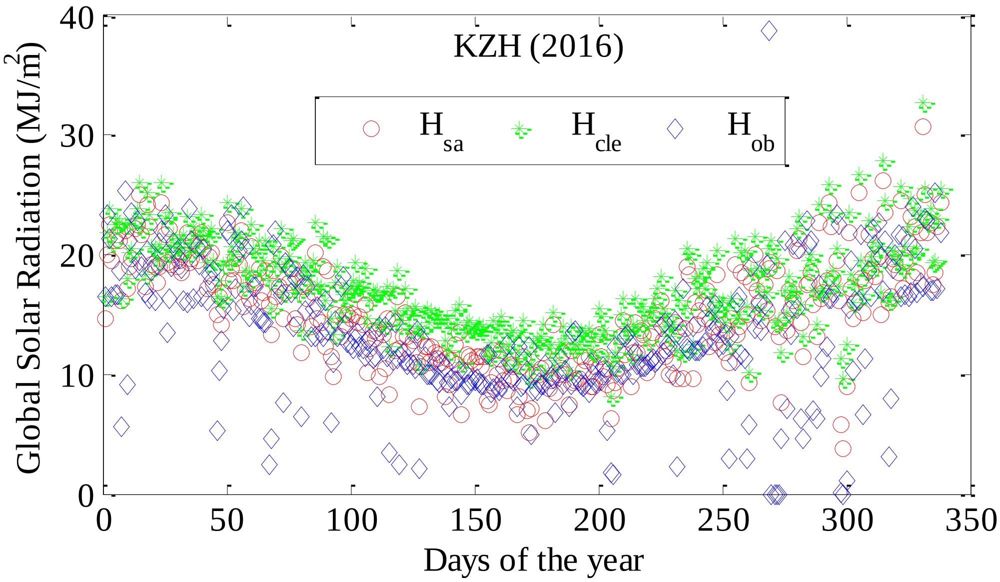

Figure 4.19: Comparison of estimated and observed daily global solar radiation for KZH in 2016.

In Figure 4.19 both models show a good correlation of daily estimated and observed global solar radiation. The graph does not show any deviations of estimated global solar radiation from observed daily global solar radiation values. The Clemence model shows some slight overestimations in April and May only, which is reasonable. The above observations of the graph are evident that both Hargreaves - Samani and Clemence models are suitable for estimating global solar radiation.

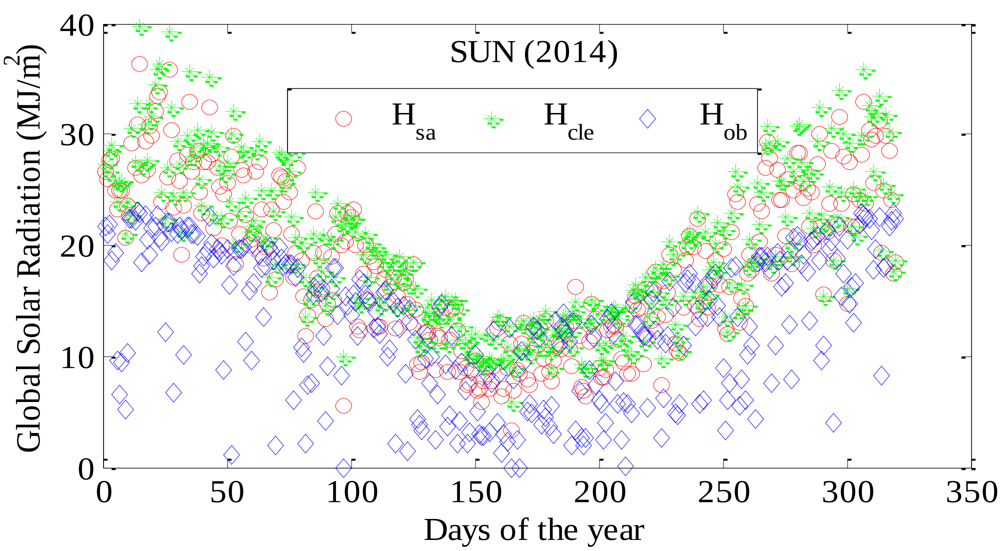

Figure 4.20: Comparison of estimated and observed daily global solar radiation for SUN station in 2014.

In Figure 4.20 it is observed that both models overestimated global solar radiation in all the months in the SUN station. This clearly shows poor performance by both models. This could be a result of the inaccuracy of air temperature data due to instability in weather during this year. SUN station also experiences cold and rainy weather during winter, sometimes being overwhelmed with floods and thunderstorms, which affect the temperature data.

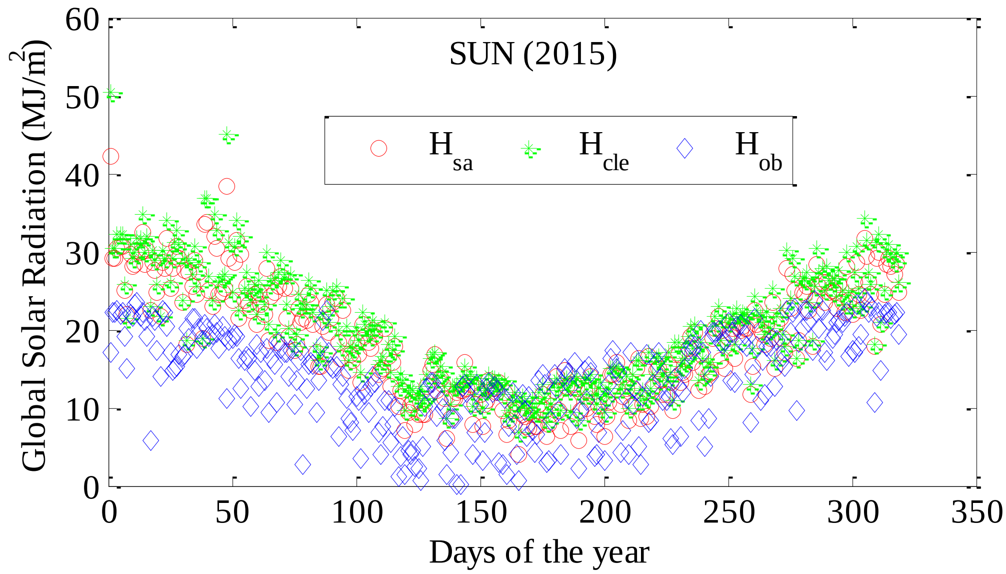

Figure 4.21: Comparison of estimated and observed daily global solar radiation for SUN station in 2015.

In 2015, it can be seen from Figure 4.21 that Hargreaves – Samani and Clemence models overestimated global solar radiation in the months of January, February, March, and April. The graph also depicts that there is a good relationship between estimated and observed global solar radiation from both models from May up to December. These results show that the models have the capacity to estimate global solar radiation for SUN stations.

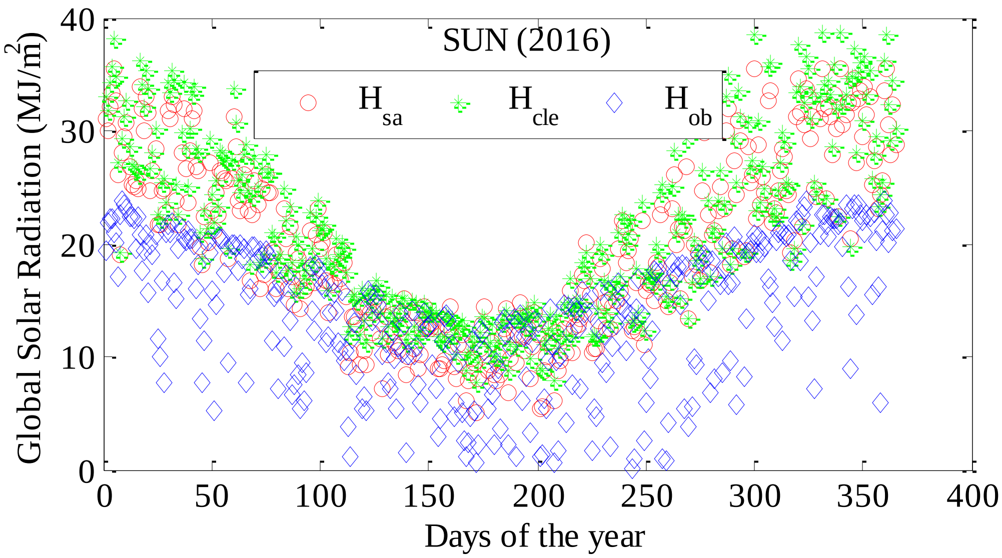

Figure 4.22: Comparison of estimated and observed daily global solar radiation for SUN station in 2016.

In 2016, it can be seen that there is a bad correlation between the estimated and observed global solar radiation for SUN stations. It can also be observed that there is a drop in global solar radiation in winter because it is a cold and wet season for Western Cape, where SUN station is situated. The models extremely overestimated for many months, i.e., January (Day 1 to 31), February (Day 32 to 59), March (Day 60 to 90), August (Day 213 to 243), September (Day 244 to 273), October (Day 274 to 304), November (Day 305 t 334), and December (Day 335 to 365). The models performed very poorly in the year 2016 for SUN station.

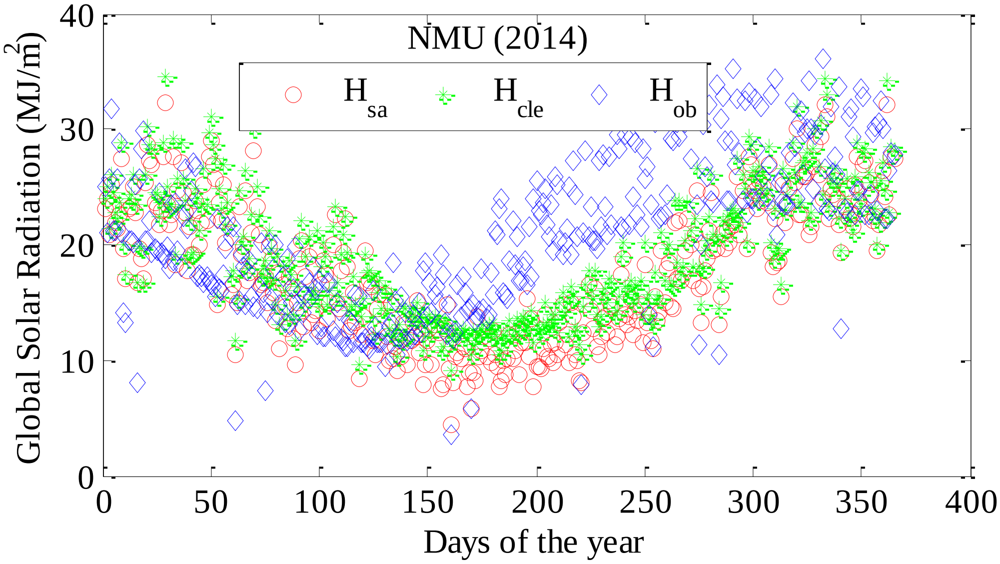

Figure 4.23: Comparison of estimated and observed daily global solar radiation for NMU station in 2014.

In Figure 4.23 it can be observed Hargreaves – Samani and Clemence models underestimated global solar radiation from the months of May to September (Day 121 to 273) in 2014 for NMU station. That can be attributed to the variation instability of weather in 2014, which might have affected the observed data. These results are evident that the models performed fairly during this year in NMU station.

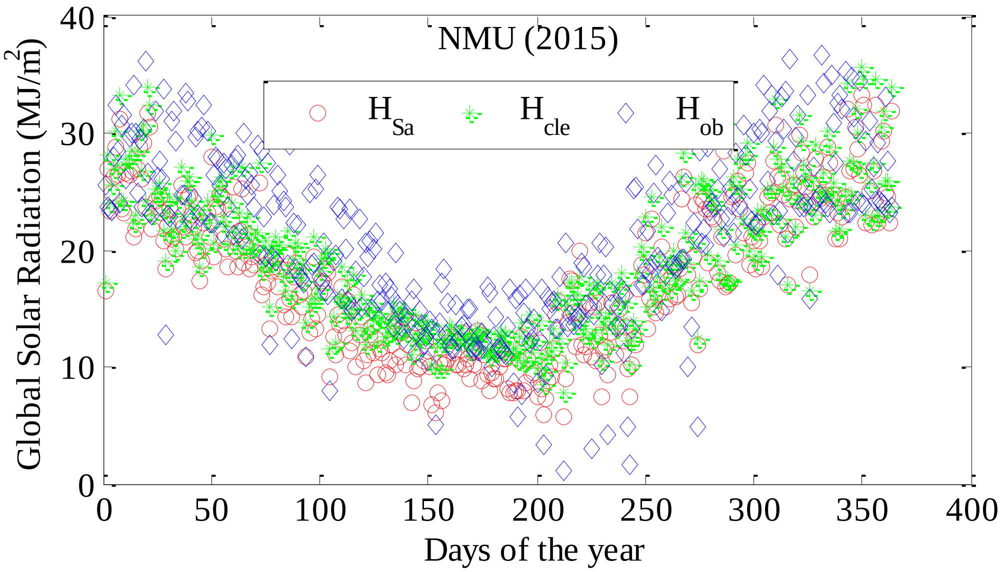

Figure 4.24: Comparison of estimated and observed daily global solar radiation for NMU station in 2015.

In Figure 4.24 the results depict some slight underestimation by Hargreaves – Samani model. in the months of February, March April, and May, which is acceptable. There is a good agreement between estimated and observed daily global solar radiation from the Clemence model throughout the year. There is good correlation between observations and Hargreaves – Samani model obtained in the months of January, May, June, July, August, September, October, November, and December. It is observed from the above results that the Clemence model performed better than the Hargreaves Samani model. These results are evidence that models have the capacity to estimate global solar radiation in this area. The Clemence model is best recommended for estimating global solar radiation in this area.

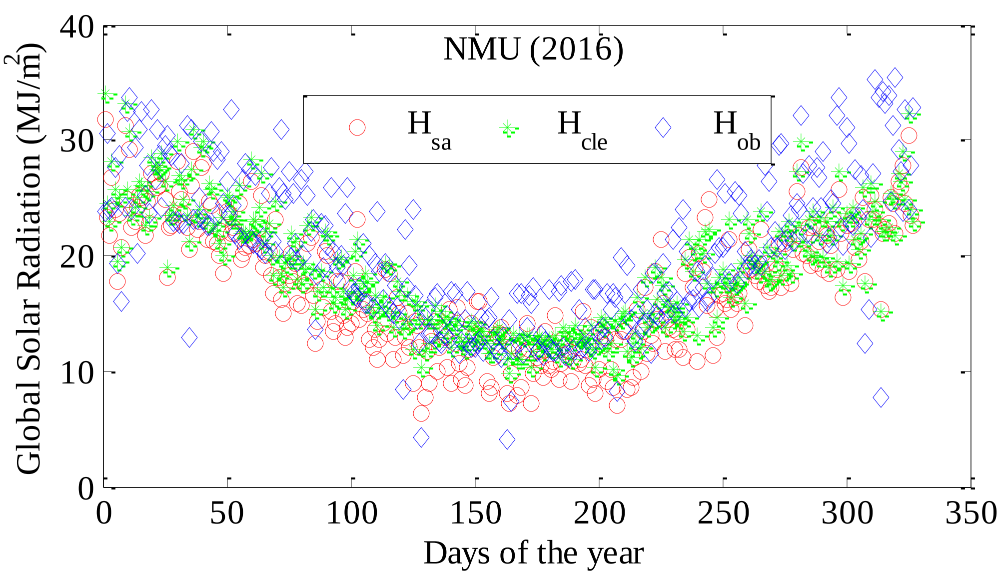

Figure 4.25: Comparison of estimated and observed daily global solar radiation for NMU station in 2016.

For the year 2016, Figure 4.25 shows that there exists a slight underestimation from the Hargreaves – Samani model in February, March, and April months only, while the Clemence model slightly underestimated the global solar radiation data in April only. The graphical representation shows a good correlation between estimated and observed global solar radiation from both models. The above results show that the Clemence model performed better than Hargreaves – Samani model in all the months. The models performed well and they are suitable for estimating global solar radiation in this area.

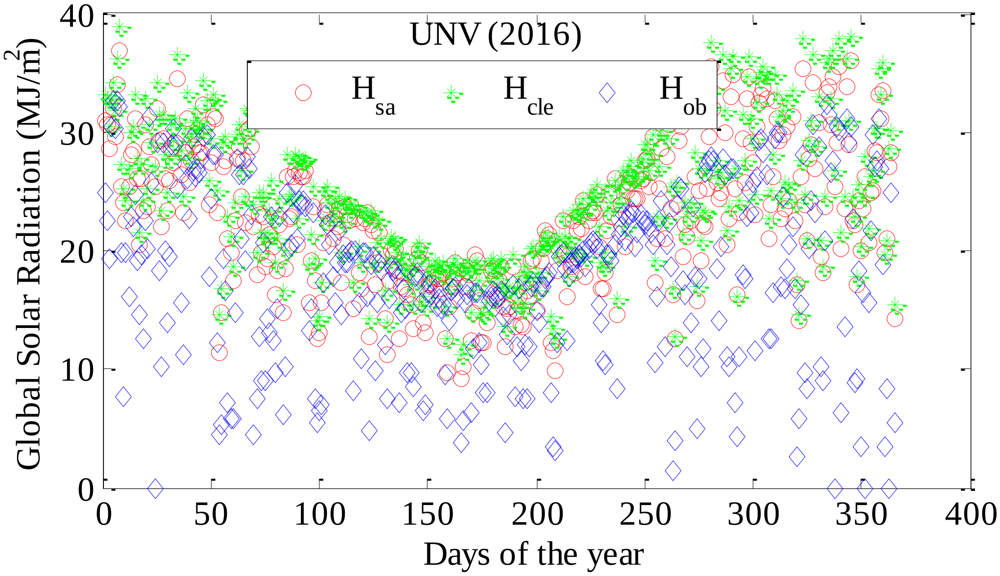

Figure 4.26: Comparison of estimated and observed daily global solar radiation for UNV station in 2016.

Figure 4.26 shows comparison of estimated and observed daily global solar radiation for UNV station in 2016. In Figure 4.26 Clemence model shows an overestimation of the global solar radiation in April, May, June, July, August, and September. This could be due to the variability of atmospheric parameters like air temperature, humidity, etc. during the measurement. It should also be noted that Limpopo Province where the UNV station is situated experiences wet weather during summer, giving a high rate of fluctuations due to heavy rains. Since Clemence model overestimated global solar radiation, evidently Hargreaves – Samani model performed better than the Clemence model in 2016. The results depict a good relation between daily estimated and observed global solar radiation in this station.

The Hargreaves - Samani and Clemence models used to estimate the daily global solar radiation in this study for the four selected stations, performed significantly well. The graphical representations are showing that both models are suitable for estimating global solar radiation in KZH, NMU, and UNV stations. In SUN station the two models performance poorly. The graphs are evidence that the models are suitable for estimating daily global solar radiation in KZH, NMU, and UNV stations.

According to Mulaudzi, et al (2015), their results suggested that Angstrom-type and Hargreaves - Samani models are suitable for estimating global solar radiation from four stations in the Vhembe region [40]. The estimated values correlated well with the observed global solar radiation, which is evident that Hargreaves - Samani model is reliable in estimating global solar radiation.

Maluta, et *al (*2018) estimated global solar radiation using Hargreaves – Samani and Clemence models. Their results suggested that both models are suitable for estimating global solar radiation in three selected ARC stations in Pretoria [39]. This study research can relate to the previous study in that it used Hargreaves – Samani and Clemence models and they only need air temperature data. Maluta et al evaluated the models in estimating global solar radiation in Pretoria and SAURAN station was one of the stations they used to collect data. while this study validated the models in estimating global solar radiation in selected SAURAN stations .

4.6 Monthly mean comparison

Figures 4.27 - 4.36 illustrate the comparison between the monthly mean daily estimated and the observed global solar radiation of the stations under study, that is KZH, SUN, UNV, and NMU. Figures 4.28 - 4.29 show that the Hargreaves – Samani model obtained a good correlation between monthly mean daily estimated and observed global solar radiation, from 2015-2016 in KZH. Hargreaves underestimated global solar radiation from March to September in 2014. (see Figure 27).

Severe cold weather was experienced by both coastal regions Eastern Cape and Western Cape in June 2014 and 2015. Eastern Cape, Western Cape, Gauteng, Limpopo provinces were affected by heavy rain weather in March 2014. Eastern Cape, Western Cape, and KwaZulu Natal experienced very cold weather in July 2016 [56].

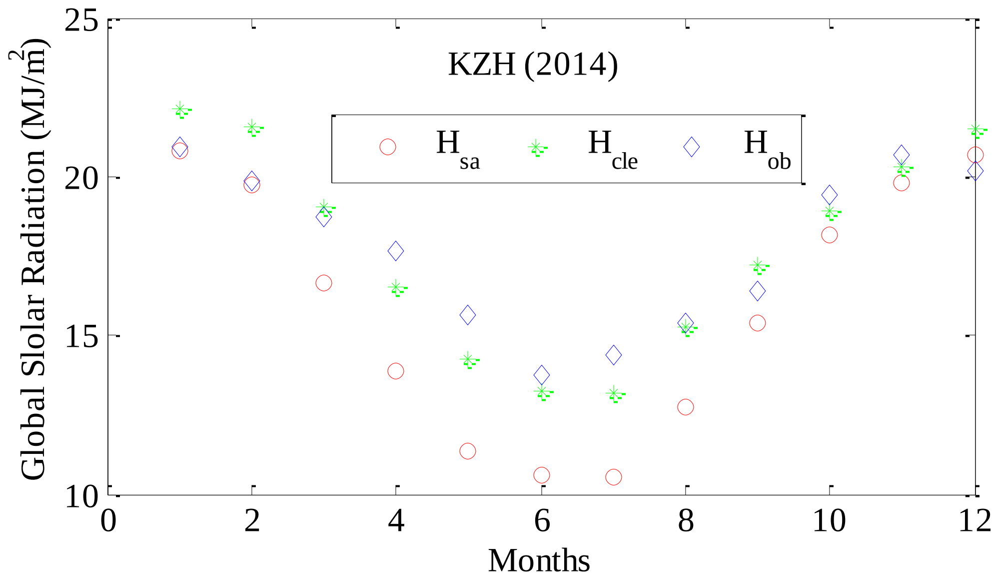

Figure 4.27: Comparison of monthly mean daily estimated and observed global solar radiation for KZH station in 2014.

Figure 4.27 shows a good comparison between monthly mean daily estimated and observed global solar radiation by Clemence models in 2014 for KZH station. Hargreaves -Samani model only underestimated global solar radiation from the months of March to November. Clemence model only overestimated in January and March. The above comparison is evidence that in 2014 Clemence model performed better than Hargreaves -Samani model in estimating monthly mean daily global solar radiation for KZH station. In some instances, the models can be applied alternatively in a year checking the suitable seasons for each model.

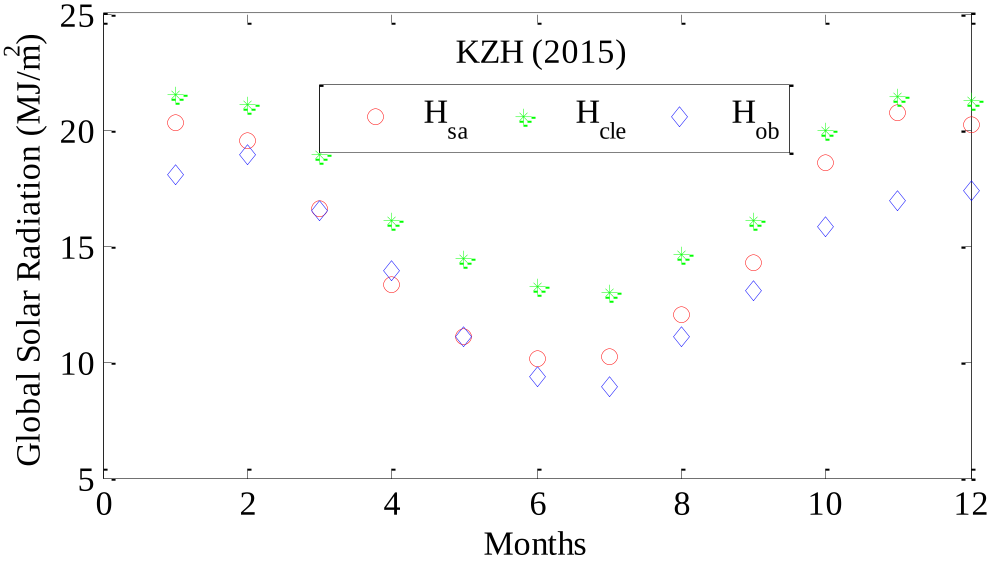

Figure 4.28: Comparison of monthly mean daily estimated and observed global solar radiation for KZH station in 2015.

In Figure 4.28 estimations of monthly mean global solar radiation through the Clemence model show overestimation from the months of January through to December in 2015. The temperature was quite very low during winter, there was also a high amount of rain in July 2015 [53]. Hargreaves – Samani only overestimated during the months of January, October, November, and December. The results show that Hargreaves – Samani model performed better than the Clemence model during this year This shows that Hargreaves - Samani model is suitable to estimate global solar radiation in this area.

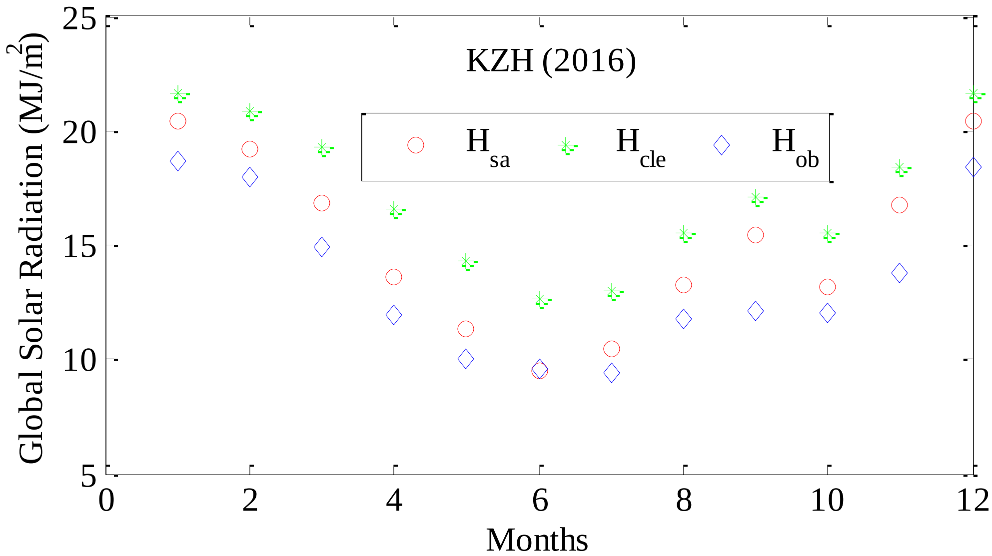

Figure 4.29: Comparison of monthly mean daily estimated and observed global solar radiation for KZH station in 2016.

In Figure 4.29, the Clemence model overestimated the monthly mean global solar radiation in all the months for 2016, while Hargreaves – Samani model slightly overestimated from July to August, which is acceptable. It should also be considered that clouds during wet seasons in KZH cause fluctuations of monthly mean observed global solar radiation. Overestimation of the monthly mean daily global solar radiation by Hargreaves – Samani model can be observed in September, November, and December only. It is evident that Hargreaves - Samani performed better than the Clemence model in 2016 and hence the model can be recommended for the estimation of the global solar radiation data in this area.

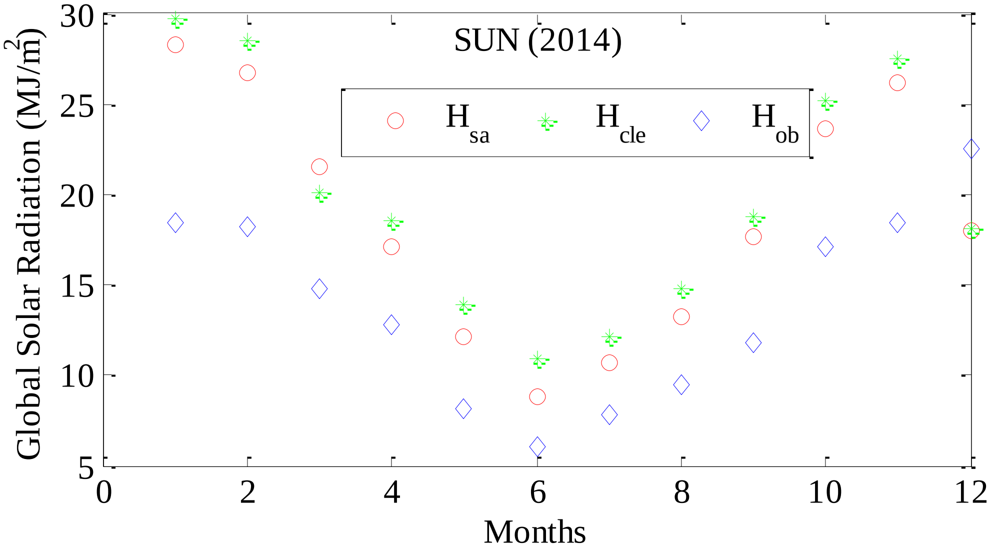

Figure 4.30: Comparison of monthly mean daily estimated and observed global solar radiation for SUN station in 2014.

In Figures 4.30 shows that both Hargreaves - Samani and Clemence models have overestimated monthly mean daily global solar radiation throughout the year in SUN station. This could be attributed to bad weather conditions that occurred from 2014 to 2016 in Western Cape [53,55,56]. Apart from that, we know that Western Cape experiences more rain and cold weather during winter. Severe cold weather was experienced by both coastal regions Eastern Cape and Western Cape in June 2014 and 2015 [55]. The wet season also contributed to a drop in global solar radiation due to the high amount of air humidity and clouds.

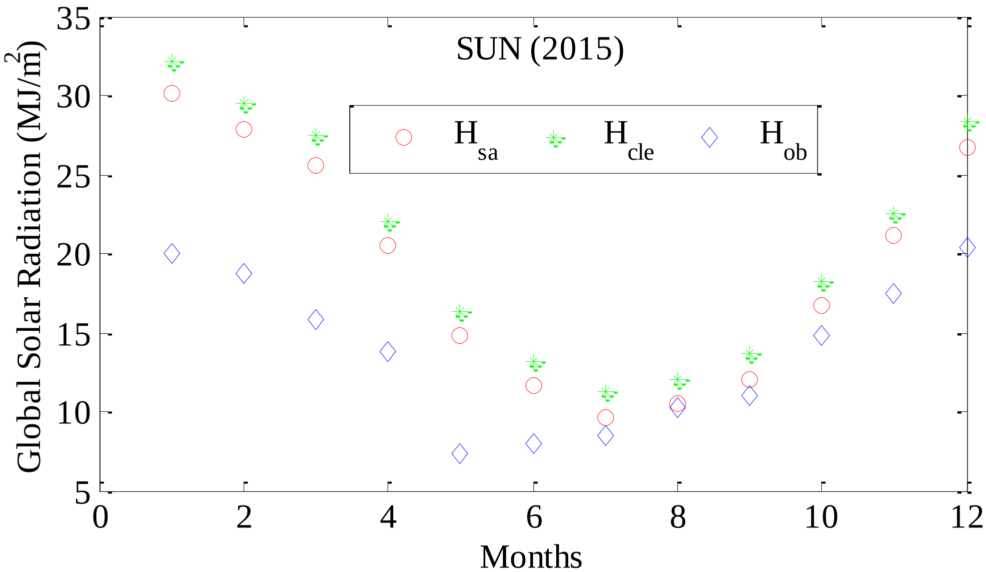

Figure 4.31: Comparison of monthly mean daily estimated and observed global solar radiation for SUN station in 2015.

In Figure 4.31 we can observe that there is a high level of overestimation from both models in the months of January, February, March, April, May, June, November, and December. It can also be observed that the estimated monthly mean global solar radiation has the highest peak in summer, approaching MJ/m^2, but in winter there was an extreme decline. This is due to the fact that Western Cape province where SUN station is situated experiences wet winter, which increases more chances of relative humidity, and hot and dry summer. Eastern Cape and KwaZulu Natal were hit by a thunderstorm and heavy rains in 2015 [53]. The above results show a bad correlation between monthly mean estimated and observed global solar radiation. The results show a bad performance by both models.

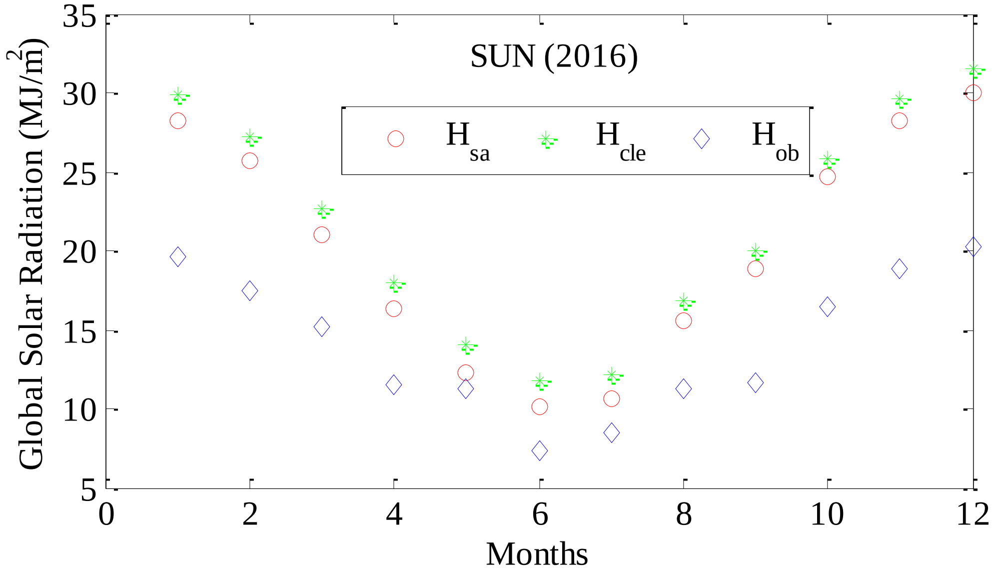

Figure 4.32: Comparison of monthly mean daily estimated and observed global solar radiation for SUN station in 2016.

Figure 4.32 above illustrates comparison of monthly mean daily estimated and observed global solar radiation for SUN station in 2016.From figure 4.32 we can see that both models did not perform well. There was overestimation by both models throughout the year. Hargreaves - Samani only performed well in the month of May. These could be due to variability in atmospheric parameters during measurements because of the instability of weather. This implies that this station needs to be monitored and thoroughly maintained to produce quality data. These results depict poor performance poor.

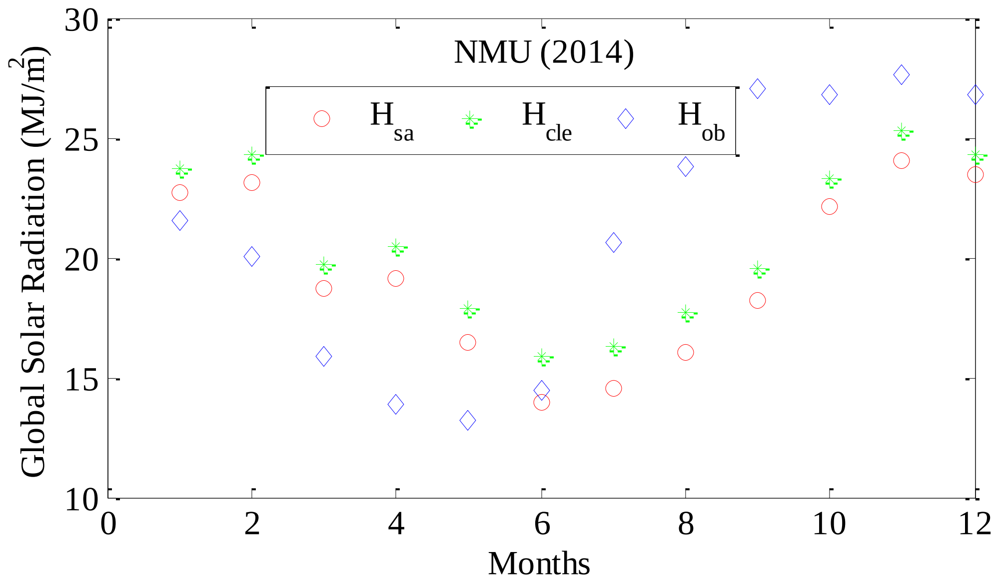

Figure 4.33: Comparison of monthly mean daily estimated and observed global solar radiation for NMU station in 2014.

In Figure 4.33 both models show a high level of overestimation of global solar radiation during the months of February, March, April, and May, and underestimation also from July to December. Certainly, the estimated values of monthly mean daily solar radiation did not correspond well with observed monthly mean global solar radiation during this year. This is evident that the models performed poor in this year.

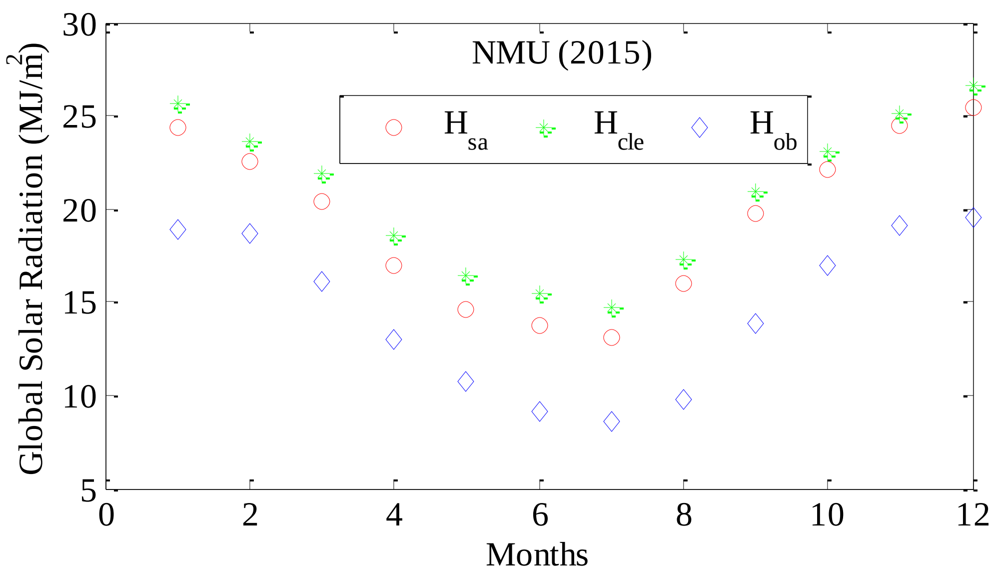

Figure 4.34: Comparison of monthly mean daily estimated and observed global solar radiation for NMU station in 2015.

In Figure 4.34 the models overestimated global solar radiation throughout the year in 2015. It can also be observed from the graphs that there is no good agreement between monthly mean estimated and observed global solar radiation. The results could be because there were too many deviations in the daily observed solar radiation data, for which the monthly mean daily solar radiation was estimated.

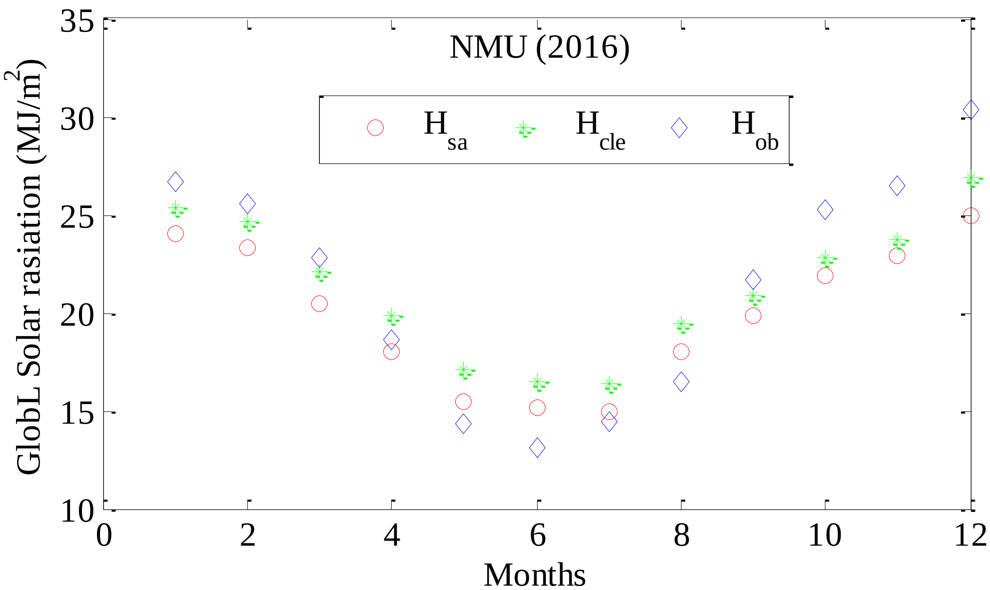

Figure 4.35: Comparison of monthly mean daily estimated and observed global solar radiation for NMU station in 2016.

Figure 4.35 shows a slight underestimation in the months of October, November, and December by Hargreaves -Samani and Clemence models. It should also be considered that the difference between monthly mean estimated and observed global solar radiation is roughly about which ± 2 MJ/m^2 is acceptable. Clemence model show a good agreement between the monthly mean daily estimated and observed global solar radiation from January to September in 2016, while Hargreaves- Samani underestimated global solar radiation in January, March and February. This is evident that Clemence model performed better than Hargreaves – Samani model in Sun station 2016.

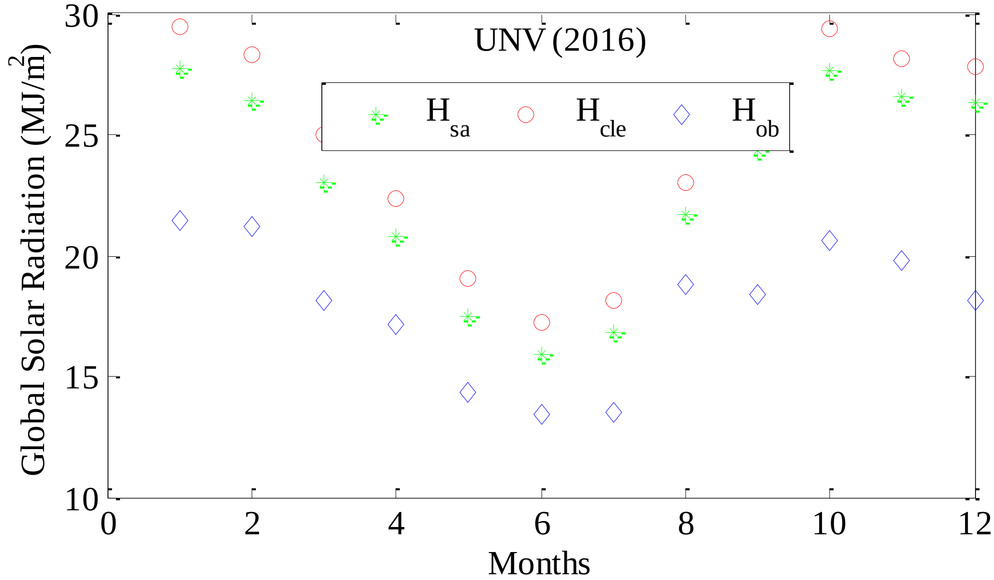

Figure 4.36: Comparison of monthly mean daily estimated and observed global solar radiation for UNV station in 2016.

In Figure 4.36 the models extremely overestimated monthly mean daily global solar radiation in all the months of the year in 2016, which shows a bad correlation. It can also be seen that the difference between monthly mean daily estimated and observed global solar radiation is roughly ± 10 MJ/m^2, which is huge. UNV station is situated in Limpopo, which experiences extremely hot and wet weather during summer, yielding to a high rate of humidity.

To further understand the monthly behavior of the estimated and observed global solar radiation, comparisons of monthly mean daily estimated and observed global solar radiation are also tabulated in Tables 8 and 9 below. Where H_{Sa} denotes monthly mean daily estimated global solar radiation from Hargreaves – Samani model, where H_{cle} denotes the monthly mean daily estimated global solar radiation from Clemence model, and H_{ob} the monthly mean daily observed global solar radiation. In Table 8 there is a slight difference of ±2 MJ/m^2 between estimated and observed global solar radiation from both models in the KZH station, from 2014. In 2015, there's a good agreement between monthly mean observed and estimated global solar radiation for Hargreaves – Samani model. It has a difference of ± 2 MJ/m^2. Deviation occurred in January, October, November, and December 2015, which shows overestimation by the Samani model. This also corresponds with Figure 4.28. Clemence model shows too much deviation between monthly mean estimated and observed global solar radiation, which is ± 3 MJ/m^2, which illustrates more overestimations for all the months. In 2016 the difference between monthly mean observed and estimated global solar radiation shows overestimation from Hargreaves - Samani model, particularly in the months of January, September, November, and December. But as for Clemence, there is a big deviation for all the months. It can also be observed in Table 8 that a difference of ± 10 MJ/m^2 resulted between monthly mean estimated and observed global solar radiation for SUN station in all the years from both models, showing overestimation, which is a fair correlation. The significant difference could be due to the calibration and maintenance of measuring equipment (pyranometers) because a meteorological instrument must be able to withstand any weather condition.

Table 8: Comparison between monthly mean daily estimated and observed global solar radiation for KZH and SUN stations.

Station	KZH									SUN								
Year	2014			2015			2016			2014			2015			2016		
Month	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)	H_{sa} (MJ/m^2)	H_{cle} (MJ/m^2)	H_{ob} (MJ/m^2)
Jan	20.8	22.1	20.9	20.3	21.5	18.0	20.4	21.7	18.7	28.2	29.7	18.4	30.2	32.1	19.9	28.2	29.9	19.7
Feb	19.7	21.5	19.9	19.6	21.2	19.0	19.1	20.9	18.0	26.7	28.5	18.2	27.8	29.5	18.7	25.6	27.2	17.5
March	16.6	19.0	18.6	16.6	18.9	16.5	16.8	19.2	14.9	21.6	20.2	14.7	25.6	27.5	15.8	21.0	22.7	15.2
April	13.9	16.5	17.7	13.4	16.1	13.9	13.6	16.6	11.9	17.1	18.6	12.8	20.6	22.0	13.8	16.3	18.0	11.6
May	11.3	14.3	15.7	11.0	14.4	11.1	11.3	14.3	10.0	12.2	14.0	8.2	14.8	16.4	7.4	12.3	14.0	11.2
June	10.6	13.2	13.8	10.2	13.2	9.4	9.5	12.7	9.6	8.8	10.9	6.1	11.6	13.1	8.0	10.2	11.7	7.3
July	10.6	13.2	14.4	10.2	13.0	8.9	10.5	13.0	9.4	8.8	12.2	7.8	9.6	11.2	8.5	10.6	12.1	8.5
Aug	12.7	15.2	15.4	12.0	14.6	11.1	13.2	15.6	11.8	13.3	14.8	9.4	10.6	12.0	10.2	15.6	16.9	11.3
Sept	15.4	17.2	16.4	14.2	16.1	13.0	15.4	17.0	12.0	17.7	18.7	11.8	12.1	13.7	11.1	18.9	20.0	11.6
OCT	18.1	18.9	19.4	18.6	20.0	15.9	13.2	15.5	12.1	23.7	25.2	17.1	16.8	18.2	14.8	24.7	25.8	16.4
NOV	19.8	20.3	20.7	20.8	21.4	16.9	16.8	18.4	13.7	26.2	27.6	18.4	21.1	22.5	17.5	28.2	29.6	18.9
DEC	20.7	21.5	20.2	20.2	21.3	17.3	20.5	21.6	18.4	18.0	18.1	22.6	26.7	28.3	20.3	30.0	31.6	20.2

Table 9: Comparison between monthly mean daily estimated and observed global solar radiation for NMU and UNV stations.

Station	NMU									UNV		
Year	2014			2015			2016			2016		
Months	H_{sa} (MJ/ m^2)	H_{cle} (MJ/ m^2)	H_{ob} (MJ/ m^2)	H_{sa} (MJ/ m^2)	H_{cle} (MJ/ m^2)	H_{ob} (MJ/ m^2)	H_{sa} (MJ/ m^2)	H_{cle} (MJ/ m^2)	H_{ob} (MJ/ m^2)	H_{sa} (MJ/ m^2)	H_{cle} (MJ/ m^2)	H_{ob} (MJ/ m^2)
Jan	22.7	23.7	21.5	24.4	25.6	18.9	24.1	25.4	26.7	27.7	29.5	21.4
Feb	23.1	24.3	20.0	22.5	23.6	18.7	23.4	24.7	25.5	26.4	28.3	21.2
Mar	18.7	19.7	15.9	20.4	21.9	16.1	20.5	22.0	22.8	23.0	25.0	18.2
Apr	19.1	20.5	13.9	17.0	18.6	13.0	18.0	19.8	18.6	20.8	22.3	17.1
May	16.4	17.8	13.2	14.6	16.5	10.8	15.4	17.1	14.4	17.5	19.0	14.4
June	14.0	15.9	14.5	13.8	15.5	9.1	15.1	16.5	13.1	15.9	17.3	13.4
July	14.5	16.3	20.6	13.1	14.7	8.5	15.0	16.4	14.4	16.8	18.2	13.5
Aug	16.0	17.7	23.8	16.0	17.3	9.8	18.1	19.5	16.5	21.7	23.0	18.8
Sep	18.2	19.5	27.0	19.8	20.9	13.9	19.9	20.9	21.6	24.3	25.8	18.4
Oct	22.2	23.3	26.8	22.2	23.1	16.9	21.9	22.8	25.3	27.7	29.4	20.6
Nov	24.0	25.3	27.6	24.5	25.2	19.1	22.9	23.7	25.3	26.5	28.2	19.8
Dec	23.5	24.3	26.8	25.4	26.6	19.5	25.0	26.9	30.3	26.3	27.8	18.2

Table 9 shows a relation between monthly mean estimated and observed global solar radiation for NMU and UNV station from both Hargreaves - Samani and Clemence models. In NMU station, the difference between monthly mean estimated and observed global solar radiation is ± 4 MJ/m^2 during 2014 from both models, showing overestimation. In 2015 from both models show too much deviation of monthly mean estimated from observed global solar radiation, which is ± 6 MJ/m^2 from both models. In 2016, we can see a good agreement between monthly mean estimated and observed global solar radiation from both models, with a difference of ± 2 MJ/m^2. In 2016 UNV station shows a difference of ± 6 MJ/m^2 between monthly mean estimated and observed solar radiation, which also shows overestimation from Hargreaves - Samani and Clemence models.

4.7. Statistical analysis

In pursuance of the objectives of this study, the performance and accuracy of the two models are assessed statistically using the computational MATLAB software. The statistical analyses used were MBE, RMSE, MPE, $R^{2,}$ and *t* - statistic test. The lower MBE, MPE, and RMSE values imply good performance of a model, whereas a positive value of MBE implies overestimation while a negative value of MBE shows underestimation. R^2 is used to assess the performance of the model and it is the best at the value of 1 while the smaller value of t implies the good performance of the model [41,47,54]. Equations (12) - (16) discussed in section 3.4.4. were used as statistical analysis.

Where, H_{im} and H_{ie} represents the i^{th} observed daily global solar radiation values and estimated daily global solar radiation values respectively, n denotes the total number of observations, $\overline{H}_{im}$ denotes the mean observed global solar radiation and n-1 represents the degrees of freedom [47]. The statistical analysis results are represented in Table 10, which shows the results of the statistical validation for estimating monthly mean global solar radiation from Hargreaves – Samani and Clemence models. Hargreaves - Samani and Clemence models were observed to be having lower desirable values of MBE, MPE, and RMSE from 2014 to 2016 for KZH station. Hargreaves - Samani obtained MBE value of - 0.0057 in 2016, showing slight underestimation, in 2014 and 2015 it obtained lower values of MBE of 0.0013 and 0.0078 respectively, which show slight overestimation since the MBE values are very low, which show good performance by Samani model. Clemence model obtained MBE values of between 0.0036 to 0.0108 for KZH station which shows a slight overestimation but acceptable. MBE values obtained by Hargreaves – Samani ranged from -0.0126 to 0.0268, while Clemence model obtained MBE values of -0.0122 to 0.0311 for SUN station. Hargreaves- Samani and Clemence models obtained MBE values of 0.0223 to 0.0265 for UNV station, -0.0147 to 0.0193 in NMU station. Both the models obtained acceptable values of RMSE in all the stations. The MBE values for the UNV station depict slight overestimation, yet acceptable. The models obtained the higher values of RMSE, MBE, in SUN station, which results in an overestimation of global solar radiation in this station, and the values of R^2 close to 1. The models obtained good lower values of MPE in all the stations and are $\pm$ 10 % (A percentage error between -10 % and +10% is desirable. Samani model obtained MPE values between 0.1285 to 0.7788 in KZH station, while Clemence obtained 0.3619 to 1.0801, see Table 10), which is acceptable and does show a slight percentage of deviation by estimated global solar radiation from observed global solar radiation. The models obtained the lowest values of R^2 from the SUN station amongst all the stations, but also close to 1, while the highest values of MBE and RMSE were obtained by the models, hence revealing overestimation. The models also obtained t - statistic value of one, which is less than the critical value and it proves all statistical methods to be scientifically relevant.

Table 10: Statistical validations of the models for estimating monthly mean daily global solar radiation in different stations.

Station	Year	MBE (MJ/m^2)		MPE %		RMSE (MJ/m^2)		R^2		*t*-Value	
		Samani	Clemence	Samani	Clemence	Samani	Clemence	Samani	Clemence	Samani	Clemence
KZH	2014	0.0013	0.0036	0.1285	0.3619	0.0246	0.0691	0.9995	0.9962	1.000	1.000
KZH	2015	0.0078	0.0108	0.7788	1.0801	0.1418	0.2063	0.9802	0.9657	1.000	1.000
KZH	2016	-0.0057	0.0088	0.5667	0.8822	0.1083	0.1685	0.9898	0.9778	1.000	1.000
SUN	2014	-0.0126	-0.0122	-1.2620	-1.2161	0.2411	0.2323	0.9343	0.9401	1.000	1.000
SUN	2015	0.0175	0.0218	1.7500	2.1830	0.3343	0.4171	0.9429	0.9208	1.000	1.000
SUN	2016	0.0268	0.0311	2.6780	3.1099	0.5116	0.5941	0.8937	0.8706	1.000	1.000
UNV	2016	0.0223	0.0265	2.2320	2.6475	0.4276	0.5058	0.9041	0.8794	1.000	1.000
NMU	2014	-0.0090	-0.0068	-0.9015	-0.6769	0.1722	0.1293	0.9803	0.9897	1.000	1.000
NMU	2015	0.0160	0.0193	1.6000	1.9294	0.3057	0.3686	0.9471	0.9298	1.000	1.000
NMU	2016	-0.0147	-0.0094	-1.4690	-0.9361	0.2806	0.1788	0.9538	0.9839	1.000	1.000

Table 11: Statistical validations for Hargreaves - Samani and Clemence models in estimating daily global solar radiations for different stations.

Station	Year	MBE MJ/m^2		MPE %		RMSE MJ/m^2		R^2		*t*-Value	
		Samani	Clemence	Samani	Clemence	Samani	Clemence	Samani	Clemence	Samani	Clemence
KZH	2014	-0.0099	-0.0083	-0.9920	-0.8296	0.1895	0.1585	0.9702	0.9803	1.000	1.000
KZH	2015	0.0112	0.0147	1.1178	1.4698	0.2135	0.2808	0.9604	0.9394	1.000	1.000
KZH	2016	-0.0038	-0.0098	-0.3810	-0.0932	0.0728	0.0188	0.9954	0.9997	1.000	1.000
SUN	2014	-0.0104	-0.0100	-1.0437	-0.9996	0.1994	0.1910	0.9577	0.9618	1.000	1.000
SUN	2015	0.0276	0.0330	2.7576	3.2966	0.5268	0.6298	0.8834	0.8536	1.000	1.000
SUN	2016	0.0204	0.0243	2.0423	2.4251	0.3902	0.4633	0.9332	0.9143	1.000	1.000
UNV	2016	0.0241	0.0275	2.4080	2.7470	0.4600	0.5248	0.6182	0.5795	1.000	1.000
NMU	2014	-0.0033	-0.0014	-0.3290	-0.1430	0.0629	0.0273	0.9980	0.9996	1.000	1.000
NMU	2015	-0.0066	-0.0035	-0.6623	-0.3468	0.1265	0.0663	0.9753	0.9941	1.000	1.000
NMU	2016	-0.0293	-0.0280	-2.9290	-2.7970	0.5596	0.5344	0.7654	0.7951	1.000	1.000

The statistical validations of the models in estimating global solar radiation were further represented in Table 11 above. It can be observed from the Table that the coefficient of determination, R^2 of both the models approaches 1, hence the correlation is good, and their *t* - statistic values are 1, less than the critical value for all the stations. The *t* - statistic values determine whether the model's estimation of global solar radiation is statistically significant. But Hargreaves

- Samani model has the higher values of R^2 than Clemence model. From Table 11 it can be observed that Hargreaves – Samani and Clemence models obtained desirable lower values of MBE, MPE, and RMSE from KZH station. Both models achieved the best values of MBE from 2014 to2016, ranging from -0.0099 to 0.0147 in the KZH station, followed by NMU with MBE values ranging from - 0.0293 to -0.0014, -0.0104 to 0.0330 for SUN station, 0.0241 to 0.0245. Both models reported higher values of MBE and RMSE for UNV station, with the lowest values of R^2. The models brought forth negative values of MBE and MPE from NMU station in 2014,2015 and 2016, showing minor underestimation, but still acceptable. The models also yielded acceptable values of MPE between ± 10 % in all the stations as well as desirable values of R^2 close to 1, which shows that both the models have the capacity to estimate global solar radiation in selected areas of study.

4.8 Chapter Summary

Following the estimation of global solar radiation from chapter 3, in this chapter, we have represented our data and results in a table form and graphically. This chapter is all about accounting for the present results. We have therefore critically analyzed and discussed our results after estimating global solar radiation. We have also validated the models using statistical analysis. Our findings suggest that the worst performance from both models was in SUN and UNV stations. The highest values of MPE, MBE, and RMSE obtained from SUN and UNV stations also revealed the highest level of overestimation by models in these stations. The statistical analysis also revealed that the two models obtained the lowest value of R^2 from the UNV station. One of the remarkable things about SUN station is that it obtained the highest amount of global solar radiation during summer amongst all the stations. This is because Western Cape province, where SUN station is located in Stellenbosch experiences dry and hot summer seasons having low air humidity. Meanwhile, SUN stations experienced an extreme drop in global solar radiation in winter due to the wet season. Western cape also experiences fire season from November to May, which affect the accuracy of data, collected from the ground. The models obtained good performance in other stations like NMU and KZH. The huge difference could be because of measuring equipment needing maintenance. More findings on the models have been further discussed in the next chapter.

CHAPTER 5: SUMMARY OF RESULTS AND CONCLUSION.

We have estimated global solar radiation using temperature-based models, Hargreaves – Samani, and Clemence models. A model can be suitable for estimating global solar radiation in a specific area, and yet unsuitable to estimate global solar radiation in another area. In this study, we have estimated both monthly mean daily global solar radiation and daily global solar radiation. We compared the monthly mean daily estimated with the observed monthly mean global solar radiation graphically. We also compared the daily estimated and observed global solar radiation. The daily estimated and observed global solar radiation showed a better correlation as well as the correlation of monthly mean estimated with observed global solar radiation. Well, the good thing about the mean data is that it is able to summarize data and eliminate possible deviations if they are minor. Hargreaves – Samani only performed well in NMU KZH, and UNV station. Hargreaves - Samani lacked consistency in NMU station, in that it performed well in 2014 and 2015 only.

Based on the statistical analysis results we have observed that Hargreaves – Samani and Clemence models yielded good values of MBE, MPE, RMSE, and R^2 values from estimating monthly mean daily global solar radiation. The estimated monthly mean global solar radiation gives a summary of the estimated daily global solar radiation. The models showed some small underestimation with negative values of MBE in NMU and KZH station, though acceptable, in estimating monthly mean daily global solar radiation. Hargreaves – Samani and Clemence models reported lower values of MPE and MBE for KZH station for all the years. Both models showed MPE values between ± 10 % in estimating both monthly mean daily and daily global solar radiation in all stations. Both models obtained a slight overestimation from UNV station, yet acceptable. Hargreaves -Samani & Clemence models achieved values of R^2 approaching 1 and *t* statistic value of 1, less than a critical value, which has proven the equations to be statistically significant from all the selected stations. The models also obtained higher values of R^2 in the estimation of monthly mean global solar radiation in all the stations.

Following the objectives of the study mentioned in section 1.5.2 in Chapter one, we have computed global solar radiation using the air temperature data from four SAURAN stations. We have examined the performance of both models through the statistical test. We have witnessed that the models achieved more remarkable values of MPE, MBE, RMSE, R^2 when monthly mean global solar radiation was correlated with monthly mean observed global solar radiation. The higher values of R^2 close obtained by the models strongly suggest a good performance, and capability to estimate global solar radiation in areas with similar climatic conditions as the selected areas under study. Even though in this case the models revealed slight overestimation in UNV station, however, the value of R^2 obtained by the models in this station was higher than R^2 obtained in SUN station, hence the lowest rank of the models' performance occurred in SUN station. This is evident that the models can be best recommended to estimate global solar radiation in KZH, NMU, and UNV stations and in areas with similar climatic conditions where the meteorological data is lacking.

This also proves our hypothesis in section 1.6 to be true in that we have correlated estimated and observed global solar radiation both graphically and statistically, and we found that indeed estimated values are in good agreement with the observed global solar radiation. The models were also proven to be accurate.

Mulaudzi et al,2015 evaluated global solar radiation in Vhembe district, Limpopo Province, in South Africa. They used Angstrom - linear type, Hargreaves-Samani, and Garcia models. They used a 4 year (2007-2010) observed global solar radiation and temperature data from ARC station and actual sunshine hours data from South African Weather Service. Their results depicted that Angstrom linear based and Hargreaves models are more suitable to estimate global solar radiation in climatic conditions in those areas [41].

Maluta, et al,2018 estimated global solar radiation in Pretoria, which is an inland region, Gauteng province. They used air temperature data of 6 years (2007-2012) from ARC stations. Their results also proved that both Hargreaves- Samani and Clemence models are more suitable for estimating global solar radiation in three ARC stations [39].

We have chosen Hargreaves-Samani and Clemence models to estimate global solar radiation since they only require air temperature data, which is always available. Now the amount of temperature is dependent on the weather. So, due to the instability of weather in places like Stellenbosch, where the SUN station is located, the temperature data resulted in more fluctuations, which the poor results of SUN station in estimating global solar radiation can be attributed to.

So, for future work, concerning above referenced studies, it would be more advisable for this research to estimate global solar radiation using long-term period temperature data. This will help us to effectively validate the models. The Clemence model was designed to estimate global solar radiation in south African sites without the meteorological measuring instrument. It would also be advisable for this study to take further research in other South African sites using the Clemence model for further validations.

The results of this research will help engineers to design solar energy systems technology, architectural designs in selected study areas. The recommended models will be used to estimate global solar radiation in areas without meteorological stations but having similar climatic and meteorological conditions.

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