UNIVERSITY OF NAIROBI

A STUDY OF SOLAR VARIABILITY AND ITS EFFECTS ON EARTH'S CLIMATE

BY

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DECLARATION

I declare that this thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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DEDICATION

This thesis work is dedicated to my mum Helen Mwanzia, my dad David Mwanzia, my brothers John Musya, Peter Mutati and Zablon Musyoka, my sisters, Viata Mueni, Muthoni Ngolania and Esther Syombua, my nieces Scarlet Hellen, Valerie Zawadi and Nadia Mbone, my nephews Fortune Muuo and Victor Muuo and all my friends, for their steadfast love and support throughout my studies.

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ABSTRACT

The Sun provides nearly all of the energy that drives the Earth's climate system. Although understanding the effects of solar variability on Earth's climatic change remains one of the most puzzling questions that have continued to attract attention of scientists. The Sun has been observed to vary on all time-scales and there is increasing evidence that this variation may have an effect on the Earth's climate. Scientists have been attempting to establish on the quantity of solar energy that illuminates the Earth and what occurs to the energy once it gets through the atmosphere. The climate response to these variations can be on a global scale but understanding the regional climate effects is more difficult. In this project research, we study the correlation between solar variability and the Earth's climatic changes over the last 17 years. We make use of solar data from Solar Radiation and Climate Experiments (SORCE) and climate data from Climate Research Unit (CRU). In order to observe how these changes have occurred, analysis of the data was done using GNU-plot and python to show the trend. As an outcome, from the results we explore for the possible correlation linking the solar variability and the Earth's climate change over the 17 years period. Our results show a linkage in the change of the climate factors which can be attributed to, but not completely to the solar variability. Further advances in understanding of the solar variability and its effect on climate are recommended from the ongoing acquisition of high-quality measurements of climate and solar variables. This knowledge is of importance as it can be used to in estimating the past and the future of solar behavior and climatic response.

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LIST OF ABBREVIATIONS/ ACRONYMS AND SYMBOLS

TSI – Total Solar Irradiance

SSI – Spectral Solar Irradiance

SEP – Solar Energetic Particle

SIM – Spectral Irradiance Monitor

SOLSTICE – Solar Stellar Intercomparison Experiment

SORCE – Solar Radiation and Climate Experiment

CME – Coronal Mass Ejections

UV – Ultraviolet

HEP – High Energy Particle

GSM – Grand Solar Minimum

SEP – Solar Energetic Particles

GCR – Galactic Cosmic Rays

CHAPTER ONE

INTRODUCTION

1.1 Background information

We live on a planet, Earth, which is part of the solar system that is Sun centered. The Sun is the main originator of energy that sustains life on Earth. It is almost an ideal sphere of hot plasma heated to blaze as a result of the nuclear fusion reactions taking place at the core hence radiating energy as infrared radiation and visible light. The Sun is known to have formed through self-gravitational collapse of a cloud of dust and gas. Majority of this matter collected in the middle via self-gravitating, as the rest flattened into an orbiting disk that formed the solar system.

The Sun has a diameter of approximately 1.39 million kilometers, or its diameter is 109 times that of the Earth, it has a mass that accounts for around 99.86% that of the solar system and it is around 330,000 times that of the Earth. It has a composition of approximately 70% hydrogen, 28% helium and other smaller quantities of heavier elements which include carbon, oxygen, iron and neon. The Sun's age is approximately 4.6 billion years and has a luminosity of 3.828×10^{26} Watts. It rotates about once every 27 days on average, with the poles rotating every 24 days and the equator every 30 days.

The Sun's structure comprises of the following layers: 1) The core, which is the innermost layer occupying between 20 to 25% of the Sun's radius, where temperatures (approximately 15 million Kelvin) and pressure (approximately 26.5 petapascals) are sufficiently high for nuclear fusion to occur. The nuclear fusion produces energy that makes the core becomes rich in helium. 2) The radiative zone, this is the layer just after the Sun's core. Energy transfer in this layer occurs by means of radiation. 3) Tachocline, which is the region that creates the boundary linking the radiative zone and the convective zone. 4) Convective zone, which is the layer between the Radiative zone and a close point to the visible Sun's surface. In this layer, the temperatures are cool such that convection can take place and this forming the fundamental method of extrinsic heat transfer. 5) The photosphere, this is the deepest section of the Sun, and can be directly observed. The Sun is made up of gas and it lacks a distinctly defined surface. The visible part is categorised into the photosphere and the atmosphere. The atmosphere is a gaseous ring of light surrounding the Sun and is made up of four parts, which are the transition region, chromosphere, the heliosphere and the corona. This layer is most visible during a solar eclipse. Figure 1 shows the structure of the Sun.

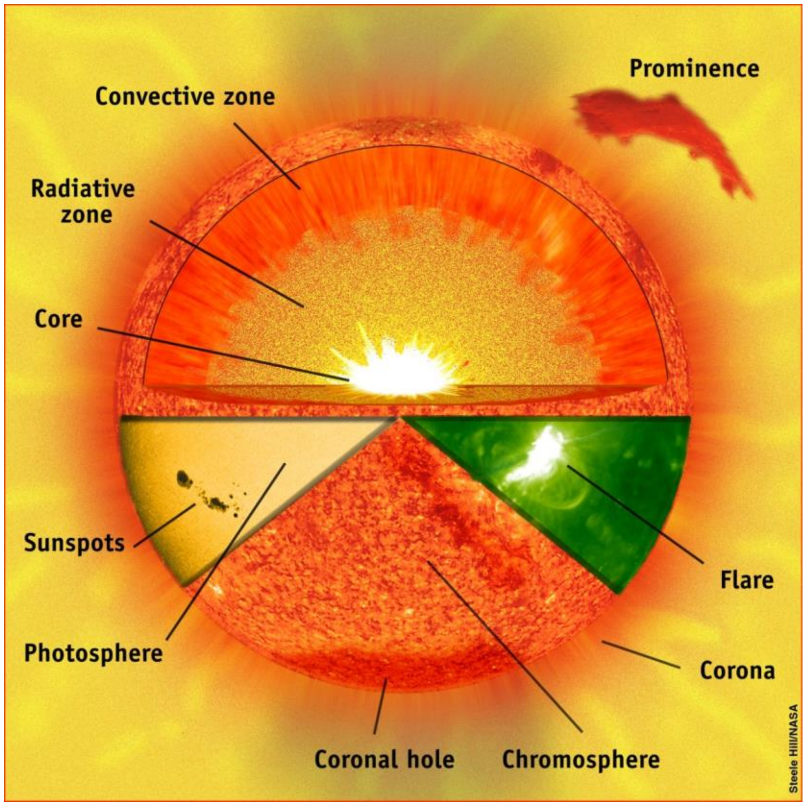

Figure 1: Structure of the Sun (Source: The Sun Today- solar facts and space weather)

Each second, the Sun's core turns four million tons of mass to energy by fusing around 600 million tons of Hydrogen to Helium, resulting in new neutrinos and solar radiation. The produced energy may take anywhere from 10,000 years to 170,000 years to exit the Sun's core, this forms the origin of its heat and light. The Sun has converted nearly 100 times the Earth's mass into energy so far, accounting for around 0.03 percent of the total mass of the Sun. It will take the Sun around ten billion years in its main sequence stage, powered by nuclear burning of Hydrogen.

The Sun's magnetic field changes over its surface, in both location and time with the prominent variation being the solar cycle that has a period of 11years. Sunspots are dark spots appearing on the surface of the Sun that correlate to the concentration of the magnetic field lines, which obstructs convective heat transmission from the solar interior. The Sun's activity changes in a relatively uniform 11-year cycle, which is quantified with regard to fluctuations of the number of detected sunspots. The terms "solar minimum" and "solar maximum" refer to periods when the number of sunspots is at its lowest and highest. During solar minimum, the visible sunspots are few and occasionally none is visible at all. Sunspots tend to appear around the solar equator as the solar cycle approaches its ceiling. The Sun's magnetic field flips during its solar cycle when the sunspot cycle approaches climax. The quantity of solar ejection and radiation of solar materials, the size and number of sunspots, coronal loops and solar flares together show a harmonized variation from active-to-quiet-to active once more with 11-years periods. The 11-year periodic sunspot cycle is half of the 22-year Leighton dynamo cycle, which agrees with an oscillating energy interchange between poloidal and toroidal magnetic fields.

The solar magnetic field stretches out far beyond the Sun itself. The interplanetary magnetic field (IMF) is created when the magnetic field of the Sun is transferred into space by the electrically conducting solar wind plasma. The movement of the plasma particles takes place along magnetic field lines in an ideal magnetohydrodynamics.

The magnetic field of the Sun causes many effects known as the solar activity. The coronal mass ejections (CME) and solar flares are most likely to occur at sunspot groups. At the photosphere surface, there is an emission of slow-varying supersonic streams of solar wind from the coronal holes. Both supersonic jets of solar wind and the coronal mass ejections carry interplanetary magnetic field and plasma to the solar system.

Extended changes in the number of sunspots are conceived to be related to long term variability of solar irradiance, which could affect the climate of the Earth in the long-term. For instance, in the 17th century, few sunspots were observed and the solar cycle seemed to have ceased for a number of decades in the time of the Maunder Minimum, which took place at the same time with the little Ice Age era when Europe encountered remarkably low temperatures. This phenomenon has steered exploration on the basis of understanding the concept of solar cycle together with the role of the sunspots, faculae and network of magnetic field features.

Solar variability is defined as the changes in the solar activity, such as the change in the amount of energy radiated by the Sun, and change in solar wind. Solar irradiance on the other hand refer to the output of light energy per unit area perceived from the Sun, and is evaluated in the wavelength range. It is expressed in Watts per square (W/m^2) in its SI units. It can be determined either at the Earth's surface following dispersion and absorption by the atmosphere or it can be determined in space. The Sun's height overhead the horizon, the tilt of the measuring surface, and weather conditions all influence the solar irradiance at the surface of the Earth. Both animal behavior and plant metabolism are influenced by solar irradiation. The measured categories of solar irradiance include; Total solar irradiance (TSI), which is an estimate over all wavelengths of the solar power on top of the Earth's atmosphere per unit area. The TSI is calculated by measuring the arriving radiation perpendicularly. Solar constant refers to a traditional measurement of average total Sun radiation at one astronomical unit (AU) distance. Total solar irradiance varies gradually on decadal and longer timescales. Spectral Irradiance is the irradiance of a surface per unit wavelength or frequency and is expressed in Watts per square meter per nanometer ($W/m^2/nm$).

The Earth is exposed to the various radiations from the Sun and its temperature is controlled by the balance between the warmth from the radiation and the shielding by its atmosphere. Any changes in the Sun's radiative output are bound to have an effect on the Earth's atmospheric energy balance and hence may have possible effect on the Earth's climate by changing the stratospheric chemistry leading to disturbance of the balance in the ozone destruction and production (Solanki, 2002). The hunt for solar cycle indication among the terrestrial temperature data, although minute, persists to inspire much exploration in the area, and two basic mechanisms have been modelled so far. The first mechanism is the bottom-up total solar irradiance path, and the second avenue is the top-down mechanism which includes absorption of UV radiation in the stratosphere (Board, 2012)**.**

The influence of the Sun has been acknowledged since the prehistoric time when the Sun was perceived of by some cultures as god. Solar calendars are based on the orbit of the Earth around the Sun and its synodic rotation, including the Gregorian calendar, which is the most widely used calendar today.

1.2 Problem statement

Climate change is becoming a great concern to humanity because it affects activities such as farming among others. Climatic drift may influence weather patterns in that, areas which previously received regular rainfall may as well develop drought. Solar activities are the main cause of climatic change on Earth. Hence, any fluctuations in the solar output are likely to influence the climate on Earth.

In this project research, we carried out a study on the nature of the Sun's variability during the last 17 years using data collected by the Solar Radiation and Climate Experiments (SORCE) (*https://lasp.colorado.edu/home/sorce/data/*) and assess the possible effects of the resulting variability on the Earth's climate using data of the Total Solar Irradiance (TSI), the Spectral Solar Irradiance (SSI) and of climate change collected between years 2003 to 2020.

1.3 Research Objectives

1.3.1 Main objective

The main objective of this research project is to carry out a study on the observed solar variability for the last 17 years as well as to explore the possible link relating the Sun's variability and the Earth's climate change using solar activity data from SORCE and climate data from Climate Research Unit (CRU).

1.3.2 Specific objectives

The specific objectives of this research are:

i) To acquire the relevant data from Solar Radiation and Climate Experiments (SORCE) and Climate Research Unit (CRU) for periods 2003 and 2020.

ii) To import the data into GNU-plot and Python and analyze the characteristics.

iii) To fit the results for variability with theoretical models.

iv) To explore the possible correlation linking solar variability and Earth's climate change over the past 17 years.

1.4 Justification and significance

The question of how solar changes and the associated solar terrestrial effects affect the Earth's climate change remains an important unsolved problem in solar Physics and climate change research. Understanding and forecasting of the solar variability is one of the biggest challenges. This study has received a lot of public interest since dependable approximates of the effect on global surface temperatures is required to reduce uncertainty in the relative significance of human activity as a possible clarification of climate change. This study is of much significance as it may be used to predict the past and future solar variability and climatic response so that the human and natural signals may be untwined in the observational record and hence more dependable estimates can be made. The analysis and computation of solar irradiance is of importance in the forecasting of energy production of solar power plants, cooling and heating of buildings as well as the climate modeling and weather forecasting.

CHAPTER TWO

LITERATURE REVIEW

Several studies have been conducted aimed at understanding the concept that the changes in solar activity may have an impact on the Earth's climatic change. A number of studies have shown a statistical connection between numerous meteorological parameters and different measures of solar activity. In this section, key studies that have been conducted on the influence of solar changes on Earth's climate are summarized and presented.

The solar variability may affect the structure of the Earth's middle atmosphere by altering the photochemical dissociation rates and the successive influence on the chemistry of ozone and other gases (Haigh, 1996). Solar and long wave radiation that arrives at the troposphere is regulated by variations in the concentration of the ozone that take place in reaction to the solar cycle. A simulation model based on the European Centre for Medium Range weather forecast in spectral model was used. The model suggested that increases in the temperature of the stratosphere in reaction to intensified solar irradiance produces powerful summer easterly winds that pass into the upper troposphere and induce tropospheric circulation pattern pole ward. The model showed variations in temperature, zonal wind, and storm track position that are same as, although generally less than those observed.

Reid, 2000 highlighted that the elementary foundation of the possible mechanisms of the correlation between Sun-climate has been proposed to three mechanisms involving: the variations in the TSI, the variations in the SSI of the UV, and changes in solar wind and flux of energetic particles. Variations in TSI which when integrated over all wavelengths can result to a change of the incident energy to the atmosphere of the Earth. The changes in the SSI in the UV can interfere with the chemical and physical processes in the Earth's surface by affecting the balance in the ozone layer production and destruction. Solar induced variations in ozone might have influence on radiative forcing and influence climate by the vigorous reaction to solar warming of the lower stratosphere. Changes of the flux of energetic particles and of solar wind, affects the cloud cover that can be induced by the Cosmic Ray flux that reach the Earth.

According to Solanki (2002), it is informational to liken climate time series and solar. If both are alike, this does not give an evidence that the Sun prompts climate change, however if they are distinct, this gives room for limits to be made on the solar effects. In his lecturer, the total irradiance is contrasted with the climate records since 1850 and the figures displaying the cosmic ray flux and the UV irradiance are the same and result to similar deductions. This is in harmony with the casual connection linking the two but by no means shows that the Sun had an effect on the climate previously. He added that other possible donations to climate change are the internal changes of the atmosphere of the Earth, volcanic activity and man-made greenhouse.

A straight forward way to analyze the influence of solar changes or of other elements causing a radiative forcing on surface temperatures is by use of an energy balance model (EBM) (Haigh, 2002). This model is a 1-D model that estimates the feedback of vertical temperatures in the atmosphere, occasionally in the ocean, to applied radiative forcing. He used a global average EBM to approximate the extent of the reaction of surface temperatures to solar indices and by contrasting the output with the observational data, they concluded that solar changes can account for 30% to 55% of climate changes on decadal to centennial time-scales.

A collection of various instrumental data undoubtedly prove that the solar constant is in fact not a constant. Besides this direct measurement of the solar constant, there are various indirect proves that the Sun is a varying star and may have an effect on climate variability. By use of cosmogenic radionuclide such as ^{14}C, ^{10}B and ^{36}Cl that are generated by interplay of cosmic rays and the atmosphere, it is workable to model the solar activity exceeding the past 10,000 years, which presents a first order approximation of solar forcing. Earlier than the industrial era, the anthropogenic effect on the climate was possibly insignificant, leaving us with volcanic forcing and solar. Attributing that most of the paleorecords indicate approximately high connection with the modeled solar activity shows that solar forcing in fact plays a significant role (Beer, 2005).

The most precise approximate of climate radiative forcing are the ones that take into account the influence of changes in the stratosphere on the radiative flux at the tropopause, (Haigh, 2007). Hence, a better approximate of radiative forcing to solar irradiance variations must take in the influence of changes in the ultraviolet on stratospheric temperature and structure. Most energy is at visible wavelength on the upper atmosphere and it is transferred through to the surface almost unaffected. Most of the radiation is absorbed before it gets to an altitude of about 40 km at wavelengths shorter than 300 nm. There is also absorption at longer visible wavelength. At the top of the atmosphere, at all wavelengths there is more energy but this is not maintained throughout the depth of the atmosphere. At wavelengths less than 300 nm and greater than 500 nm there is less radiation that gets to the troposphere at solar maximum than at solar minimum since the increased concentrations of stratospheric ozone are leading to greater absorption at this wavelength.

The solar changes may penetrate the Earth's climate system by influencing the El Nino Southern Oscillation and the Quasi-Biennial Oscillation. Comparing the record of the sunspot numbers and the historical record of El Nino events, the El Nino events are detected to be two or three times more periodic when solar irradiance and sunspot activity are minimum as during the Maunder Minimum. One may perceive that a rise in sunspots would reduce solar output, but on the contrary, there is an increase in brightness of the faculae. The intensification in brightness of these faculae is the domineering factor in altering of the solar output rather than sunspot darkening (Marsh, 2007).

Gray, *et al.*, 2010 discussed that the processes put forward to clarify the climate reaction to tiny solar fluctuations can be divided into two groups. The first is a reaction to changes in solar irradiation. Nearly all of the irradiance arriving on the top of the Earth's atmosphere is in the visible, ultraviolet, and infrared ranges, with about half of it penetrating the atmosphere and being absorbed at the surface. Some of the energy is absorbed by water vapor in the troposphere in many wavelength bands and stratospheric ozone in the UV region. The second explanation is that energetic particles, such as solar energetic particle (SEP) occurrences and galactic cosmic rays (GCR), are involved. Particle precipitation and generated ionospheric currents are two ways in which solar wind particles with low energy affect the thermosphere above 100 km. Longer-wavelength photons deposit energy in the upper atmospheric layers, but the more energetic particle precipitation are the ones that reaches lower latitudes. Modulation of galactic cosmic ray fluxes into the atmosphere by solar activity may have an impact on cloudiness and thus be a potential Sun-climate mechanism.

The fractional decline required during the Maunder Minimum may be less than the complete disappearance of small flux tubes needed by the earlier irradiance models concluding from recent findings of the solar photometry (Foukal, 2011). The results propose that abundant radiative flux per unit area of faculae is inversely related to the cross-section. This relation proposes that climatically important variations in total solar irradiance can be reached without the necessity of the total vanishing of photospheric magnetism. He added that the current approximate of the quiet networks in addition to total irradiance are unresolved due to the restrain on angular resolutions, angular coverage or wavelength coverage. If the endowment to TSI of the quiet network is notable, it is significant to gauge if the network's area decayed. The most coherent indices of network area pointed a reduction by 5% to 10% lower than the mean of the past least values in the course of the recent minimum activity between the years 2008 and 2009. The quantity of reduction throughout a minimum which was almost one year extended than normal suggest a higher reduction in the course of a maunder-minimum like episode lasting 70 years.

Workshop report by climate Board, 2012 focused majorly on magnetically driven solar change and the Earth's climate changes of the amount or energy dispensation received at Earth when they persist for long periods. The key areas dealt with determining the integrated data of the solar modified particles and solar output that extend from prescientific past to present. Helioseismic quantification discloses the compounded depth dependence of solar rotation well into the radiative core and throughout the convection zone. However, the shift of these proceeds into refined mastery of the dynamo activities that cause solar magnetism has shown to be difficult.

The workshop report highlighted that the agreement between total solar irradiance and numerous proxies to be that the dimension of heliosphere regulates quantity of the cosmic rays which get to Earth's surface. The magnetic field of the Earth controls quantity of the cosmic rays that make it to the atmosphere. The common isotopes used in studies of how to recover the information about the solar activity, based on analysis of cosmogenic isotope data in the past, are ^{14}C present in tree rings and ^{10}Be present in ice cores. Since the magnitude of Galactic Cosmic Rays (GCR) has a negative relation with the sunspot number, this is the reason for using ^{14}C and ^{10}Be as a variable measure of solar activity in the past. GCR flux in the atmosphere alters isotopic abundances generating ^{14}C and ^{10}Be. Baker, who was a presenter in the workshop, also pointed out that galactic cosmic rays get into the troposphere and stratosphere and they are useful top-down mechanism for the coupling of Sun-climate effect. GCRs are anticipated as isotropic in space just exactly after the heliosphere and enter the solar system with almost same magnitude from every direction. They undergo both intensity and energetic variation as they penetrate the solar system. The radio isotope information in ^{14}C and ^{10}Be gives details about the changing aggregation of the isotopes present in the biosphere over previous millennia. The resultant cosmic ray flux changes have been in cooperated in studies of Sun-climate relation. These isotopic evidences provide the finest chance of establishing how much solar magnetic field reduced and how much the Sun dimmed during a certain period. The response of ^{14}C to change of the solar cycle is influenced by the certainty that ^{14}C is absorbed by carbon dioxide. ^{14}C stays in the atmosphere for about 7years to 8 years where it has a lengthy habitation period in the big reservoir of ocean. It continues to interchange with the biosphere and atmosphere before getting cornered in tree rings. ^{14}C on the 11-year timescales or longer records a more global signal. ^{10}Be is made in the stratosphere, and then gets joined to the aerosols, which is delicate to stratosphere-troposphere interchange activities before getting dumped in ice cores. ^{10}Be is somehow a direct variable for cosmic rays with notable noise related with climate influences and location.

The workshop report also pointed out that the behavior of Sun-like stars provides the capacity to gain a deeper understanding of how solar forcing may change and the Sun's activity in the future. For a collection of Sun like stars, the percentage of dormant stars is comparable to percentage of solar period spend in Maunder-Minimum like state. The frequency in solar like stars of grand minimum frequency ranged between 10-30 percent, signifying that Sun's effect might be empowering. For an old star that is approaching the end of its main sequence lifetime, very low activity may be evident.

Zharkova, 2020 proposed that the periodic appearance of sunspots on the surface of the Sun is detected to be controlled by the background solar magnetic field, which may be utilized as a current variable of solar activity. It is possible to trace magnetic wave pairs caused by double dynamo in the solar interior layers with a bit different frequency and a phase difference in a current principal analysis of the solar magnetic field in cycles 21-23. These magnetic waves are duplicated using mathematical formulae, allowing us to anticipate solar activity over millennia, leading to the discovery of a 350–400 years grand solar cycle brought about by tampering of these waves. The solar activity and solar magnetic field are considerably reduced when the waves are out of phase, approaching great solar minimum (GSM). From 1645 to 1715, the Maunder minimum was observed and it lasted for six cycles of eleven years a period when the Danube and Thames rivers froze over. The Sun is already approaching the contemporary GSM in 2020, which will continue for only three solar cycles of eleven years, from 2020 to 2053. During this GSM, solar radiation and ground temperatures are likely to be lowered. These two processes will result to a decrease in terrestrial temperature, a decrease in solar activity, and a rise in total solar irradiance during the contemporary GSM.

CHAPTER THREE

THEORETICAL BACKGROUND

3.1 The Sun as a blackbody

The Sun is a near perfect blackbody and the electromagnetic radiation emitted from it is a black-body radiation. A blackbody is an idealized body that takes up all electromagnetic radiation arriving on it, it is an ideal absorber and emitter of wavelength radiation.

The Sun's photosphere, where the emitted light is formed, is conceptualized as a layer inside which photons of light interact with the photosphere's material to reach a common temperature that is maintained through time. Although some photons escape and are expelled into space, the energy they carry is replaced by energy from within the Sun, resulting in a practically constant temperature of the photosphere. Normally, the Sun emits black-body radiation at the photosphere's temperature.

The Stefan-Boltzmann law explains the amount of energy a body radiates and where in the electromagnetic spectrum peak radiation takes place. This is built on the idea that the source of energy behaves as a blackbody. The amount of energy, M, an object emits (per given surface area) is a function of the surface temperature of the object which is indicated by the Stefan-Boltzmann law as:

$$\mathrm{M} = \sigma \mathrm{T}^4 \qquad (1)$$

Where σ is the Stefan-Boltzmann constant and T represents the temperature of the emitting material.

This gives the total energy being radiated by the blackbody at all wavelengths. By locating the peak of the curve, we can resolve at what wavelength the highest amount of energy that is radiated at and the area under the curve gives the energy of the body emitting the radiation.

By obtaining the value of the wavelength at the peak, and using Wien's displacement law, the temperature of the radiating body can be determined as;

$$\lambda_{\max}\,\mathrm{T} = 2.898 \times 10^{-3}\ \mathrm{m.K} \qquad (2)$$

Where $\lambda_{\max}$ is the wavelength at the peak and T is the temperature of radiating body.

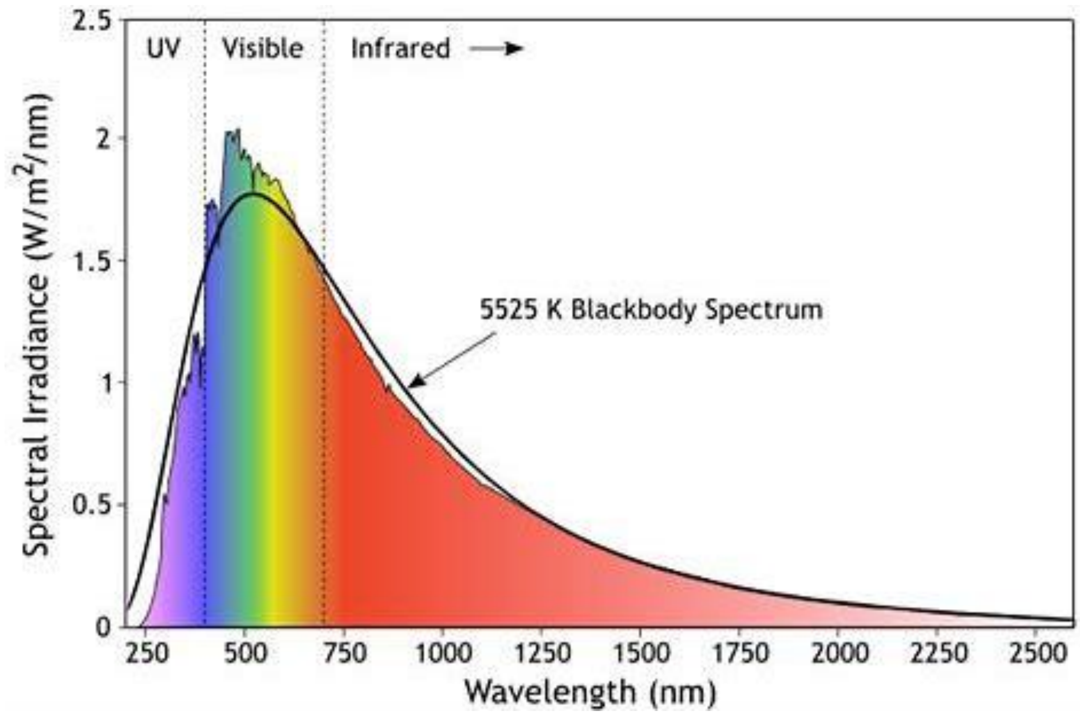

Figure 2: Spectral Irradiance of the Sun against wavelength (Source: Science Direct)

3.2 Solar Luminosity

The power radiated in the form of photons is measured as solar luminosity, which is a unit of radiant energy. The solar constant, written as$\mathrm{I_O}$, is the principal irradiance on top of the Earth's atmosphere. The power per unit area is referred to as irradiance. The irradiance encountered at the Earth (the solar constant, whose value is 1361 W/m2) multiplied by the area of a sphere whose radius is the Earth-Sun distance gives the solar luminosity,$L_{\odot}$, which is the total power radiated by the Sun. The following is an equation to represent it:

$$L_{\odot} = 4\pi \mathrm{k I_O A^2} \tag{3}$$

Where A represents the unit distance and k is the constant (which has a value of close to 1) that indicates that the mean distance from the Earth to the Sun is not precisely 1.

One nominal luminosity has a value of 3.828×10^{26} Watts as given by the International Astronomical Union. Including the solar neutrino luminosity with which adds $0.023L_{\odot}$, total of 3.916×10^{26} Watts is obtained.

3.3 Effective temperature

For a body such as a planet or a star, the effective temperature is the temperature of a blackbody that would radiate the equal amount of electromagnetic radiation (Archie and David, 2003). Effective temperature means that the influence of the atmosphere or oceans is left out on the average global temperature.

It is mostly treated as an approximate of a body's surface temperature when the function of wavelength is unknown.

When the planet's or the star's net emissivity in the wavelength band is below that of a blackbody, the exact temperature of the body will be greater than the effective temperature.

By looking at the case of our planet excluding the water or air, we can be able to calculate how hot or cold our planet is. The visible light produced by the Sun transports energy to the solar system. The energy is taken up by the surface of the planet hence warming the ground. An object that has a temperature higher than absolute zero radiates electromagnetic radiation. For planets, the reflected electromagnetic radiation has the form of infrared light. Planet's surface warms up until the leaving infrared radiation equalize the incoming energy, reaching a state of thermal equilibrium.

To evaluate the total quantity of energy getting to the Earth, we have to know the area that is lit, which is then multiplied by the insolation to obtain the total amount of incoming energy.

The full amount of energy interrupted by the Earth is;

$$\mathrm{E_{int}} = \mathrm{k_s} \pi \mathrm{R_E^2} \tag{4}$$

Where $\mathrm{k_s}$ the solar insolation and has a value of 1361 W/m^2 and $\mathrm{R_E}$ the radius of the Earth which has a value of 6371 km.

Plugging in the values of $\mathrm{k_s}$ and$\mathrm{R_E}$, then solving for $\mathrm{E_{int}}$ gives a value of. 173.5×10^{15} Watts. The Earth intercepts around 174 petawatts of sunlight.

Upon striking the Earth's atmosphere, not all of this energy is absorbed, some of this energy is radiated back by atmospheric aerosols, clouds, ice, snow and even ocean surface. The absorbed energy is taken up by the ocean, land and the atmosphere. Individual layers of the atmosphere take up different wavelengths of the energy. The absorbed solar energy warms up the planet's atmosphere and surface, but this energy does not remain trapped in the Earth's environment, otherwise the Earth would be extremely hot and inhabitable. As the air, the rocks and the sea warm up, they radiate thermal energy of the type of long-wave infrared which finally leaves the Earth letting it to cool to habitable temperatures. The quantity of long-wave energy leaving the Earth must balance the absorbed radiation from the Sun in order to maintain the Earth's temperatures stable. The term albedo is used to explain the amount of light a surface or planet radiates away. In order to determine the energy that the Earth takes up from sunlight, we multiply the intercepted energy by one minus the Albedo value:

$$\mathrm{E_{abs}} = \mathrm{k_s}(1 - \mathrm{Al})\pi \mathrm{R_E^2} \tag{5}$$

Where Al stands for the Albedo.

The Earth radiates electromagnetic radiation in the form of long wave infrared radiation. The equation that relates the amount of radiation to the temperature of the object is called Stefan-Boltzmann law. The radiated energy is equivalent to the 4th power of the temperature as in equation (1).

To evaluate the amount of energy radiated by the Earth, we multiply this energy emission by the total area of Earth surface. Since the Earth rotates, its entire surface is warmed by sunlight, and hence the entire of the spherical planet's surface radiates infrared energy.

$$\mathrm{E_{emit}} = \sigma \mathrm{T}^4 4\pi \mathrm{R_E^2} \tag{6}$$

According to the energy conservation law, the energy radiated has to be equivalent to the absorbed energy.

$$\mathrm{E_{abs}} = \mathrm{E_{emit}} \tag{7}$$

$$\mathrm{k_s}(1 - \mathrm{Al})\pi \mathrm{R_E^2} = \sigma \mathrm{T}^4 4\pi \mathrm{R_E^2} \tag{8}$$

$$\mathrm{k_s}(1 - \mathrm{Al}) = 4\sigma \mathrm{T}^4 \tag{9}$$

Hence the temperature of the Earth can be computed as:

$$T = \sqrt{\frac{k_s(1 - Al)}{4\sigma}} \tag{10}$$

The Earth's albedo is about 0.31. Plugging the values in the equation, the expected Earth's temperature at 1AU is approximately 253.7K or -19.5^{0}C.

Based on this, the Earth is warmer than predicted by 34^{0}C since the global temperature on average is about 14^{0}C. This big difference is brought about by particular gases in the atmosphere that trap additional heat hence heating the Earth. The additional warming is referred to as the greenhouse effect which without it, the Earth would become a frozen ball.

3.4 Radiative forcing

The difference between the energy reflected back to space and the absorbed energy by the Earth is known as the radiative forcing. It is the measure of the impact a factor has on the equilibrium of outgoing and incoming energy into the Earth's atmospheric system, as well as an indicator of its significance as a mechanism of potential climate change. It provides the foundation for the planet's greenhouse gas impact and is used in many analytical models of the energy balance of the Earth and climate. Warming is caused by positive radiative forcing, which takes place when the Earth takes more incoming energy than it emits to space. In contrast, negative radiative forcing takes place when the Earth radiates more energy to space than it absorbs, resulting in cooling. A planet with zero net radiative forcing and a planetary equilibrium temperature is considered to be in radiative equilibrium with the rest of space and with its parent star.

Radiative forcing is computed at the top of the stratosphere and the top of the tropopause. It is computed in Watts per square meter and expressed as mean over the globe's entire surface area. The average world temperature is regulated by the balance of emitted and absorbed energy.

The Sun supplies almost all of the energy that influences the Earth's climate in the form of radiant energy. Factors such as cloud or gas reflectivity, solar energy intensity, absorption by various greenhouse gases, and surface and heat outputs by various materials all influence the radiation balance.

The area subjected to the Sun (πr^2) is equivalent to a fourth of the Earth's surface area ($4\pi r^2$), and the solar feed in per unit area is a fourth of the variation in solar intensity. Given that there is radiation that is reflected back, the percent of incident sunlight that is absorbed is multiplied by this reflected radiation. The amount of absorbed incident sunlight is calculated as follows:

$$F = (1 - R) \tag{11}$$

Where R refer to the Earth's reflectivity, and has a value of approximately 0.3. So, F has a value of approximately 0.7.

3.5 Atmospheric gas forcing

The data indicating the relationship linking solar variations to Earth's climate is often discharged as mere relations since there is no conventionally welcomed foundation to describe the correlations. Which is an appropriate position given that the powerful argument is in bias of greenhouse gases, such as carbon dioxide driven climate change, since carbon dioxide absorbs the long wavelength infrared radiation.

For greenhouse gases, such as CO_2, the radiative transfer codes that look into every spectral line for atmospheric conditions can be utilized to evaluate the change of the absorbed sunlight ΔF as a function of varying concentration. A 1st order approximation expression for CO_2 is given as the equation below (Myhre, *et al.*, 1998);

$$\Delta F = \alpha \ln \frac{C}{C_0} \tag{12}$$

Where C is the concentration of carbon dioxide by volume in parts per million, C_0 is the concentration at a given reference time and α is the sensitivity of the climate to changes in carbon dioxide concentration whose value is 5.34.

3.6 Role of the middle atmosphere

The Sun emits energy across the whole electromagnetic spectrum, but it gets climax in the visible near infrared, with 80 percent of the TSI falling between 14nm and 1600 nm. Although in the near-infrared, water vapor bands produce absorption in the lower troposphere, most visible near-infrared energy travels past the atmosphere unaltered to the tropopause finally to the Earth's surface.

In the middle atmosphere, shorter UV wavelengths are absorbed, causing local heating and ozone generation. The stratosphere causes raised emission of thermal infrared energy in the troposphere, while increasing ozone is prone to hide the lower atmosphere from most incident UV. As a result, the ozone response determines the nature of variations in the UV and thermal infrared radiation fields. The upper and lower stratospheres experience the most changes, while the middle stratospheric experiences essentially no changes.

The mechanisms suggested explaining the reaction of the Earth's climate to solar variability is said to be magnetically driven and grouped into three mechanisms involving: the changes in the TSI, the changes in the SSI in the UV and changes of the solar wind and flux of energetic particles. Variations in TSI when integrated over all wavelengths can result to a change in energy precipitation to the Earth's atmosphere, where the Near-IR irradiance, visible, and Near-UV influence the surface temperature directly, they constitute 99% of the TSI output. The variations in the spectral irradiance in the UV can interfere with the chemical and physical processes in the atmosphere of the Earth by affecting the balance in the ozone layer production and destruction. Solar induced variations in ozone might cause an influence on radiative forcing and influence climate by vigorous reaction to solar heating of lower stratosphere. Fluctuations of the flux of energetic particles and the solar wind, affects the cloud cover that can be induced by the Cosmic Ray flux reaching the Earth.

3.7 Effect of energetic particle precipitation (EPP) on the atmosphere

The energetic particle precipitations (EPP) are protons and electrons produced by CMEs, geomagnetic storms and solar flares. They intensify the making of HO_X and NO_X that alter ozone in the upper stratosphere and mesosphere when they precipitate in the Earth's Polar Regions. HO_X constituents have a short lifetime and this makes majority of the climate-relevant and atmospheric EPP focus to be on the NO_X. Solar electrons and protons have periodic solar cycle and seasonal effect in the polar mesosphere. In years when remarkable winter time metrological events take place, according to measurements and models, EPP-enhanced NO_X is transferred from the lower thermosphere and upper mesosphere to lower altitudes where their influence may last for a few months hence lowering the ozone layer by small a percentage. There is possibility of a top-down influence where the EPP- NO_X induced ozone destruction causes variations in surface air temperature. NO_X and HO_X can also be created by GCR but at lower altitudes as a result of their high energy in comparison to solar particles.

3.8 Bottom-up and Top-down mechanisms

These are mechanisms that have been proposed to explain locally amplified responses of the Earth's climate to solar forcing as a result of thermodynamical feedback processes.

The Bottom-up mechanism focuses on the effects of changes in visible and near-infrared radiation on the surface temperature. The solar radiation intensity on Earth in the tropics affects this mechanism, but the majority of it gets to the surface in cloud-free subtropical regions. Evaporation absorbs a significant amount of this radiant energy over the oceans. The resulting increased humidity of the air is transferred to the tropics, where it converges and rises, resulting in the region's heavy precipitation and deep cloud.

The Top-down mechanisms relies on UV radiation absorption in the stratosphere. This mechanism operates through variations in the shorter wavelength and more energetic constituents of the solar spectrum that affect the winds and stratospheric temperatures directly through absorption by stratospheric ozone layer.

CHAPTER 4

METHODOLOGY

4.1 Introduction

This chapter puts forward a summary of the procedure and methodology used in this research work. The chapter is divided into four subsections; Source of data, data acquisition and analysis, graph smoothing and linear regression. The data described in this chapter contains both the Sun's data and the climate data.

4.2 Source of data

The Sun's data used in this research project was obtained from the Solar Radiation and Climate Experiments (SORCE) which is a joint partnership between National Aeronautics and Space Administration (NASA) and the University of Colorado's Laboratory for atmospheric and Space physics (LASP) supported satellite mission that gives the state-of-the-art values of incoming ultraviolet, X-ray, near-infrared, visible, and total solar radiation. The SORCE mission provided data for 17 years of exceptional monitoring of the TSI and SSI, at wavelengths ranging from ultraviolet to the near-infrared, from 25th Feb, 2003 up to 25th Feb, 2020.

The lifetime of the SORCE mission allowed quantification of two of the Sun's eleven-year solar cycle detecting solar cycle least conditions in both 2008 and 2019 that are significant for the circular incline of solar irradiance. SORCE conveyed four instruments: Total Irradiance Monitor (TIM), two identical Solar Stellar Irradiance Comparison Experiments (SOLSTICE), Spectral Irradiance Monitor (SIM) and the XUV photometer system (XPS).

The TSI data was devised using quantification made by the SORCE TIM instrument and it is accessible both in daily average and 6-hourly average formats. On the other hand, the SSI data comprises of quantifications made by the SORCE spectral instruments; the XPS data with measurements ranging between 1nm-40nm, the SOLTICE-A data with measurements ranging between 115nm-180nm, SOLTICE-B data with measurements ranging between 310nm-2416nm. The TSI and SSI data products were made publicly available right after they were processed by the data processing system. The data is accessible by interactive access or by direct download on the SORCE interactive Data Access website (*https://lasp.colorado.edu/home/sorce/data/*).

The climate data was acquired from Climate Research Unit (CRU), which is a part of the University of East Anglia and a leading institution involved with the research of anthropogenic and natural climate change. CRU has provided a number of the data sets used in climate research, as well as statistical software packages and climate models as well as a range of climate data sets, covering precipitation, temperature, circulation and pressure both global and regional. This research work made use of carbon dioxide concentration and global temperature anomalies for the climate data. The data products are publicly accessible from the CRU website (*https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/*).

4.3 Data acquisition and analysis

Acquisition of the SORCE and CRU data was done by downloading it from the respective websites to the local computer after which it was filtered and saved as data files.

The analysis of solar activity data and the climate data was done using GNU plot and Python programs. GNU plot is a free and open-source command-line program that can produce two- and three-dimensional plots of data, functions and data fits. The program is able to read data from simple text files. It is the most widely used program to plot and visualize data and it is compatible with many operating systems including Windows and Linux.

Python is an interpreted high-level general purpose programming language that permits the user work swiftly and assimilates systems more successfully. Python's design philosophy stresses on code readability with its outstanding use of indentation.

Codes written in Python programming language were used in data visualization and analysis. The "load" command was used in GNU-plot for data analysis and visualization.

4.4 Data smoothing

Data smoothing is a technique that is done to remove noise from a data set by removing random variations and shows trends and cyclic components.

In this research work, the smoothing process made use of *acsplines* in GNU-plot.

The resulting solar variability graphs were observed to contain a lot of noise and sharp peaks. To deal with this, a simple smoothing technique was applied to increase the quality of the graphs by reducing the noise.

4.5 Linear regression

This is a technique that tries to model the connection linking two variables by fitting a linear equation to observed data. It seeks to find a best line of fit for the graph.

One of the variables is taken to be an explanatory variable while the other variable is taken to be a depended variable.

This was achieved by first defining the function that we need to fit to the data. A linear regression line has an equation expressed in the form:

$$y = f(x) = mx + b \tag{13}$$

Where y is the dependent variable and x is the explanatory variable.

Then best values of the model parameters are given by the values of m and b, after running the "fit" command.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents the results obtained in the research work and the discussion. It is divided into 3 main sections; Section 5.2 presents the results obtained for the data analysis of solar variability, section 5.3 presents the results for climate change and section 5.4 presents the results explaining the connection between solar variability and climate change.

5.2 Solar variability results

5.2.1 Total Solar Irradiance (TSI)

In order to understand how the total solar irradiance of the Sun has been varying for the last 17 years, a graph of TSI against time for the period 25th Feb, 2003 to 25th Feb, 2020 was plotted and displayed as in figure (3).

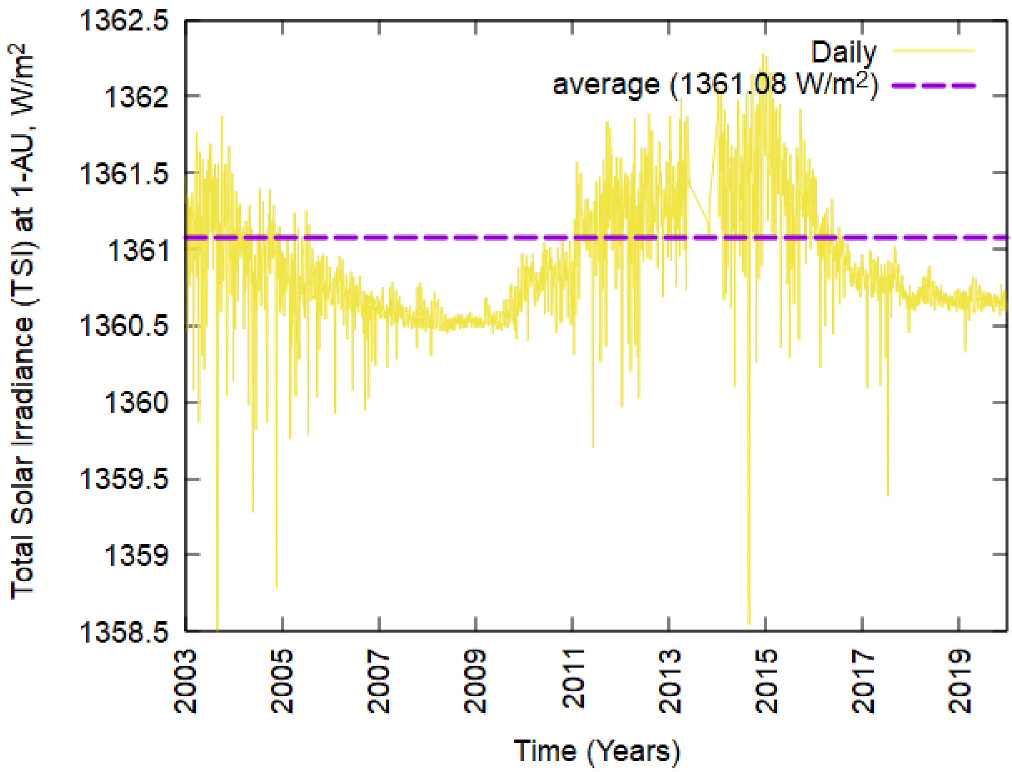

Figure 3: A graph of total solar irradiance over the 17 years

This graph shows that the solar radiation getting on top of the Earth's atmosphere, on average, is 1361.08 W/m^2, which exhibits the power per unit area of solar irradiance over the surface of a sphere around the Sun with a radius of the Earth-Sun distance, which is 1 AU. Minimum solar activity is observed in the years 2008 and 2009 as well as in 2019, and maximum activity is observed in the year 2015.

The graph was fitted with a polynomial function and the resulting graph was plotted as in figure (4).

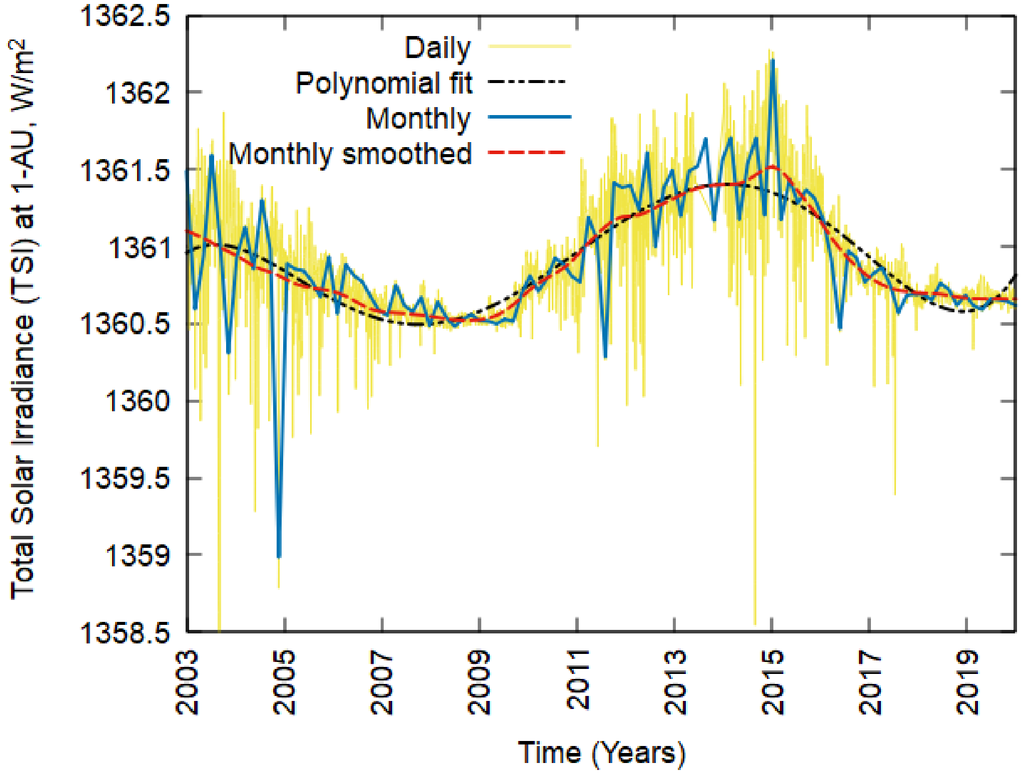

Figure 4: A graph of total solar irradiance over the 17 years fitted with polynomials.

The graph is in agreement with a polynomial of order five as expressed in the equation;

$$y(x) = (1.17685 \times 10^{-17}x^5) + (-1.73827 \times 10^{-13}x^4) + (8.47064 \times 10^{-10}x^3) + (-1.46281 \times 10^{-6}x^2) + (0.000521178x) + (1360.96) \tag{14}$$

This is the law that approximates how the Sun's total irradiance has been varying.

5.2.2 Solar Effective Temperature

Using the formula in equation (8), the effective temperature on top of the Earth's atmosphere was computed and the results were plotted in a graph as shown in figure (5).

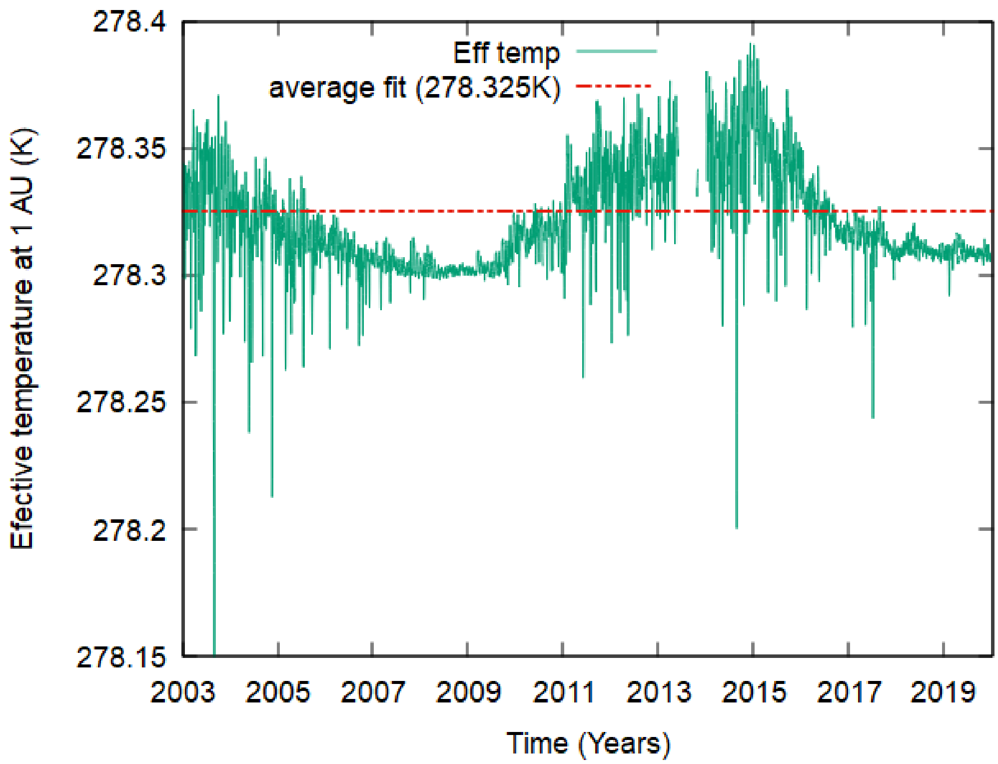

Figure 5: A graph of computed effective temperature at 1AU

This graph shows that on average, the effective temperature on top of the Earth’s atmosphere is 278.325K. This differs from the theoretical value of 253.7K by a value of 24.625K. This difference may have been caused by the disparity in calibration of the measuring instruments.

The graph was fitted with a polynomial function and the resulting graph was plotted as shown in figure (6).

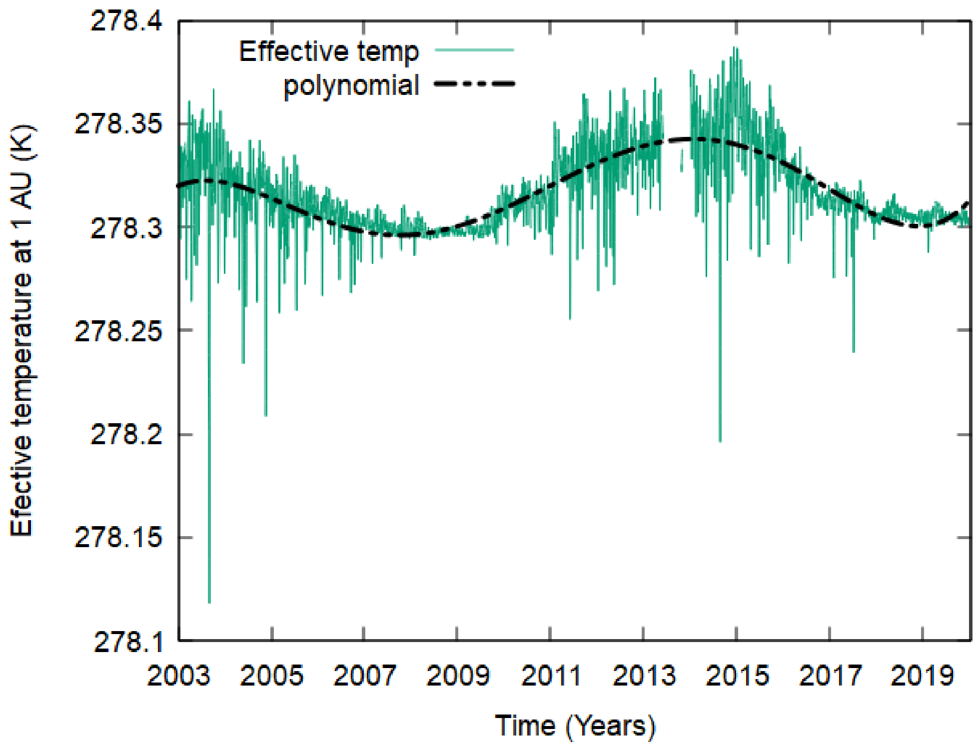

Figure 6: A graph of computed effective temperature at 1AU fitted with polynomial.

The graph is in agreement with the polynomial of order five as expressed by the equation;

$$y(x) = (6.016 \times 10^{-19}x^5) + (-8.88637 \times 10^{-15}x^4) + (4.33 \times 10^{-11}x^3) + (-7.47517 \times 10^{-6}x^2) + (2.664x) + (278.32) \tag{15}$$

5.2.3 Computed Solar Luminosity

The solar luminosity on top of the Earth's atmosphere was computed using the formula in equation (2) and the results were plotted in a graph as shown in figure (7).

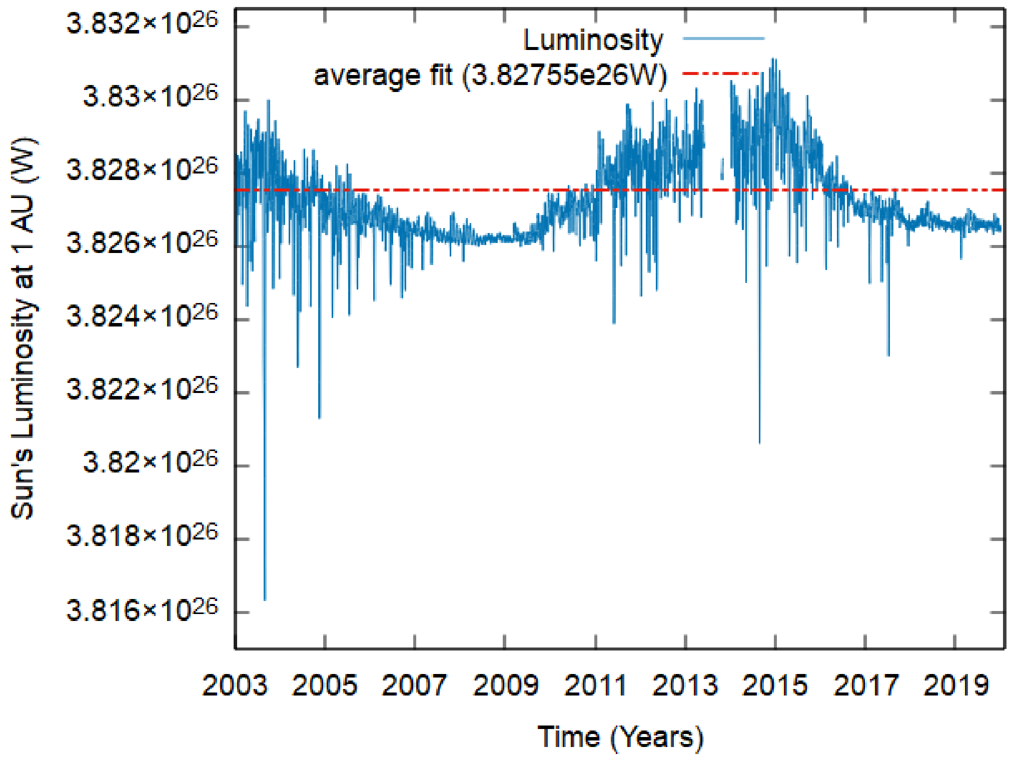

Figure 7: A graph of computed solar luminosity at 1 AU

The graph was fitted with a polynomial function and the resulting graph was plotted as in figure (8).

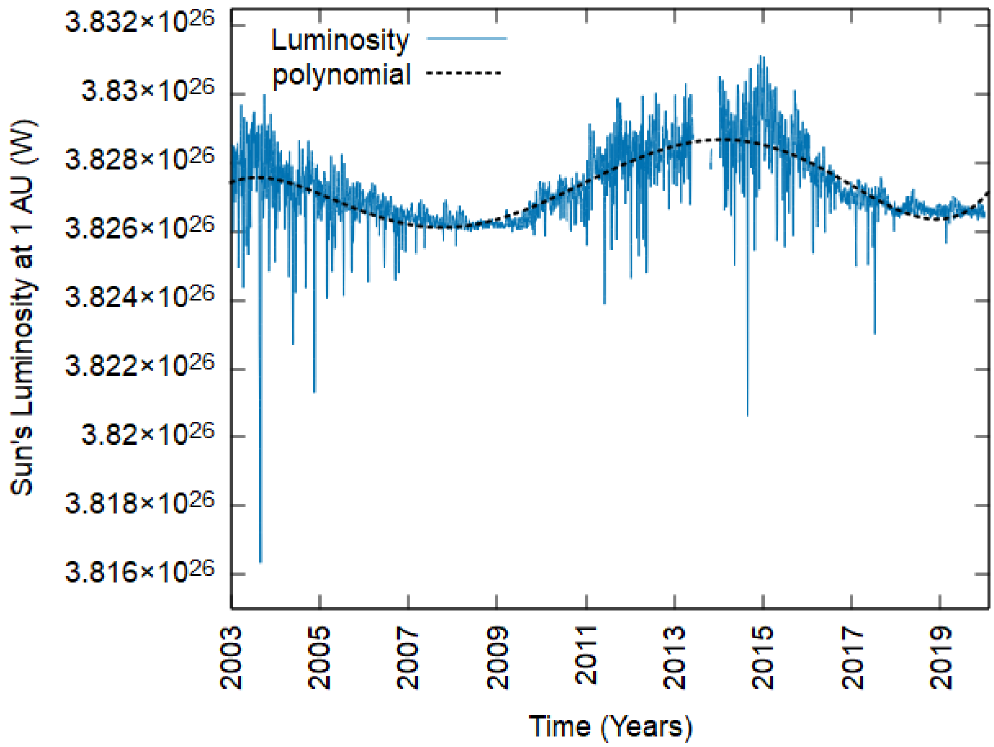

Figure 8: A graph of computed effective temperature at 1AU fitted with polynomial.

From the graph, we can conclude that on average the Sun emits a luminosity of value 3.827555×10^{26} W, which coincides with the theoretical value of solar luminosity which has a value of 3.828×10^{26} W.

The graph is in agreement with the polynomial of order five as expressed by the equation;

$$y(x) = (3.30965 \times 10^{-6}x^5) + (-4.89017 \times 10^{-10}x^4) + (2.38219 \times 10^{-14}x^3) + (-4.11385 \times 10^{17}x^2) + (1.4657 \times 10^{20}x) + (3.827 \times 10^{26}) \quad (16)$$

5.2.4 Sunspot Numbers

In order to understand the variations of the sunspot numbers on the surface of the Sun over the past 17 years, a graph of sunspot numbers against time for the period 25th Feb, 2003 to 25th Feb, 2020 was plotted and displayed in figure (9).

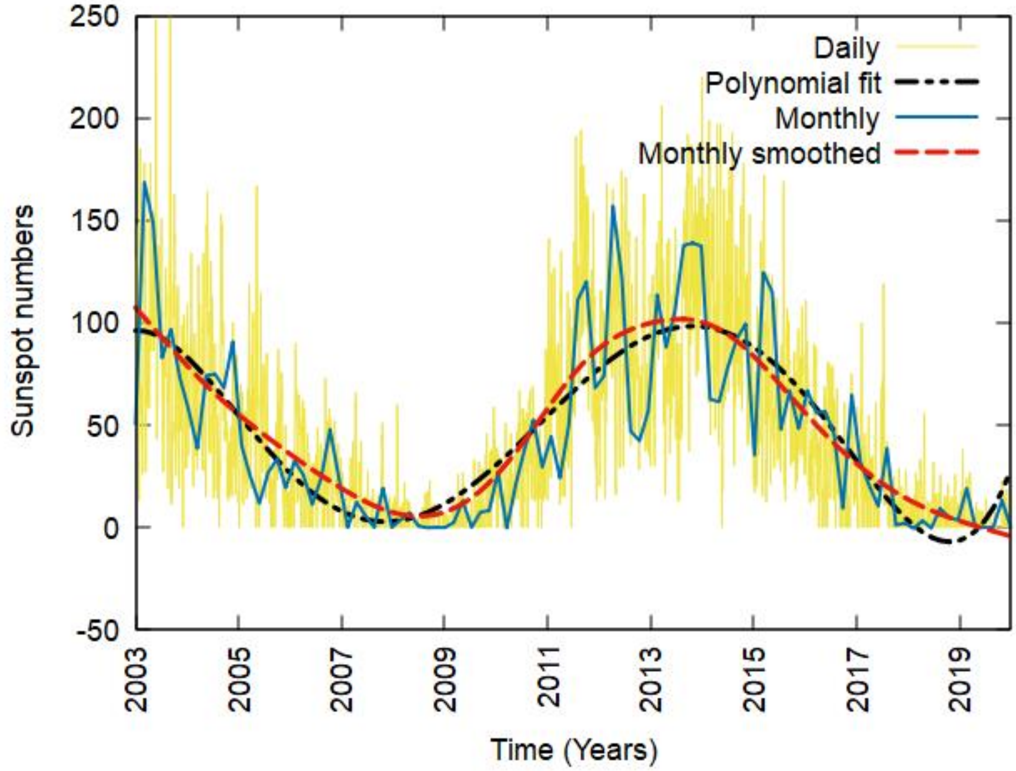

Figure 9: A graph of sunspots numbers over the 17 years.

The graph shows the variation of sunspot numbers, and they are observed to be almost zero in the years 2008 and 2009; this can be concluded that the Sun's activity was at minimum during this period as well as in the year 2019.

This graph reflects the changes of the magnetic field of the Sun since appearance of sunspots is affected by the intensity of the magnetic activity that causes the disturbances in the Sun's magnetic field to move up to the photosphere. That is, intensifying of the magnetic field results to increase of the sunspot numbers on the solar surface.

The graph is in agreement with a polynomial of order five as expressed by the equation;

$$y(x) = (1.37272 \times 10^{-15}x^5) + (-1.97628 \times 10^{-11}x^4) + (9.21089 \times 10^{-8}x^3) + (-0.000141372x^2) + (-0.00455022x) + (96.1117) \tag{17}$$

5.2.5 Spectral Solar Irradiance (SSI)

To better understand the Sun's radiation over the wavelength band, a graph of the SSI against the wavelength range of 0nm-2500nm was plotted and displayed as in figure (10).

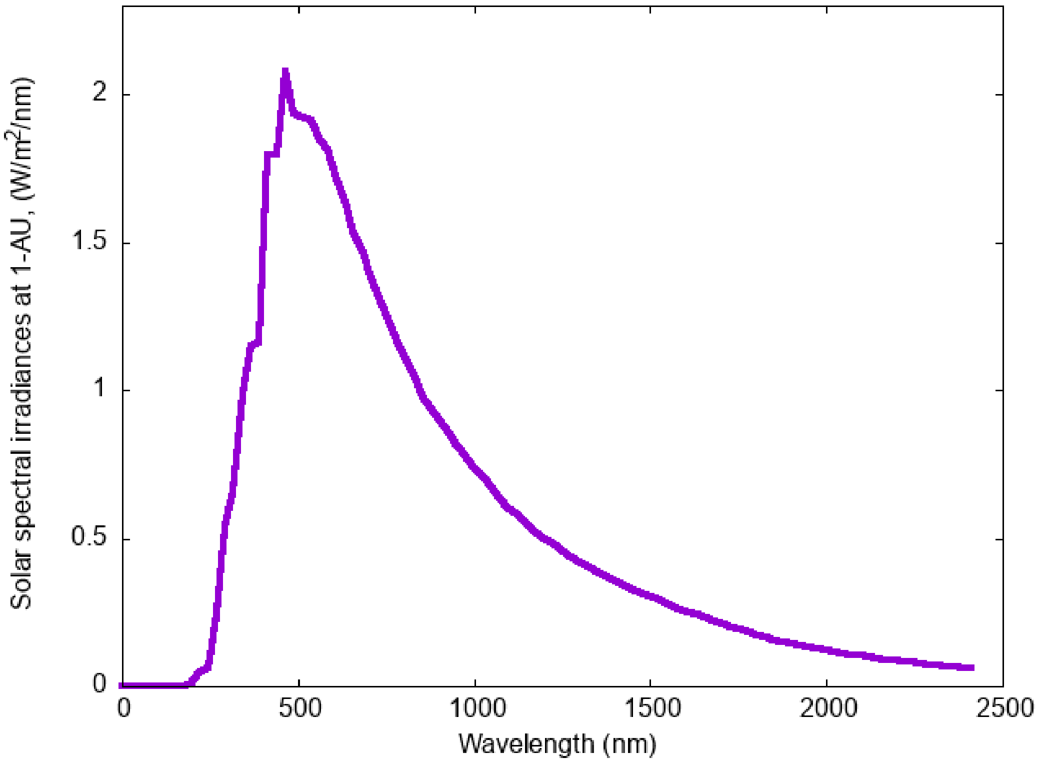

Figure 10: A graph of Spectral Solar Irradiance against the wavelength range

This graph shows that the Sun emits maximum radiation at a wavelength of approximately 500nm.

By using the Wien's displacement law as in equation (2), substituting the values into the equation gives a value of T as 5796 K. This value gives the temperature of the Sun's surface. Comparing the value obtained to the theoretical value which is 5778 K, the values do not show a big difference.

5.3 Climate variability results

5.3.1 Carbon dioxide concentration

To gain a better view of how the carbon dioxide concentration has been changing in the atmosphere, a graph of carbon dioxide concentration for the period between 2003 and 2017 was plotted and displayed as in the figure (11).

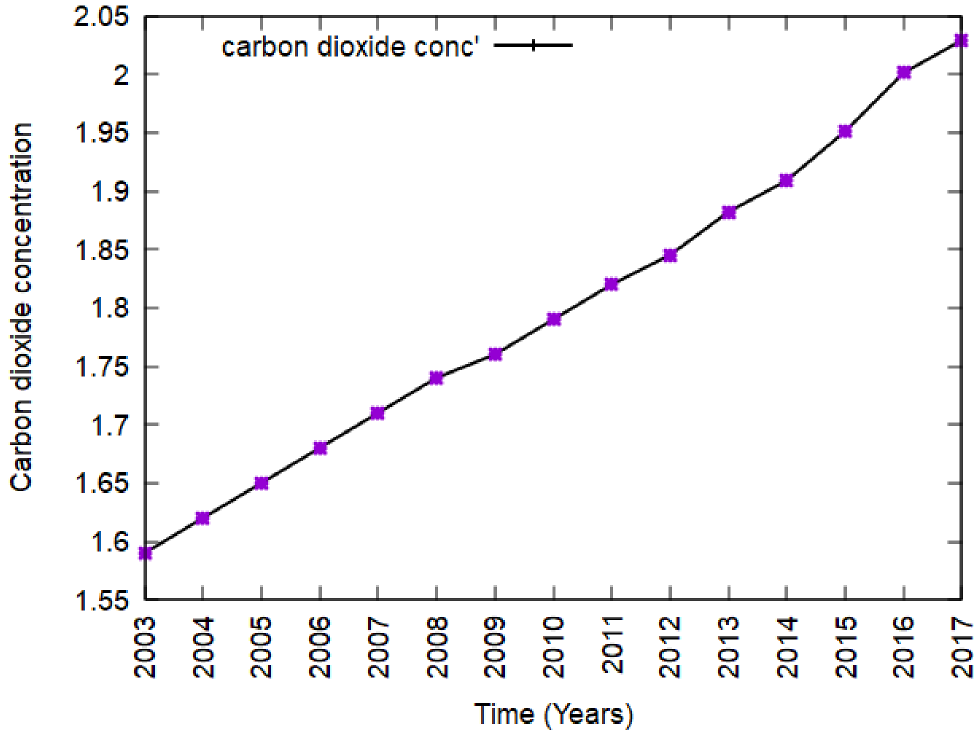

Figure 11: A graph of carbon dioxide concentration for the years 2003-2017

The graph shows that the carbon dioxide concentration in the atmosphere has been constantly increasing. To better understand the trend, a linear fit was made on the graph and the resulting graph was plotted as shown in figure (12).

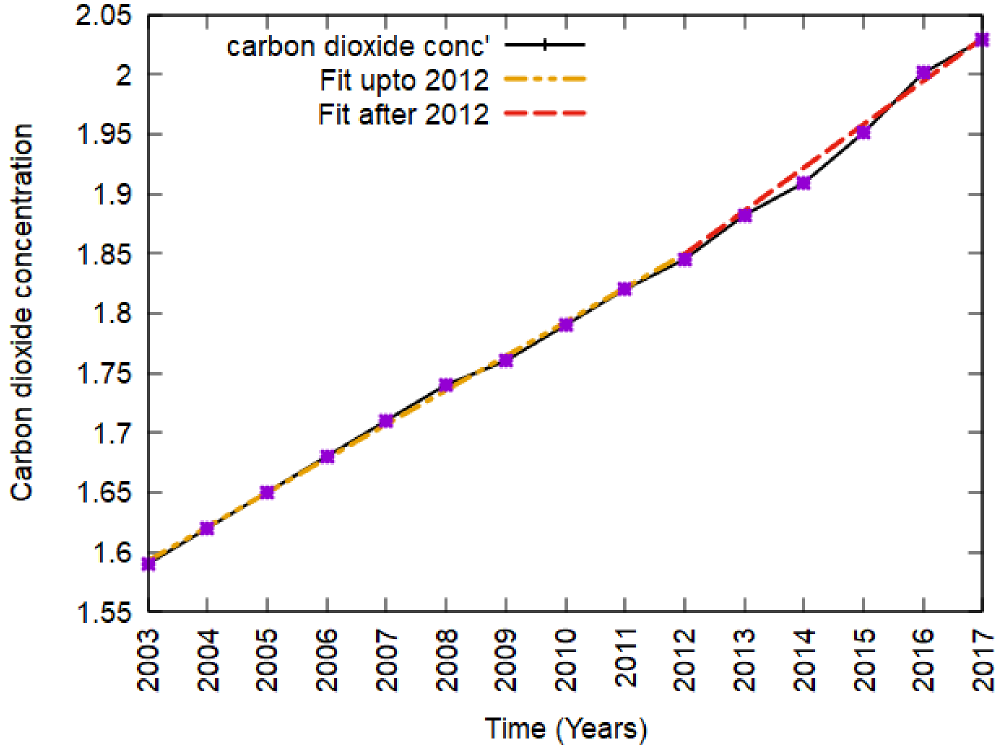

Figure 12: A graph of carbon dioxide concentration for the years 2003-2017 fitted with linear fit.

From the graph, the linear fit of up to 2012 indicates a change of the carbon dioxide concentration at a steady rate of 0.0286 per year, this value is obtained from the final set of parameters produced by GNU-plot. However, the linear fit after 2012 indicates an increased rate of change of carbon dioxide concentration to a rate of 0.03059.

This is an alarming trend since carbon dioxide is a greenhouse gas that has an effect directly on the climate by altering the concentration of the ozone layer and acts as a blanket that traps the emitted radiant heat energy from the Earth which in turn leads to global warming.

5.3.2 Global temperature anomalies

To better understand how the global temperatures have been varying in the past 17 years, a graph of global land and ocean temperature anomalies against time for the period 25th Feb,2003 and 25th Feb, 2020 was plotted as in figure (13).

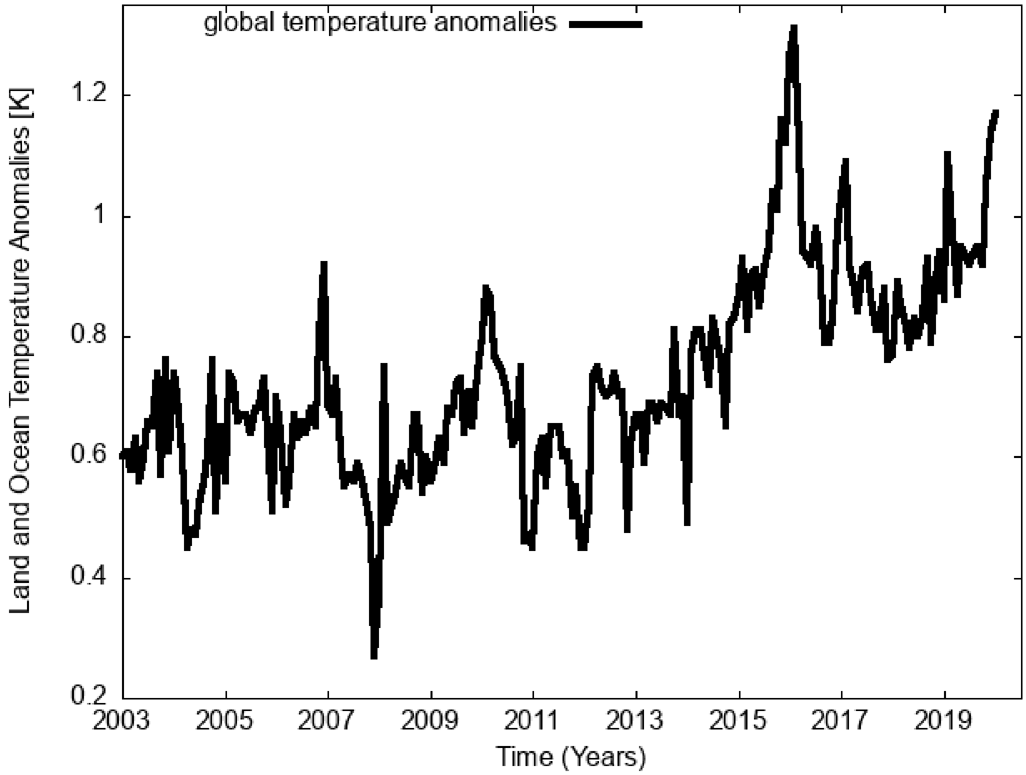

Figure 13: A graph of global temperature anomalies over the 17 years.

In order to show the general trend of the change of the global temperatures, smoothing technique was applied as well as a linear fit made and the result was plotted and displayed as in figure (14).

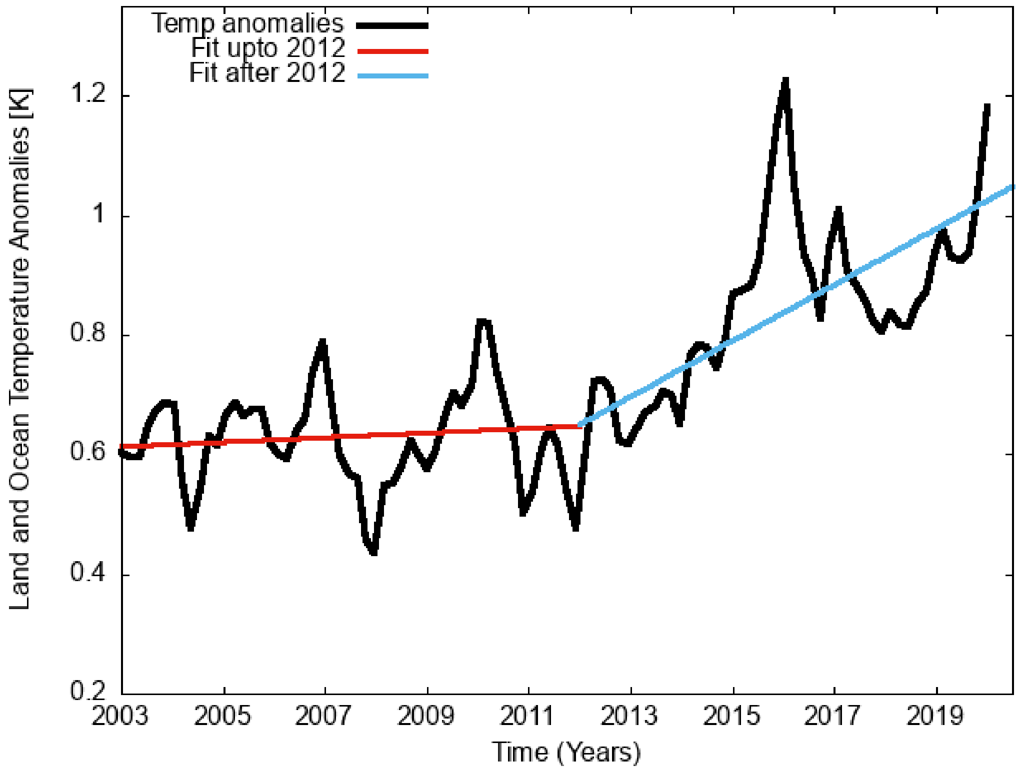

Figure 14: A graph of global temperature anomalies with linear fit.

This shows that on average, the trend of the global temperature anomalies has been rising over the entire period of 17 years.

Up to the year 2012, the change of the global temperatures is observed to have a minimal change at a rate of 0.00032 K per year as obtained from the final set of parameters produced by GNU-plot. However, after the year 2012, the change is observed to rise steadily at a rate of 0.0039 K per year.

From the trend observed, one can predict that the temperatures will continue to rise for the years or decades to come. This will have an impact on the climate in ways such as observed change of precipitation pattern and more drought and heat waves as the summer temperatures will continue to rise which may in turn lead to reduction of soil moisture.

5.3.3 Global temperature anomalies of the northern hemisphere

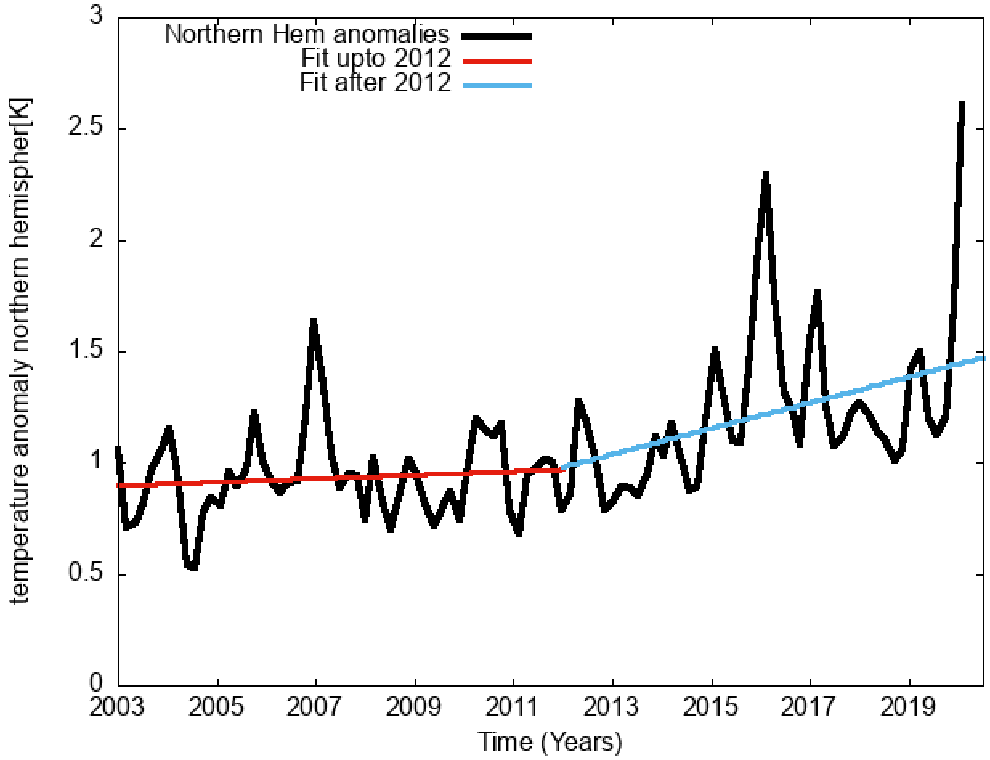

Figure 15: A graph of global temperature anomalies of the northern hemisphere for the 17 years with linear fit.

From the graph, a similar trend is observed for the change in northern hemisphere anomalies as that of the global temperature anomalies.

Up to the year 2012, the change of the northern hemisphere anomalies is observed to have a minimal change, at a rate of 0.000664225 K per year as obtained from the final set of parameters produced by GNU-plot. However, after the year 2012, the change is observed to steadily rise at a rate of 0.00481963 K per year.

5.3.3 Global temperature anomalies of the southern hemisphere

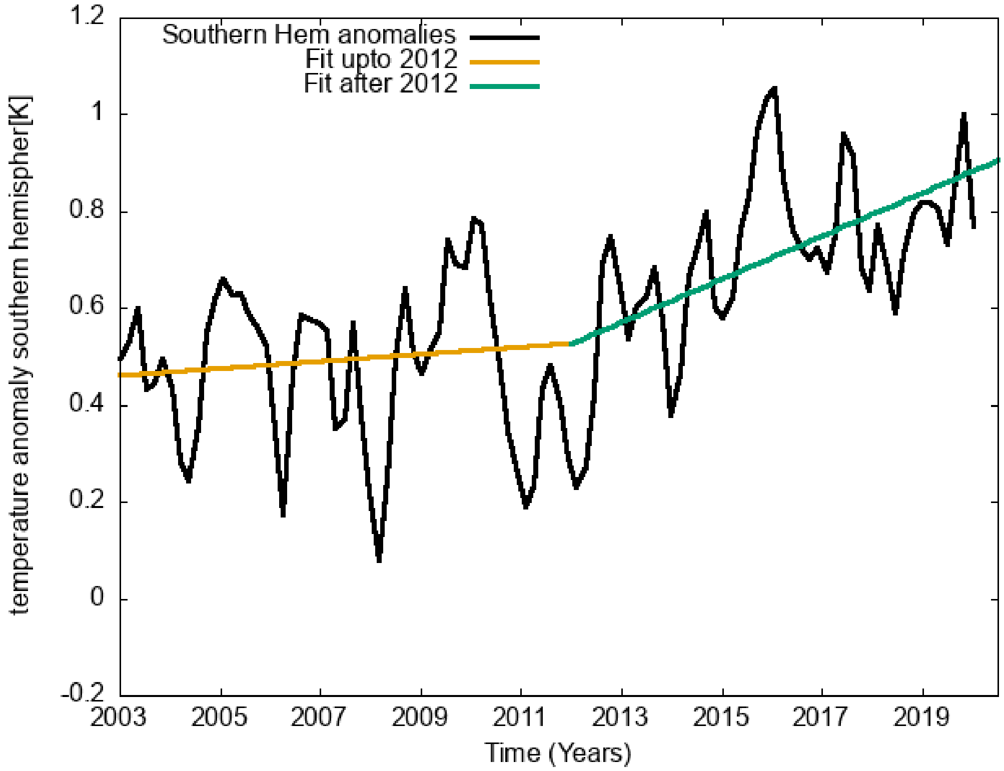

Figure 16: A graph of global temperature anomalies of the southern hemisphere for the 17 years.

The graph shows a similar trend as that displayed by both the global temperature anomalies and of the anomalies of the northern hemisphere.

Up to the year 2012, the change of the global temperatures is observed to have a minimal change, which is at a rate of 0.000622588 K per year as obtained from the final set of parameters produced by GNU-plot. However, after the year 2012, the change is observed to steadily rise at a rate of 0.00371248 K per year.

5.3.4 Global temperature anomalies of both hemispheres

A graph to show the relationship between the temperature anomalies of the two hemispheres was plotted and displayed as in figure (17).

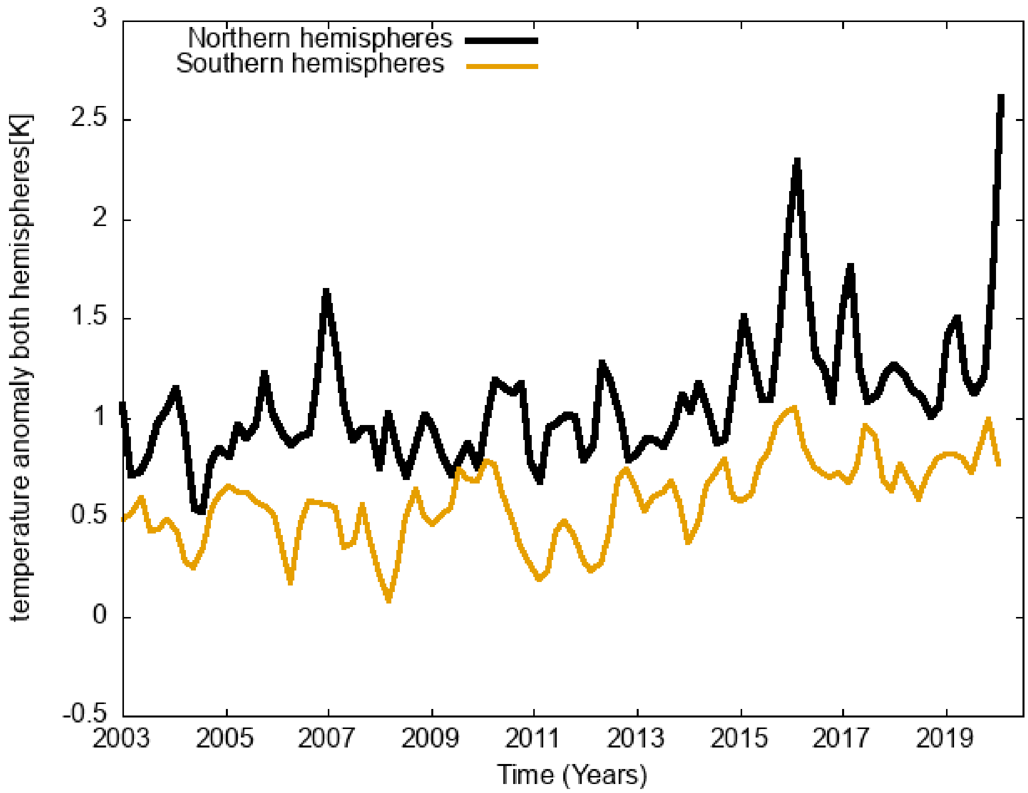

Figure 17: A graph of global temperature anomalies of both hemispheres for the 17 years.

From the graph, it can be observed that both hemispheres indicate a similar trend over the 17-years period although the northern hemisphere records higher temperature anomalies compared to the southern hemisphere. This difference in temperatures is as a result of the northern hemisphere having much more land mass which loses heat quickly in comparison to the southern hemisphere which has less land mass.

5.4 Solar variability and climate change

5.4.1 TSI and Sunspot numbers

To get a better understanding of the correlation between the TSI and sunspot numbers, a multiplot graph was plotted and displayed as in figure (18).

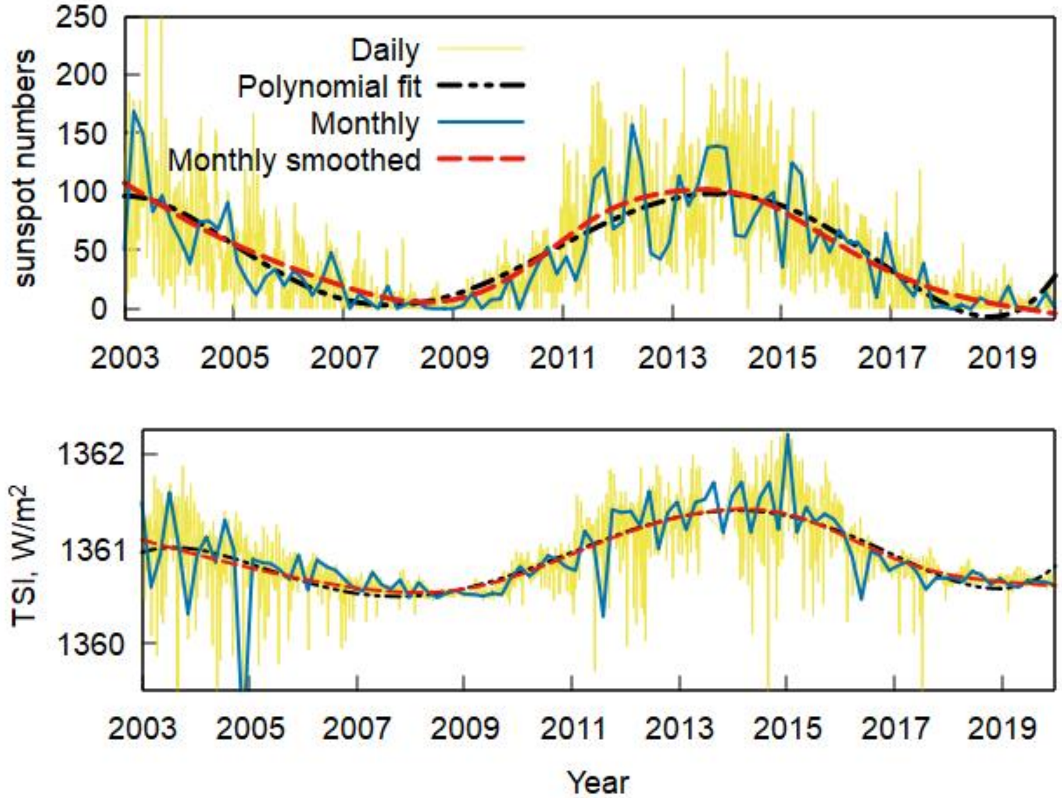

Figure 18: A graph showing the comparison TSI and Sunspot number

The graph shows that the TSI and the Sunspot numbers are positively correlated although the TSI lags the sunspot numbers. In the years 2008 and 2009, both the TSI and the Sunspot numbers were minimum, this indicates that the Sun's activity was at minimum during this period and maximum in the years 2014 and 2015.

Since sunspots are marked by intense magnetic activity, that is, the intensifying of magnetic field results to the rise in the number of sunspots. The difference of the magnetic field in sunspots is the probable cause of the lag which is about 29 days, roughly a period of one solar rotation.

5.4.2 Global temperature anomaly and carbon dioxide concentration

To gain a better view of the relationship between the trends of carbon dioxide and the global temperatures anomalies, a multiplot was plotted and displayed as in figure (19).

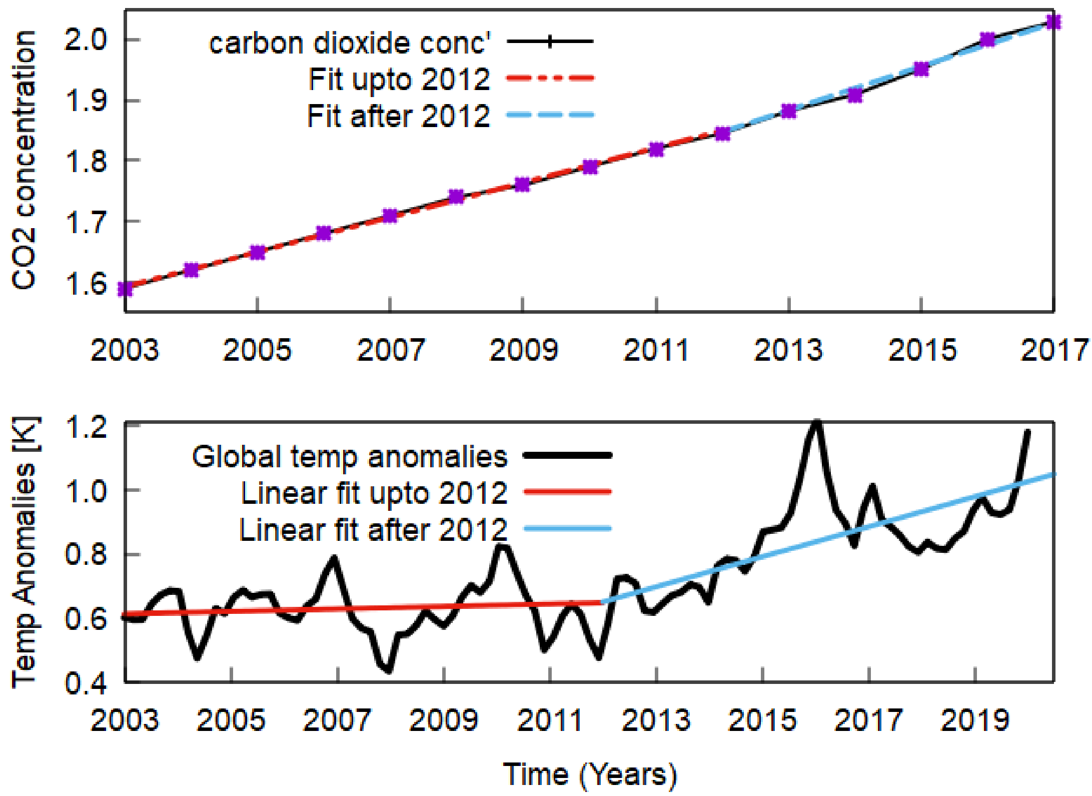

Figure 19: A graph of global temperature anomalies against carbon dioxide concentration.

From the graph, both the carbon dioxide and the global temperature anomalies portray a similar trend. After the year 2012 both carbon dioxide concentration and temperature anomalies rise at a steady rate. This trend is in agreement with a report done by the National Oceanic and Atmospheric Administration (NOAA) which pointed out that the 2012 summer anomaly was unusually large. This trend is associated with the natural oscillations of the tropical Pacific Sea surface temperatures.

The long-term warming trend of the global temperature anomalies has conclusively been linked to the change of carbon dioxide concentration and the other greenhouse gases. Since carbon dioxide is a greenhouse gas, it takes up and emits heat. When the land and ocean surfaces are heated by the sunlight, they continuously emit radiant heat which is absorbed by the greenhouse gases and release it slowly over time. They have an effect on the climate as they act as a blanket when they trap the emitted radiant heat hence, preventing it from getting back to the space, which in turn results to rise of the global temperatures.

5.4.3 Temperature anomalies and TSI

To gain a better view of the correlation between the global temperature anomalies and the variation of TSI over the past 17 years, a multiplot graph was plotted and displayed as in figure (20).

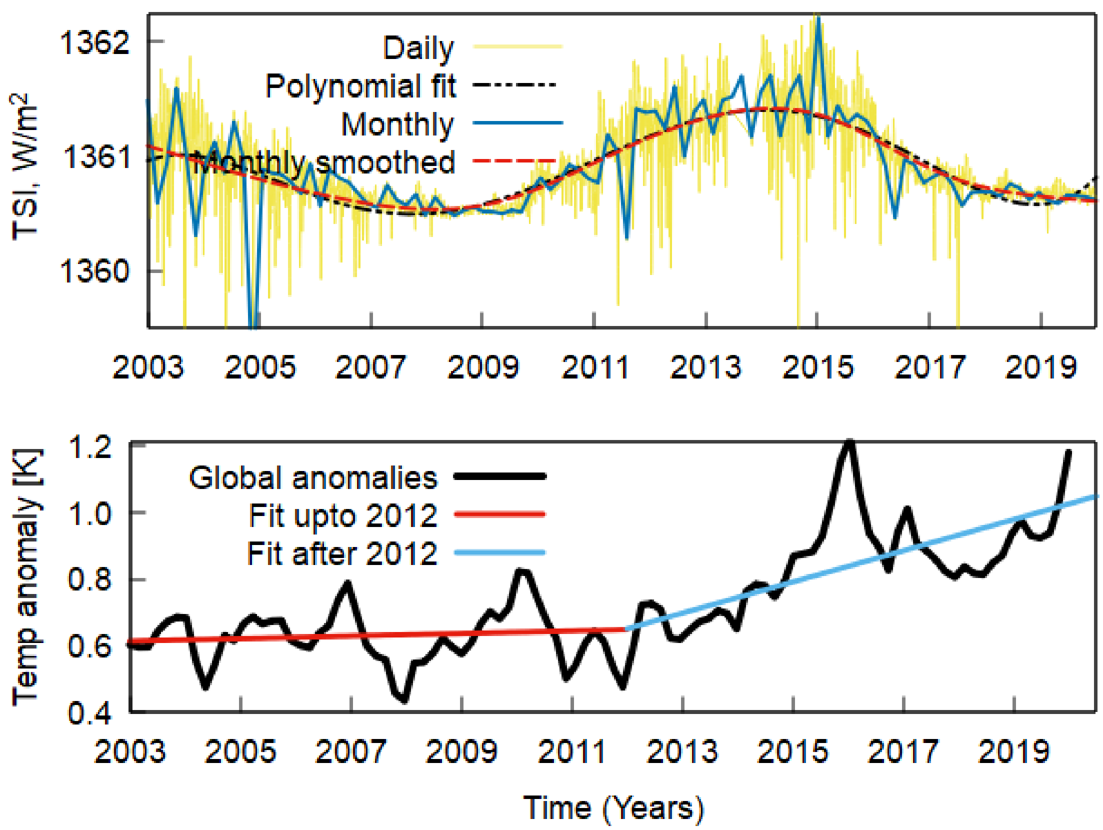

Figure 20: A graph of global temperature anomalies and the TSI

From the graph, a correlation is observed in the year 2008 as global temperatures indicate a reduction which corresponds to a reduction of the TSI in the same year, during solar minimum. Another correlation is observed in the year 2016 as the global temperatures indicate a rise as the TSI is at maximum, during solar maximum. However, the temperature anomalies indicate a rise in the years after 2018 when the TSI shows a reduction towards minimum.

It can therefore be deduced that a percentage of the temperature variations can be explained by the action of TSI changes. Although these variations of temperature anomalies cannot be completely attributed to TSI as other factors may likely have an influence since the trend is observed to be rising on average while the TSI variations indicates a balanced trend.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this research project, 17 years data from SORCE has been used to show the observed variability of the Sun while climate data from CRU has been used to show the climate change. The data was analyzed using GNU-plot and python, and the resulting graphs of total solar irradiance and of sunspot numbers were fitted with a theoretical model which is in agreement with a polynomial of order five. The graphs of TSI, sunspot numbers, effective temperatures and Sun's luminosity were all observed to vary with a period of 11 years which is equivalent to one solar cycle.

The correlation linking solar variability and Earth's climate was then sought and concluded that the climate responds to solar variability as observed from the graph of global average anomalies which changes in phase with solar activity, although, it is not possible to fully assign the trend of global warming to solar variability since other factors may be contributing to the climate change.

However, comparing the temperature anomalies of the northern and southern hemispheres, it was observed that the northern hemisphere records higher temperatures than the southern hemisphere which is attributed to the northern hemisphere having much more land mass which loses heat quickly.

6.2 Recommendations

From this research, we recommend that further advances in understanding of the solar variability and its effect on climate will be of importance for longer time-scales as well as seeking of geographical variations. Care also needs to be taken as factors other than the Sun's variability may have an influence on the climate change, for example occurrence of events like volcanic eruptions.

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