Ascendancy of Solar Variability on Terrestrial Climate: A Review

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Abstract: In the present paper, we have briefly reviewed the impact of solar activities on the terrestrial climate. Increased/decreased solar activity affects the various processes going on into the Sun-Earth system and alters the composition of parameters responsible for the climate change. The amount of high solar activity (sunspots) is directly related with the total solar irradiance (TSI) while the spectral index is associated with the ultraviolet (UV) radiations coming from the Sun. Contrary to the above, decreased solar activity is accountable for increased incidence of the galactic cosmic rays (GCR) which play significant role in cloud formation and ultimately responsible for the changed climate conditions of terrestrial environment. The influence of solar variability on the Earth's climate can be explained by exploring various mechanisms involved. There are no fool proof evidences that the solar variations are a major factor in driving recent global climate change but there are considerable evidences of solar influence on the climate of particular regions as well as throughout the terrestrial environment. During high solar activity, higher temperatures and larger ozone concentrations are observed in the tropical stratosphere. The solar influences on the Earth's climate mainly includes; the changed occurred due to variations in the Sun's radiant output (TSI and UV) and the changes occurred due to the Sun's influence on the energetic particles reaching to the Earth (Solar Energetic Particles, Galactic Cosmic Rays). Following the above regime, we have provided the evidences for the existence of physical links between solar activity and terrestrial climate. Summary of our present understanding of the mechanisms involved in the Sun-climate dynamics are presented.

Keywords: Solar activity, Total solar irradiance, Solar energetic particles, Terrestrial atmosphere, Climate change.

1. INTRODUCTION

The Sun is the most prominent driving force of terrestrial climate and affects our planet in various ways on time scales of minutes to millennia. We are progressively trying to understand that how the terrestrial climate system reacts to these changes of solar forcing [1-9]. Though it is known fact that the radiative forcing (~ 2.83 watts per square meter) due to heat trapping gases is 56 times greater than the increase in radiative forcing (~0.05 watts per square meter) from the solar energy [8]. Herschel [10] was first who speculated that small variations in the Sun can play decisive role in the variability of the terrestrial climate and this was followed by various researchers who presented evidences and significant correlations for the same [11, 12]. To explain the influence of changing solar activity on the climate, three major mechanisms have been proposed till date. The first mechanism is the variations of the total solar irradiance (TSI) that leads to the changes in the direct energy input into the Earth's atmosphere [13, 14]. The second mechanism involves the variations in the spectral solar irradiance (SSI) causing variations in stratospheric chemistry and dynamics primarily because of UV irradiance [15, 16] and the third mechanism deals the variations in solar wind modulating cosmic ray flux [17] and/or the cloud coverage [18]. Two out of three mechanisms, i.e., the TSI and the SSI are associated with the sunspot numbers while the third one is associated with low solar activity, i.e., modulation of cosmic rays. Figure **1** has depicted the sketch of various forcing involved in the Sun-Earth climate system.

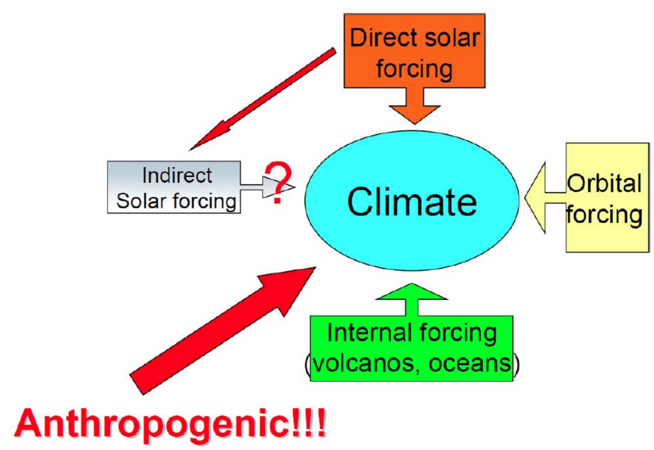

Figure 1: A schematic view of the climate forcing where question mark represents the indirect solar forcing which are not yet clearly understood.

Total solar irradiance (TSI), the radiative power density (Wm^{-2}) at normal incidence on top of the atmosphere at Sun-Earth distance (1AU) is called solar constant and being observed regularly since 1978 [18, 19]. The TSI varies over timescales of minutes to decades and even longer [14] but the most noticeable variation is of 0.1% modulation accordance with the solar activity/sunspot cycle. The total solar radiation that reaches to the terrestrial atmosphere depends on

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various factors, viz. energy production of the Sun in the core, energy transport through the Sun's radiative/convective zone, emission of radiation from the photosphere and the distance between the Sun and the Earth [20]. The total solar irradiance (TSI) which is basically the spectrally integrated radiative power density of the Sun incident on terrestrial atmosphere is being monitored continuously since 1978 [18, 21, 22]. The changes in the total solar irradiance (TSI) incident on the Earth's atmosphere can produce imbalances in the radiation budget of the Earth which further induces temperature shifts in terrestrial environment [23, 24]. Observations have revealed only about 0.1% variation in the total solar irradiance during last four decades with solar activity cycles [23, 25, 26]. Though the amount of changes in the total solar irradiance is very small (0.1%) to have a significant impact on the climate, yet there is growing evidences that, on the longer time scales, solar variability is much more pronounced and the climate system is much more sensitive to the solar forcing due to feedback mechanisms [6]. Data from the satellite based measurements over the past few decades have revealed a clear correlation between the solar irradiance and the solar activity parameters based on the 11-year cycle [27]. Further, changes over an 11-year cycle in step with the variations of sunspots amplitude of nearly 0.1 percent and this variation can have considerable imprecision in climate change records [23, 25]. This observation has further strengthened the impetus for theoretical research on the solar activity and various roles played by the Sun [28-30].

Solar activity and fluctuations in associated parameters influence both the interplanetary space and the geospace as a result of chain of processes involved. Figure **2** has shown the various chain of energy transfer involved in the Sun-Earth system. To mitigate the dangerous impact on the mankind, physical understanding of this chain of processes is essential which includes combination of observations, data analysis and interpretations and theoretical modelling [31]. Actually, the variation in energy flow changes the physical and chemical composition of the atmosphere and is responsible for the coupling of the Sun-Earth system and the climate change [6, 32]. The response of the climate system to changes in solar forcing depends not only on the intensity of the radiation, but also on its spectral composition, seasonal distribution over the globe and on feedback mechanisms connected with clouds, atmospheric water vapour, ice cover, atmospheric and oceanic transport of heat and other terrestrial processes. Because of their larger variability below 400 nm, the ultraviolet (UV) radiations play a key role in the change of terrestrial climate through radiative heating and ozone photochemistry [33]. Larger variations in UV emissions which arise from the chromospheres are observed [34] and which influence the stratosphere (10-50 km) [6]. Solar X-rays and extreme ultraviolet (EUV) emissions originated from the corona are some times more dominant and reach to the thermosphere (90km) [35]. The variability of visible and near-infrared bands reaching below 200 nm [36] and their impact on the Earth's climate is expected to be small, though it may involve amplification mechanisms [37, 38]. It can be interpreted as a result of effects induced by the evolution of surface magnetism in the solar atmosphere [39].

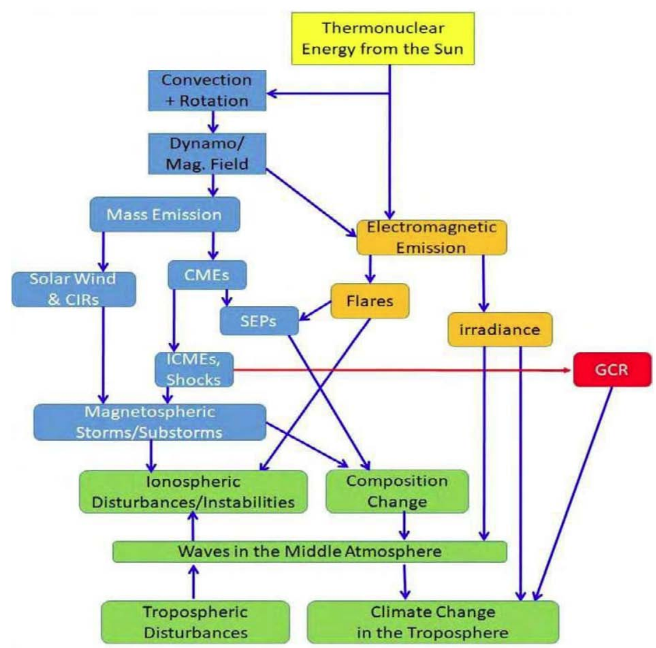


Figure 2: Chain of energy flows involved in the Sun-Earth system (Credit: http://www.issibj.ac.cn/Publications/Forum_Reports/201404/W020200522380996345108.pdf).

Apart from the above mentioned mechanism related with higher sunspot numbers, the Sun modulates energetic charged particle fluxes incident on the Earth [1]. Solar energetic particles (SEPs) incident upon the Earth's atmosphere in polar regions, enhances the destruction of stratospheric ozone [40, 41] while galactic cosmic rays (GCRs), generated from supernovae explosions, modulated by the Sun also reaches to the Earth and influences the terrestrial climate [42]. The cosmic ray flux reaching to the Earth surface is modulated by the strength of the solar wind and now proven fact that decrease in cosmic rays is because of the changes in the magnetic field geometry of the heliosphere and the bubble blown in the interstellar medium by the solar wind [18, 43]. Higher levels of solar activity lead to a decrease in the cosmic ray flux on the Earth and these are potentially implicated in climate change on the Earth [43]. Air ions generated by galactic cosmic rays enable Earth's global electric (thunderstorm) circuit [44] and modulate the formation of low-altitude clouds [45]. The influence of solar activity became more apparent when the winters were grouped according to the phase of the quasi-biennial oscillation (QBO) [46, 47]. Nearly 2 year oscillations of the Easterly and the Westerly zonal winds in the equatorial lower stratosphere are known as QBO [6, 48]. Some other relationships between proxies for solar activity and climate have been noted, including variations in ozone, temperatures, winds, clouds, precipitation, and modes of variability such as the monsoons and the North Atlantic Oscillation (NAO) [6]. There are some other indirect mechanisms which play their role in climate variability. Various types of indirect mechanisms have been proposed and most of them include amplification of the solar signal via positive feed-back of the solar total or spectral irradiation employing non – linear dynamical coupling between different parts of the climate system [6].

The present paper is divided in seven sections. Sections are organized on the basis of the climatic factors of interest. In each case, we define the manner in which the factor may have influenced terrestrial climate, provide an estimate for the characteristic time scales over which the factor is thought to vary, and give a summary of some of the research that has been done in relating this factor to climatic change, with an assessment of its likely importance. Spacecraft missions and ground-based observations have provided evidence that climatic changes have occurred on other objects in the solar system. Therefore, where relevant, we also consider the possible influence of the above factors for the climate variability.

2. THE SOLAR ACTIVITY

The earlier indication of solar variability came from the observation of sunspots in the seventeenth century [49-51]. However, it was the mid-nineteenth century when the 11 year cycle for sunspot numbers first recognized [52]. This may be associated with the fact that magnetic field originating in a dynamo action inside the Sun shows 11 year periodicity having maximum and minimum activities [53-55]. Understanding the role of variability in the solar activity is essential for the interpretation of its influence on the climate and for the future predictability of the climate change. High speed solar wind, solar flares, coronal mass ejections, prominences and solar energetic particles are the major solar transients responsible for variable solar activities [56-59]. Increased solar irradiance and decreased cosmic ray fluxes occur during greater solar activity [60].

2.1. Solar Wind

Solar wind emanates from the Sun are the low energy charged particles [61-64]. Since the solar wind plasma is highly electrically conductive, the solar magnetic field lines are dragged away by the flow and the wind attains a constant terminal speed, and its density then decreases radially in proportion to the square of the radial distance [65]. A small amount of the solar wind energy incident on the Earth is extracted by the geomagnetic field is responsible for changes in the behaviour of the thermosphere [66-68] which further changes the physical and chemical composition of the middle/lower atmosphere and ultimately contribute to the climate variations. The solar wind which consists of magnetized flares sometimes influences galactic cosmic rays (GCR) that may in turn affect the cloud cover on the Earth [69, 70]. As the Sun's output increases the solar wind shields the atmosphere from GCR fluxes, consequently the increased solar irradiance is accompanied by reduced low cloud cover, amplifying the climatic effect. Similarly when solar output declines, increased GCR fluxes enter the atmosphere, increasing low cloudiness and adding to the cooling effect associated with the diminished solar energy [71, 72].

2.2. Solar Flares

Solar flares, intense burst of radiation caused by the mechanism of tearing magnetic loops of instability and reconnection of the magnetic field lines in the Sun's chromospheres, release enormous magnetic energy across the electromagnetic spectrum varied from radio waves, to x-rays and gamma rays [73-77]. The increased level of x-ray and extreme ultraviolet (EUV) radiation results in the ionization of the lower layers of the atmosphere of the Earth specially the D-region [78-80]. The D-RAP (D-Region Absorption Prediction) product correlates flare intensity to D layer absorption strength and spread [79]. Solar flares usually take place in active regions, which are areas on the Sun marked by the presence of strong magnetic fields typically associated with sunspot groups [81]. Solar flares cause disturbances in geomagnetic field which further affect the terrestrial environment and human infrastructure. Strong geomagnetic storms increase the level of radiation hazard in the Earth environment and generate irregularities in ionospheric density [82].

2.3. Coronal Mass Ejections (CMEs)

The outer solar atmosphere (corona), structured by strong and closed magnetic fields with confined sunspot groups, can suddenly and violently release bubbles of gas and magnetic fields called coronal mass ejections (CMEs) [65, 83, 84]. CMEs, sometimes may be associated with flares and sometimes can occur independently, determine the state of the Earth's geomagnetic field in significant ways and greatly impact the Earth's upper, middle, and lower atmospheres and even on the surface. CMEs can induce abnormalities in and can damage modern systems, including economic systems, affecting the entire modern societal infrastructure and terrestrial environment [82]. Details of the source region are usually obtained using non-coronagraphic observations such as in X-rays, EUV, microwaves, and H-alpha [83, 85]. Photospheric magnetograms show that the CMEs source regions have generally enhanced magnetic fields compared to the quiet sun regions. It is believed that free energy can be stored in the coronal field lines which are then released in the form of CMEs [86]. A large CME contain billion tons of matter that can be accelerated to several million miles per hour in a spectacular explosion [87, 88]. Solar material streams out through the interplanetary medium, impacting any planet or spacecraft in its path as well as the terrestrial atmosphere [89]. Based on the initial speed of the CME and the ambient solar wind speed it takes 1-5 days to reach at the Earth [90]. The relative speed of CME with respect to preceding solar wind exceeds the local magnetosonic speed, a fast forward shock wave forms ahead of the CME and in that case a turbulent region of piled up magnetic field and compressed plasma develops between the shock and the CME [86, 91]. Short- or long-term service disruptions may spread from a directly affected system to many other systems due to dependencies and interdependencies among, for example, electric power supply, transportation and communications, information technology, etc.

2.4. Solar Prominences

Solar prominences, large, bright feature extending outward from the Sun's surface, are the other transient which provide impetus for increased solar activity [92, 93]. The prominence plasma flows along a tangled and twisted structure of magnetic fields generated by the Sun's internal dynamo. These are formed over timescales of days to months looping hundreds of thousands of miles into space. An erupting prominence occurs when such structures become unstable and bursts outward releasing the plasma [94, 95]. Similar to the Sun, prominence material is made almost completely of Hydrogen and Helium [96, 97]. Prominence properties depend upon the environment where they form and in particular upon the magnetic field below them. Filaments are always found above the neutral lines separating opposite polarities of the photospheric magnetic field called polarity inversion line (PIL). The filament width, length and shape follow and adapt to the extension of the neutral line. The extension of the PIL depends upon the strength and distribution of the local magnetic field so that filaments and the local magnetic field are closely interrelated. Since PILs can be found almost everywhere on the Sun, so can prominences, particularly during the maximum of the solar cycle [98, 99].

2.5. Solar Energetic Particles (SEP)

Solar energetic particles (SEPs) are another important source of radiation that affects the terrestrial atmosphere [100, 101]. SEPs consist of electrons, protons, and heavier nuclei that are accelerated to high energies and travel along IMF lines and through interplanetary space. SEPs radiation can penetrate deep into the atmosphere and initiate chemical reactions and in particular lead to the depletion of the ozone layer, which protects the Earth from the damaging effect of ultraviolet radiation. In the middle mesosphere at the height of 55 km, the content of atmospheric ozone can be reduced by 70% [102]. Solar flares and CME-driven interplanetary shocks are two main locations where energetic particles are accelerated. Particles accelerated at flares are known as impulsive SEP events, whilst those accelerated by shocks are called gradual SEP events. When gradual SEPs event are detected near the Earth, they are known as energetic storm particle (ESP) events [103-106]. Magnetic reconnection is responsible for the impulsive release of magnetic energy in the form of SEP [107]. The magnetic reconnection at the flare location is believed to heat the plasma and accelerate electrons along the IMF lines. The peak intensities and spectral shapes for a gradual SEP event are usually related with the strength of the CME shock [108, 109]. Further particles associated with SEP events, in some cases can be detected at locations widely separated in latitude and longitude [110-112].

Association between SEP events and solar activity observations suggest that SEP events are less likely to be associated with confined and eruptive solar activity [113]. Few SEP events are found to be associated with CMEs [114]. Sophisticated statistical methods suggest that SEP peak intensities are correlated significantly with both CMEs speed and flare parameters, especially soft x-ray fluence [100, 115-118].

3. SOLAR VARIABILITY AND SPECTRAL IRRADIANCE

Variability of the Sun plays a key role in the observations of total solar irradiance (TSI). The TSI is the solar electromagnetic power, integrated over all wavelengths and per unit cross sectional area, reaching to the Earth. Because TSI instruments have a limited lifetime, data from different instruments have been 'daisy-chained' together to estimate the long-term variation (now covering more than three solar cycles), which requires inter-calibrating the instruments using intervals when both were in operation. Historically, there have been three main data composites that have been in widespread use: (i) TSI_{PMOD}, generated and maintained at Physikalisch-Meteorologisches Observatorium Davos (PMOD); (ii) TSI_{RMIB}, produced at the Royal Meteorological Institute of Belgium, RMIB and (iii) TSI_{ACRIM}, generated using data from the series of three Active Cavity Radiometer Irradiance Monitor (ACRIM) instruments [14, 119, 120]. Figure **3** shows the TSI variations observed by various instruments over the period 1995 to 2020. The PMOD composite mainly comes from the Variability of Solar Irradiance and Gravity Oscillations (VIRGO) measurements, which are a combination of instruments on the SOHO spacecraft, with small data gaps filled in using ACRIM-2 data [121, 122]. The ACRIM composite comes from the ACRIM-2 and ACRIM-3 instruments and the RMIB composite comes from the DIfferential Absolute RADiometer (DIARAD) instrument on SOHO and the SOlar Variable and Irradiance Monitor (SOVIM) instrument on Eureca-1. TSI data for the above mentioned period are also provided by the Total Irradiance Monitor (TIM) instrument on the SOlar Radiation and Climate Experiment (SORCE) satellite [123], by Total Solar Irradiance Calibration Transfer Experiment (TCTE) which operated from November 2013 to June 2019 on board the US Air Force Space Test Program spacecraft STPSat-3, from the PREcision MOnitor Sensor (PREMOS) [124] and SOVAP instruments [125] on the Picard satellite. In addition, a new data composite, the Community

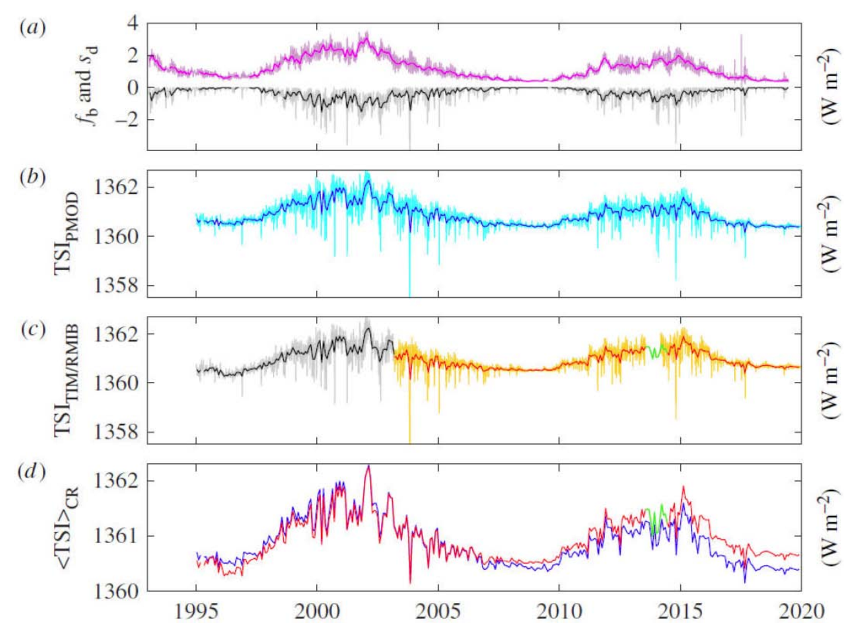


Figure 3: Total solar irradiance (TSI) variations during the period 1995 - 2020 where panel (**a**) indicates the SATIRE (Spectral And Total Irradiance REconstructions) reconstructions of two contributions to TSI (the integrated facular brightening (f_b) shown in violate and sunspot darkening (s_d) in grey). Panel (**b**) in the figure represents the PMOD (Physikalisch-Meteorologisches Observatorium Davos) composite of TSI observations of TSIPMOD (daily means in cyan and CR means in blue). Panel (**c**) of the figure shows the RMIB (Royal Meteorological Institute of Belgium) composite of TSI observations (TSIPMOD) splined with data from the TIM (Total Irradiance Monitor) on the SORCE (SOlar Radiation and Climate Experiment) satellite. Panel (**d**) has represented the comparison of means of two observation series: PMOD composite (in blue) and the RMIB/TIM spline (in red) (Figure is adopted from Lockwood and Ball [145].

Composite, has been developed which uses maximum-likelihood techniques to give the variation of the best estimate and its uncertainty over time [123].

Observation indicates that variability in the TSI arises almost entirely from the distribution of sizes of the patches where magnetic field threads through the photosphere [6, 7, 126]. The emergence of the solar magnetographs has revolutionized our understanding about changes over the solar cycles [127]. Theory of how the photospheric magnetic fields influence the TSI has been developed [128]. Quantifying of such small variations is a major technological challenge and is strongly motivated by the desire to understand solar variability and TSI/SSI to understand the terrestrial energy budget [129]. The TSI is the spectral integral of the SSI over all wavelengths but its weak variability masks the fact that relative SSI variations show strong wavelength dependence. Figure **4** shows the spectral distribution of solar radiation and its variability. Upper panel (a) in red line has shown the amount of solar electromagnetic radiation (milliwatts per square per nanometer wavelength) that falls on the top of the Earth's atmosphere compared with the relative amount of radiation (dashed blue line). The lower panel (b) of Figure **4** has indicated the percentage variability of solar radiation in these wavelengths. In the visible and near-infrared spectrum the variation is at most about 0.1%, and only slightly more in the far infrared. Figure also indicates that the highest variation is not surprisingly found in the short-wave radiation that emanates from the Sun's more volatile upper atmosphere [130].

The Upper Atmosphere Research Satellite (UARS) spacecraft provided the longest records of SSI measurements by SOLar STellar Irradiance Comparison Experiment (SOLSTICE) and Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) instruments [131, 132]. These instruments recorded the solar UV radiation between 120 and 400 nm during 2001-2005 [36, 131, 133], although the solar cycle variability of solar radiation above approximately 250 nm remained relatively uncertain due to insufficient long-term stability of the instruments [134]. Merging all UV observations into a single homogeneous composite record is a major challenge [135] that is hampered by several problems. The lifetime of most instruments does not exceed a decade which makes things very difficult and unable in long term observations which is

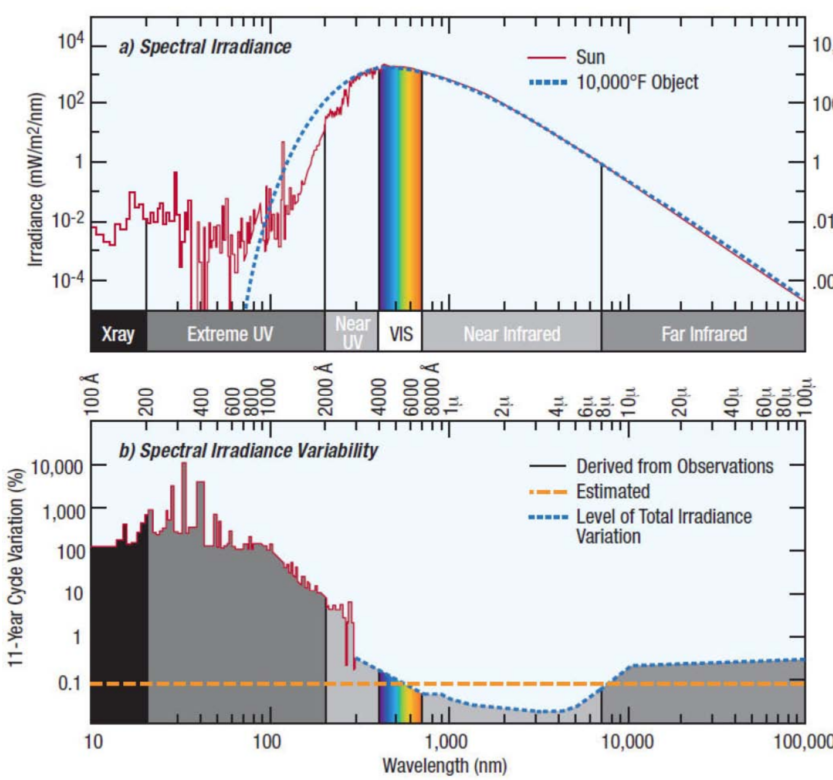


Figure 4: Spectral distribution of solar radiation and its variability where panel (**a**) shows the amount of the spectral irradiance (in milliwatts per square per nanometer wavelength) for different wavelengths that falls on the top of the Earth's atmosphere compared with the relative amount of radiation (dashed blue line). Where panel (**b**) shows the percentage variability of solar radiation in these wavelengths; Source: Eddy, [130].

of prime interest for climate models. Other obstacle is the changing technologies and modes of operation of various space-based instruments [23, 136-138]. The most critical challenge for the SSI instruments is the optical degradation caused by the energetic radiation into the space environment [139, 140]. There is no consensus on the amplitude of historical solar forcing. The estimated magnitude of the total solar irradiance (TSI) difference between the Maunder minimum and the present time ranges from 0.1 to 6 W m^{-2} making the simulation of the past and future climate uncertain. Egorova *et al*. [141] have implemented the new quietest Sun model and found that the relative solar forcing compared to the largest previous estimation have increased about 25-40 % between the Maunder minimum and the present.

Comprehensive reviews of the potential influences of solar variability of climate have been presented in recent years by Gray *et al*. [6], Solanki *et al*. [142] and Owens *et al*. [143]. The one factor that has not been discussed much in those reviews is potential variations in the quiet-Sun contribution to total solar irradiance (TSI). The term 'quiet Sun' refers to the relatively featureless areas of the visible solar surface (the photosphere) where there is no detected magnetic field threading the surface that can alter the emission of the surface; hence, it is the part of the solar surface that is separate and distinct from any magnetic features such as sunspots, active region faculae, network faculae and ephemeral flux. We have very little reliable information on variations of the quiet Sun, but recent papers postulating their existence have derived significant solar radiative climate forcings [141, 144]. It should be stressed that neither the postulated quiet- Sun irradiance variations nor the causal magnetic fields have, as yet, been detected. Recently Lockwood and Ball [145] have studied the quiet-Sun TSI since 1995 and they have shown that the most likely upward drift in quiet-Sun radiative forcing since 1700 is between +0.07 and −0.13 Wm^{-2}. Hence, we cannot yet discriminate between the quiet-Sun TSI being enhanced or reduced during the Maunder and Dalton sunspot minima, although there is a growing consensus from the combinations of models and observations that it was slightly enhanced.

4. SOLAR ACTIVITY AND TERRESTRIAL CLIMATE

There are many ways that small fluctuations in solar activity can affect the terrestrial climate but their nature has various complications. The TSI shows the association with sunspots while the SSI has resemblance with 10.7 cm spectral index while the solar energetic particles and cosmic rays can reduce ozone levels in the stratosphere and in turn alters the behaviour of the lower atmosphere. A persistent correlation has been seen among solar cycles, carbon dioxide (CO_2) and surface temperature since last century. Figure **5** shows the variation of sunspots, CO_2 and the surface temperature of about 170 years which clearly reveals the changes in these parameters with time. Christoforou and Hameed [146] have shown the correlations of the solar cycles and surface pressure and temperature in some regions of the Pacific. Sometimes solar cycle interacts with various oscillations within the climate system at decadal scale [147]. Solar activity could favour some synoptic regimes that favour the advection of polar cold air over Western Europe [148]. It is not possible to establish a simple quantitative relationship between climate changes in the past and the solar variability. There is, however, growing evidence that periods of low solar activity coincide with the advance of glaciers, changes in lake levels and other significant environmental changes. These findings indicate that the Sun played an active role in past climate changes in concert with other geophysical climate forcing factors such as volcanic eruptions, greenhouse gases and internal variability of the climate system.

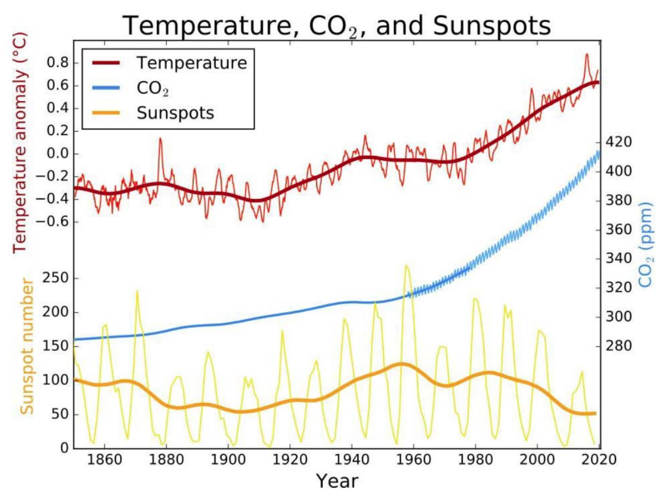


Figure 5: Cycle wise variations in sunspot numbers, concentration of CO_2 and surface temperature anomaly (Source: https://commons.wikimedia.org/wiki/File:Temp-sunspot-co2.svg).

The mechanism involved into the physical and chemical processes is the strong absorption of ultra-violet radiation by the ozone cycle which heated the air and modulates the temperature gradients of the region [149]. During a solar cycle, the relative variations in ultra-violet radiation are 10 to 100 times larger than the variations in total solar irradiance [150, 151]. This variation in ultra-violet radiations impacts on the stratosphere and affect the intensity of the Arctic polar vortex during winter season and ultimately affects the lower troposphere at high/mid-latitudes [46]. The radiation of the Sun is modulated during the solar activity and also the flow of energetic particles get modulated which penetrate the Earth's atmosphere [152]. Solar modulation of the flow of energetic particles has a very limited direct climatic impact, but a very strong amplification can exist with galactic cosmic rays control on cloud formation. Radiative fluxes in the range of visible and infrared wavelengths also play role on heat exchange into the clouds in the climate system. The various proposed correlations between energetic particle fluxes and cloud cover are still highly debated issues [153]. Recent observations have shown a small but detectable contribution of the solar activity to the surface temperature variations on various scales. The contribution of strong volcanic eruptions to the temperature variations has increased effects at decadal and even centennial scales [154].

4.1. Total Solar Irradiance (TSI) and Climate Connections

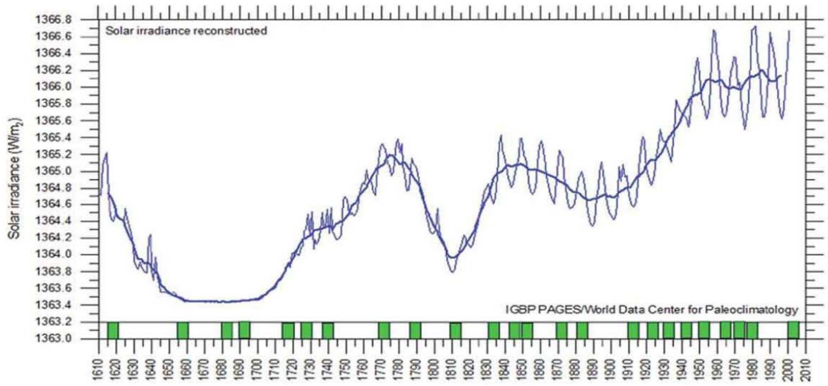
Many observational studies have found the TSI influences on climate on various timescales [155, 156]. There are some evidences that the TSI variations are a major factor in driving recent global climate change. The Sun has impact on the lower atmosphere, at the surface of the Earth and into the ocean [157]. The total solar irradiance (TSI) is actually the total energy of the Sun integrated over the whole spectrum and normalized at 1AU and being monitored continuously by the spacecraft NIMBUS 7 since year 1978 [158]. The most accurate value of total solar irradiance during the 2008 solar minimum period is 1360.8 ± 0.5 W m^{-2} according to measurements from the Total Irradiance Monitor (TIM) on NASA's Solar Radiation and Climate Experiment (SORCE) and a series of new radiometric laboratory tests [159]. This value is significantly lower than the canonical value of 1365.4 ± 1.3 W m^{-2} established in the 1990s, which energy balance calculations and climate models currently use. Various other experiments onboard satellites are monitoring the solar constant [14]. The original measurements require corrections for sensitivity changes due to instrument degradation. There are three different composites currently available are ACRIM [160] and IRMB [161] and PMOD [14]. There is some disagreement in the various levels of solar irradiance at solar minima this may be because of the different cross-calibrations and drift adjustments applied to the radiometric sensitivities [14]. Much surface temperature variability observed in the recent past appears to arise from causes that can be identified and their impacts quantified using auxiliary observations. Solar irradiance cycles produce warming of ~0.1^{0}C during epochs of high-solar activity [162].

4.1.1. Past Evidence of Connection between TSI and Global Surface Temperature (GST)

During Maunder minimum period, very few sunspots appeared on the surface of the Sun, and the overall brightness of the Sun was slightly decreased. Upper panel of the Figure **6** has shown the reconstruction of the cycle-averaged solar total irradiance back to 1610 which also suggests a decrease of the solar irradiance by a value of about 3 W/m^2 [163]. This occurred because the total solar irradiance was reduced by 0.22% that led to a decrease of the average terrestrial temperature measured mainly in the Northern hemisphere in Europe by 1.0-1.5 ^{0}C as shown in lower panel of Figure **6**. This seemingly small decrease of the average temperature in the Northern hemisphere led to frozen rivers, cold long winters, and cold summers [164]. Shindell *et al*. [165] have shown that the drop in the temperature was related to dropped abundances of ozone created by solar ultra-violate light in the stratosphere, the layer of the atmosphere located between 10 and 50 km from the Earth's surface. Since during the Maunder Minimum the Sun emitted less radiation, in total, including strong ultraviolet emission, less ozone was formed affecting planetary atmosphere waves, the giant wiggles in the jet stream. The change to planetary waves during the Maunder minimum kicked the North Atlantic Oscillation (NAO) - the balance between a permanent low-pressure system near Greenland and a permanent high-pressure system to its south-into a negative phase, that led to Europe to remain unusually cold during the Maunder Minimum [165].

4.1.2 Response of Climate Parameters with Variation in Total Solar Irradiance (TSI)

One important way to track and communicate the causes and effects of climate change is through the use of indicators. The total radiative energy reaching the Earth from the Sun is not exactly constant and varies from the average value of 1361.6 W/m^2 on a daily basis. This variation in total solar irradiance is directly attributed to the variation in the sunspot numbers [14, 166, 167]. Bottom panel of Figure **7** shows the cycle wise variability of about 2.5 W/m^2 (~0.1%) in the TSI from peak to minima during last forty



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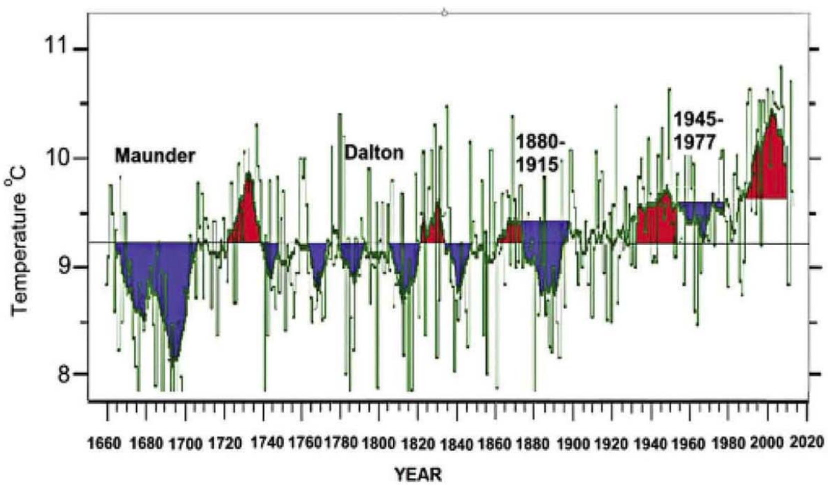

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Figure 6: (**a**) Restored total solar irradiance for the years 1600 - 2014.

(**b**) Central England temperatures (CET) recorded continuously since 1658 where the reoccurring cool periods are shown in blue colour while red colour areas have shown the warm periods. This plot also shows that all times of solar minima are coincident with cool periods in CET [238].

years (1978-2018). Second panel (from bottom) of Figure **7** has shown the variation in the global temperature anomaly during the period 1978 to 2018, here we have noticed that the value of the global temperature anomaly has reached from 0.13^0C to 0.99^0C and has shown the increment of 0.16^0C per decade. The variation of the global mean sea level (GMSL) is shown by the third panel (from bottom) of Figure **7**, here have noticed a continuous increase in the sea levels since 1993 to present time. This rapid change in GMSL has indicated that the climate of our planet is changing. The global-mean sea level rise on decadal time scales was caused by warming and hence reduction in density of seawater, and by increase in the mass of the ocean through transfer of water from other stores in the climate system. According to the assessment of [168], thermal expansion provided the largest contribution to global-mean sea level rise during the twentieth century.

Fourth panel of the Figure **7** has shown the present status of sea-ice extent which is about 24.3 million sq. km. The rate of reduction of the global ice extent was 0.06 million sq. km per year. The fifth panel of Figure **7** has showed the global precipitation anomaly. Based on the moving averages it can be seen that precipitation anomaly was lower than 1 mm in the year 1981 and was approximately -2 mm during 1986-1990. Zhang *et al*. [169] have studied the precipitation anomaly from 1998 to 2015 and have concluded that average annual precipitation anomaly values were less than the previous one.

Bhargawa and Singh [9] have analysed the influence of solar irradiance on climate parameters. Firstly they have used the impulse response function analysis on the data. Figure **8a** has shown the impulse response of solar irradiance shock and it's percent variations with global temperature anomaly, global

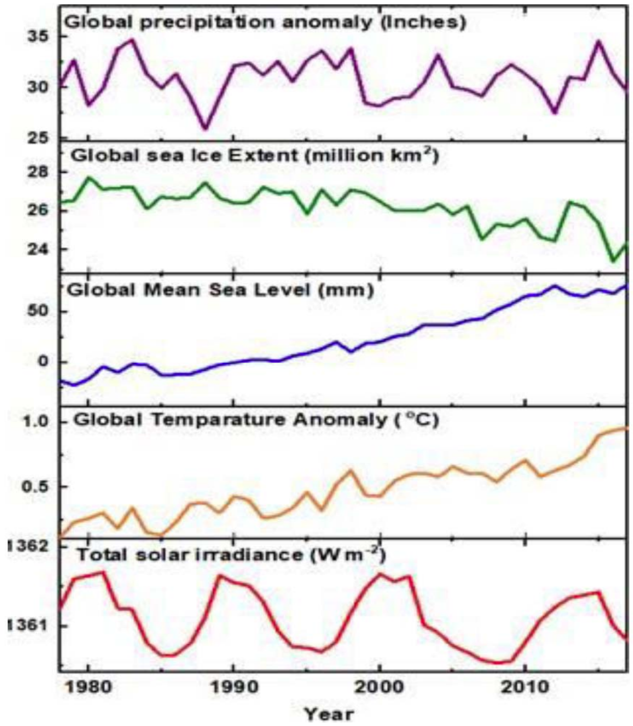

Figure 7: Variations in the total solar irradiance, TSI (First panel), the global average surface temperature anomaly (Second panel), the global mean sea level (Third panel), the global sea-ice extent (Fourth panel), the global precipitation anomaly (Fifth panel) during the years 1978 – 2018 (Bhargawa and Singh, [9]).

mean sea level, global sea-ice extent and global precipitation anomaly for next ten years. It is clear from the Figure **8a** that the global precipitation anomaly has shown the negative response for next two years but it become positive for rest of the period. The shocks to solar irradiance have shown positive and significant initial impacts on various climate parameters. This has confirmed a direct and positive impact of solar irradiance on these climatic parameters. Figure has also indicated that the initial impact of solar irradiance on global temperature anomaly was slightly higher in comparison to other parameters. It simply meant that the effect of solar irradiance on global temperature anomaly will last for longer time. Figure **8b** has shown the variance decomposition results in response to solar irradiance. Figure **8b** has revealed approximately 4.7% of future changes (during 2018-2028) in global temperature due to changes in total solar irradiance. The TSI have influence on future changes in global mean sea level by about 0.67 % while after the 10^{th} period a small variation in TSI results in 5.3% reduction in the future change of global sea-ice extent and a quick response in changes in global precipitation anomaly and TSI have no long term effects on it [9].

4.2. Solar UV Irradiance, Atmospheric Ozone and Climate

The thermal structure and composition of the atmosphere is determined fundamentally by the incoming solar irradiance. Radiation at ultraviolet wavelengths dissociates atmospheric molecules, initiating chains of chemical reactions-specifically those producing stratospheric ozone and providing the major source of heating for the middle atmosphere, while radiation at visible and near-infrared wavelengths mainly reaches and warms the lower atmosphere and the Earth's surface. Thus the spectral composition of solar radiation is crucial in determining atmospheric structure, as well as surface temperature, and it follows that the response of the atmosphere to variations in solar irradiance depends on the spectrum. Daily measurements of the solar spectrum between 0.2 µm and 2.4 µm, made by the Spectral Irradiance Monitor (SIM) instrument on the Solar Radiation and Climate Experiment (SORCE) satellite since April 2004, have revealed that over this declining phase of the solar cycle there was a four to six times larger decline in ultraviolet than would have been predicted on the basis of our previous understanding. This reduction was partially compensated in the total solar output by an increase in radiation at visible wavelengths. Haigh *et al*. [170] have shown that these spectral changes appear to have led to a significant decline from 2004 to 2007 in stratospheric ozone below an altitude of 45 km, with an increase above this altitude. The amplitude of UV variability is uncertain, yet it directly affects the magnitude of the climate response: observations from the SOlar Radiation and Climate Experiment (SORCE) satellite show broadband changes up to three times larger than previous measurements. Ball *et al*., [171] have presented estimates of the stratospheric ozone variability during the solar cycle. They estimated the photolytic response of stratospheric ozone to changes in spectral solar irradiance by calculating the difference between a reference chemistry–climate model simulation of ozone variability driven only by transport (with no changes in solar irradiance) and observations of ozone concentrations. They stated that at altitudes above pressure levels of 5 hPa, the ozone response to solar variability simulated using the SORCE spectral solar irradiance data are inconsistent with the observations.

Figure **9** shows the variations of total ozone column and stratospheric temperature during 1981-2019 which clearly indicates that during high solar activity, larger ozone concentrations and higher temperature are

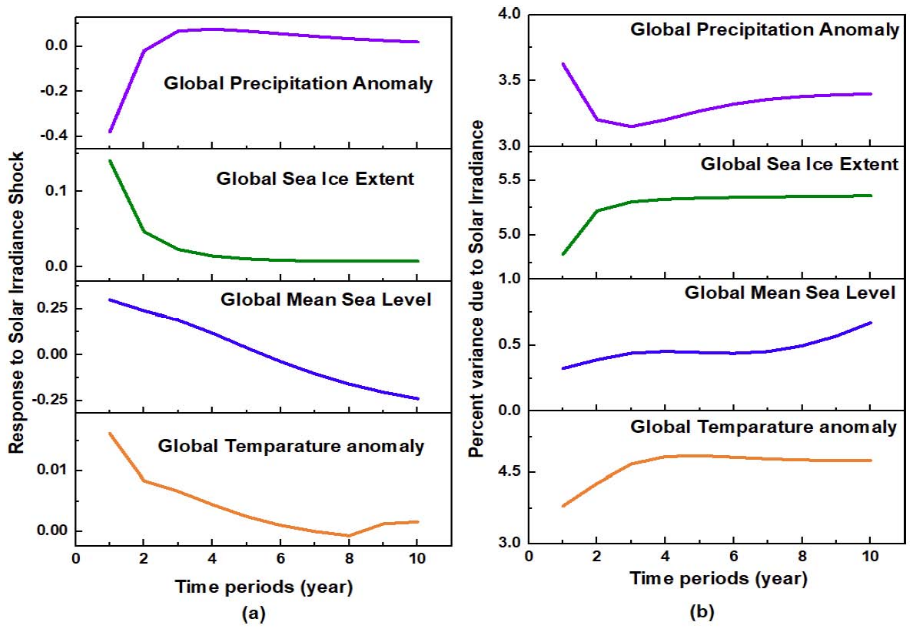

Figure 8: (**a**) Impulse response of the global surface temperate anomaly, the global means sea level, the global sea-ice extent and the global precipitation anomaly to the total solar irradiance for a time period of 10 years (2018-2028) (Bhargawa and Singh, [9])

(**b**) Variance decomposition charts of global surface temperate anomaly, global mean sea level, and global sea ice extent and global precipitation anomaly in response of changes in total solar irradiance for the period of next 10 years (2018-2028) (Bhargawa and Singh, [9]).

observed which may be due to stronger pressure gradients [172]. Solar variability can influence surface climate by affecting the mid-to-high-latitude surface pressure gradient associated with the North Atlantic Oscillation1. One key mechanism behind such an influence is the absorption of solar ultraviolet (UV) radiation by ozone in the tropical stratosphere, a process that modifies temperature and wind patterns and hence wave propagation and atmospheric circulation. The North Atlantic Oscillation (NAO) which is a feature of the natural variability of the climate characterised by the difference in surface pressure between the Icelandic low and Azores high, is associated with stronger westerlies, more northerly storm tracks and milder winters in Europe and North America [173, 174]. During solar minima, the stratospheric winter polar vortex is weaker and negative zonal wind anomalies extend to the surface. This represents a negative phase of the NAO and hence weaker westerlies and cold, snowy winters in Europe and North America. Studies suggest that the NAO response peaks a few years after the solar cycle maximum, possibly due to atmosphere-ocean interactions over the North Atlantic [175]. Solar cycle signals have been also observed in the tropics where stronger trade winds, a stronger overturning circulation and shifts in precipitation, as well as changes in sea surface temperature patterns, occur during solar maxima [6, 38]. There is some observational evidence for a connection between geomagnetic activity and surface air temperatures. During active geomagnetic activity, which are characterised by energetic particle precipitation towards the Earth and which peak a few years after a solar cycle maximum, typical regional surface temperatures pattern have been reported

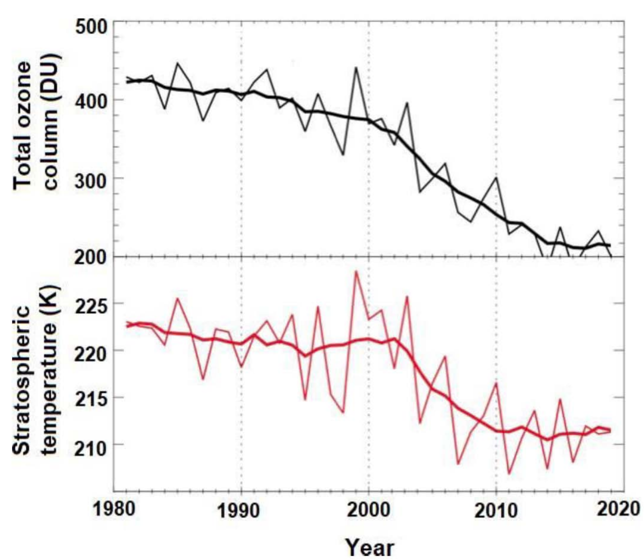

Figure 9: Variations in the total ozone column (DU) and the stratospheric temperature (K) during the period 1981-2019. (Source: Atmospheric Chemistry and Dynamics Laboratory NASA; https://acd-ext.gsfc.nasa.gov).

(Thejll and Lassen, 2000). The solar irradiance, directly absorbed by the Earth and ocean surface, changes precipitation and vertical motions which in turn influence trade winds and ocean upwelling [176]. The solar maximum lead to the stronger Hadley and Walker circulations and associated colder Sea Surface Temperatures (SSTs) in the tropical Pacific [177]. However, the details of the bottom-up mechanism and even the sign of SST response in the tropical Pacific are still under debate [178].

Fractional variations in the UV radiation of the solar radiative output are much larger than those in the visible and near Infrared region reaching 5 to 8% in the stratospheric region important for ozone chemistry [51, 179]. The enhanced UV radiation during solar maximum leads to a warming in the tropics around the stratopause and to greater ozone formation down below. The ozone absorbs UV radiation at longer wavelengths and gives an additional warming [180]. The warming in the tropics leads to stronger winds in the subtropical upper stratosphere [181], which influence the background state for planetary waves propagating upward from the troposphere [182]. Through complex interactions between the atmospheric flow and planetary waves, the signal in the middle atmosphere is transmitted down to the troposphere, where it modifies the NAO and leads to measurable regional effects [181, 183]. Since a number of other factors, such as ENSO, the QBO or volcanic eruptions influence the temperature of the lower stratosphere [140]. The processes involving stratospheric heating by solar UV and subsequent dynamical adjustment have been confirmed in a number of climate modelling studies [6, 39, 181].

The UV absorption composes only a small proportion of the total incoming solar energy and it has relatively large variations during the 11 year solar cycle. Studies have shown up to 6% variations present near 200 nm where oxygen dissociation and ozone production occur and up to 4% in the region 240-320 nm where absorption by stratospheric ozone is prevalent [141, 184]. The direct effect of irradiance variations is amplified by an important feedback mechanism involving ozone production, which is an additional source of heating [185, 186]. The origins of the lower stratospheric maximum and the observed signal that penetrates deep into the troposphere at mid-latitudes are less well understood and require feedback/transfer mechanisms both within the stratosphere and between the stratosphere and underlying troposphere. The variation at different wavelengths intervals may have an important impact on the terrestrial climate system. However, the time series of spectral solar irradiance is still too short to allow a reliable estimate of the solar influence on the Earth's climate. Variations of the total solar irradiance at wavelengths longer than 300 nm have been successfully reproduced [28, 51, 179, 180, 187, 188].

4.2.1. Indirect Effects through the Stratosphere

Out of the Sun's mean total radiative output of 1365 Wm^{-2} about 15 Wm^{-2} (~1 %) of energy is in the ultraviolet spectrum and does not reach completely to the Earth's surface [33]. This energy is deposited in the stratosphere, where it drives ozone destruction/ formation. Although unavailable for direct forcing of climate, it may induce indirect climate effects as a result of radiative and dynamical coupling of the stratosphere and troposphere [189-191]. The regional pattern of such indirect climate forcing is likely quite different from the effects of direct surface heating by solar radiation. The effect of solar cycle UV irradiance changes on stratospheric ozone are now relatively well established as a result of extensive space-based datasets that span about four solar activity cycles [192-194]. Observations revealed that the 11year cycle of ~1% peak to peak amplitude in middle UV radiation is associated with a 2-3% modulation of global total atmospheric ozone. Though the solar UV-induced ozone effects vary with geographic location and altitude, and appear to induce a significant tropopause response [195].

The solar cycle (SC) stratospheric ozone response is thought to influence surface weather and climate. To understand the chain of processes and ensure climate models adequately represent them, it is important to detect and quantify an accurate SC ozone response from observations. Chemistry climate models (CCMs) and observations display a range of upper stratosphere (1–10 hPa) zonally averaged spatial responses; this and the recommended data set for comparison remains disputed. Recent data-merging advancements have led to more robust observational data. Using these data, Ball *et al*. [196] have shown that the observed SC signal exhibits an upper stratosphere U-shaped spatial structure with lobes emanating from the tropics (5–10 hPa) to high altitudes at midlatitudes (1–3 hPa).

There is now growing evidence that solar-driven energetic particle precipitation (EPP) is another important source for stratospheric variability. Auroral electron precipitation provides direct forcing at polar thermospheric altitudes (above about 100 km), while solar proton events (SPE) and medium-energy electron (MEE) precipitation generate excess ionization in the polar middle atmosphere (between about 30 and 80 km). This leads to significant changes in the neutral atmosphere through the formation of odd nitrogen (NO_x) and odd hydrogen (HO_x). Enhanced production of NO_x and HO_x affects stratospheric and mesospheric ozone (O_3), which then has the potential to further influence atmospheric dynamics [197]. Solar Energetic particles (SEPs) produced during eruptive solar events can also produce significant episodic ozone depletion, primarily at higher latitudes (where the particles preferentially enter the Earth's atmosphere) and for relatively short periods (days). Ozone depletion arises from the odd nitrogen chemical destruction cycle that the particles initiate [40]. These depletion events, whose frequency and strength vary with solar activity, are superimposed on the more sustained solar UV radiation-induced ozone changes that occur during the 11-year solar cycle.

Recently, Bhargawa *et al*. [198] have studied the variation of UV radiations and total ozone column during super storm events occurred in solar cycles 22, 23 and 24. To that end, they had chosen seven storm events having Dst< -300 nT and by applying the superposed epoch analysis also analyzed the impact of solar proton density on the total ozone column and the UV radiation level by applying the superposed epoch analysis (SEA). Figure **10** has presented the result of SEA where it has clearly revealed that in most of the cases during increased solar proton density during the storm period there was nearly 22 ± 6.8% decrement in the total ozone column and about 26 ± 11.2% increment in the UV index. The lower panel of the figure has displayed the variation in Dst index for seven days where '0' corresponds to the storm day while + and - mean the subsequent post- and pre- storm days respectively. The depletion in the ozone column continued for 24-36 hours after the peak of the Dst index, this time delay in the observation of storm effects on the total ozone column might be associated with the delay in arrival of odd nitrogen or hydrogen molecules produced at higher altitudes [199]. As a response to the reduction in ozone level, the UV index showed an increment of 26±11.2% [198]. The extent to which solar UV radiation and energetic particle effects have indirect climatic impacts depends on the coupling of the stratosphere with the troposphere. Since ozone absorbs electromagnetic radiation in the UV, visible, and IR spectral regions, changes in ozone concentration can affect Earth's radiative balance by altering both incoming solar radiation and outgoing terrestrial radiation.

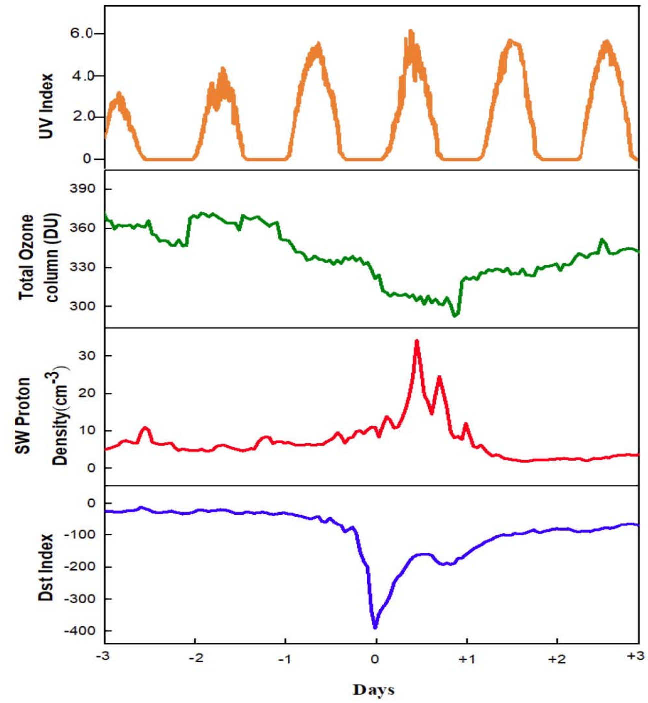

Figure 10: Outcome of superposed epoch analysis (SEA) during the super storm day (0), while (+) and (-) indicate the subsequent post- and pre- storm days respectively (Bhargawa *et al*., [198]).

With tropospheric climate, the solar induced ozone changes occur simultaneously with other natural and anthropogenic effects that must be understood and quantified in order to isolate the solar component [200, 201]. Solar-induced indirect effects on climate may also involve altered modes of variability. Model simulations and analyses of patterns of variability suggest that the Arctic Oscillation (AO), or Northern Annular Mode (NAM), and its subset the North Atlantic Oscillation (NAO) propagate from the stratosphere to the troposphere [202-204].

4.3. Role of Cosmic Rays in Sun-Climate Connections

The idea that cosmic ray changes could directly influence the weather was proposed by Ney [152]. Dickinson [205] considered that modulation of GCR fluxes into the atmosphere by solar activity might affect cloudiness and hence might be a viable Sun-climate mechanism. During solar minimum, the GCR flux is enhanced and is responsible for increased atmospheric ion production. The flux of GCR is modulated by the solar magnetic activity which provides a link between solar variability and climate [45, 206]. Tinsley [207] has proposed the GCR-cloud link through the global atmospheric electric circuit, where global circuit causes a vertical current density in fair-weather flowing between the ionosphere and the surface. Charging modifies the cloud microphysics, and hence, as the current density is modulated by cosmic ray ion production, the global circuit provides a possible link between solar variability and clouds. The GCR flux on the Earth is further modulated by the slowly changing geomagnetic field which does not allow the least energetic but most abundant CR particles to impinge on the Earth [208]. Both GCR modulation mechanisms are independent and act on different time scales which need the clarity of the GCR effect on the Earth.

The Cosmics Leaving OUtdoor Droplets (CLOUD) experiment was created to systematically test the link between galactic cosmic rays (GCR) and climate, specifically, the connection of ions from GCR to aerosol nucleation and cloud condensation nuclei (CCN), the particles on which cloud droplets form. The CLOUD experiment subsequently unlocked many of the mysteries of nucleation and growth in our atmosphere, and it has improved our understanding of human influences on climate [209]. Figure **11** has summarizes the various steps of relationship among the low solar magnetic field, the sunspots, the galactic cosmic rays, the cloud formation and the global cooling [208, 210, 211]. It is proposed that ionised aerosols can act preferentially as cloud nuclei and hence a higher incidence of GCRs might increase cloud cover. The processes necessary are under critical revision specifically with cloud chamber experiments at the CERN particle accelerator [206]. GCRs also contribute to variations in the Global Electric Circuit (GEC) and another area of research concerns whereby cloud formation could be affected [207, 212-214].

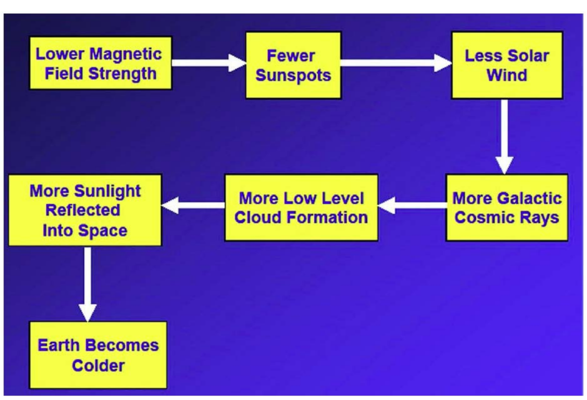

Figure 11: Summary of relationship among low solar magnetic field, sunspots, galactic cosmic rays, cloud formation and the global cooling.

Cosmic ray induced ionization is the principle source of the ionization of the low and middle atmosphere and can slightly modulate cloud formation [215]. Even a small change in the cloud cover modifies the transparency/absorption/reflectance of the atmosphere and affects the amount of absorbed solar radiation, even with no changes in the solar irradiance. High energy protons passing through the atmosphere cause ionization and produce nuclei for condensation of water droplets. Condensation tends to occur readily in the atmosphere because it is often supersaturated with water vapour. Clouds reflect incoming solar irradiance, which results in atmospheric cooling [216, 217]. Figure **12** has presented the percentages variation of cloud cover with global surface air temperature which revealed that how cooling takes place. Thus the cloud generating cosmic rays provide a satisfactory explanation for both long-term and short-term climate changes [212, 218]. In addition, the impact of cosmic rays on the radiative budget is found to be an order of magnitude larger than the TSI changes. Additional support for a cosmic ray–climate connection is the remarkable agreement that is seen on timescales of millions and even billions of years, during which the cosmic ray flux is governed by changes in the stellar environment of the solar system; in other words, it is independent of solar activity. This leads to the conclusion that a microphysical mechanism involving cosmic rays and clouds is operating in the 20 Earth's atmosphere, and that this mechanism has the potential to explain a significant part of the observed climate variability in relation to solar activity [219].

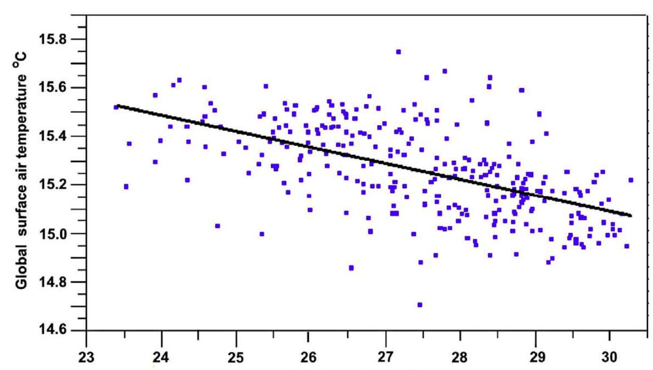

Figure 12: Percentage variations of the low cloud cover with the global surface air temperature and indication of atmospheric cooling (Singh and Bhargawa, [220]).

4.3.1. Causality between Cosmic Rays, Cloud Cover and Global Surface Temperature

Recently, Singh and Bhargawa [220] have tested the causality of climatic parameters like total solar irradiance, cosmic ray intensity, global cloud cover and global surface temperature by adopting the variance decomposition method using Vector Auto Regression (VAR) model. During the process they have analysed 35 years data, so have assumed 35 periods as the long run and 3 periods for the short run. Figure **13** has shown the variance decomposition of the cosmic ray intensity with the total solar irradiance which has further revealed that the contribution of the TSI in variation of the cosmic ray was about 0.65±0.02% in short run (3 years) but in case of long run (35 years) the TSI index has contributed about 8.77±0.42% in the variation of the cosmic ray intensity. Similarly, Figure **14** has shown the variance decomposition of the cloud cover and its dependency in the variations of the TSI, the cosmic ray intensity as well as the global surface temperature. Considering the short run impacts of the TSI, it has contributed 0.66±0.01% fluctuations in the variance of the cloud cover but for the long run this contribution increased up to 1.68±0.03%. The cosmic ray intensity has contributed 0.55±0.01% to the fluctuation of the cloud cover in the short run and contributed 4.89±0.08% in the long run. The figure has also indicated that the surface temperature have maximum impact on the cloud cover as 1.06±0.06% in the short run and has contributed 10.87±1.41% in the long run. Figure **15** has presented the variance decomposition of the global surface temperature which revealed that the TSI and the cloud cover have played important role in the variation of the global surface temperature. In fact in the short run, the TSI and the cloud cover has caused 0.36±0.08% and 0.84±0.04% fluctuations in the global surface temperature respectively while the long run contribution of these two parameters increased to 5.07±0.47% and 14.42±2.13% respectively.

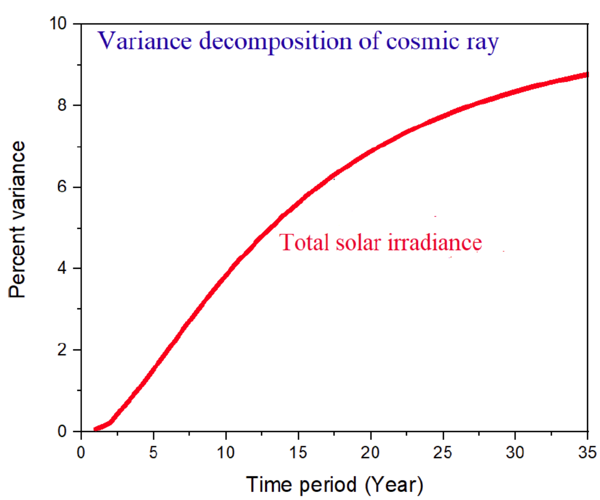

Figure 13: Percentage variations of total solar irradiance (TSI) with time responsible for variation in cosmic ray intensity obtained from the variance decomposition method (Singh and Bhargawa, [220]).

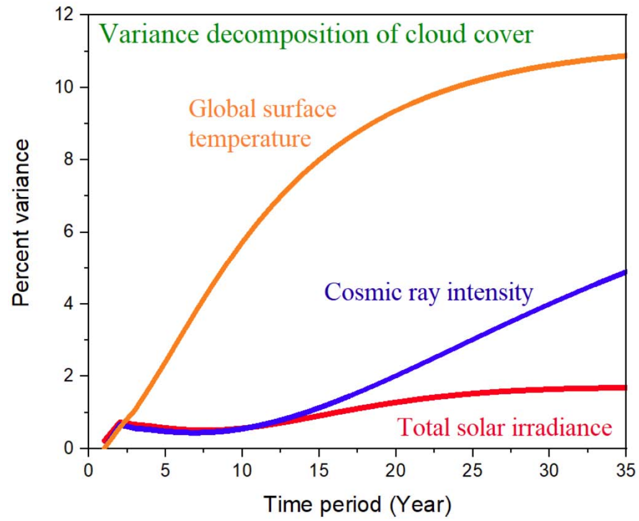

Figure 14: Percentage variations of the TSI, cosmic ray intensity and global surface temperature with time responsible for variation in cloud cover obtained from the variance decomposition method (Singh and Bhargawa, [220]).

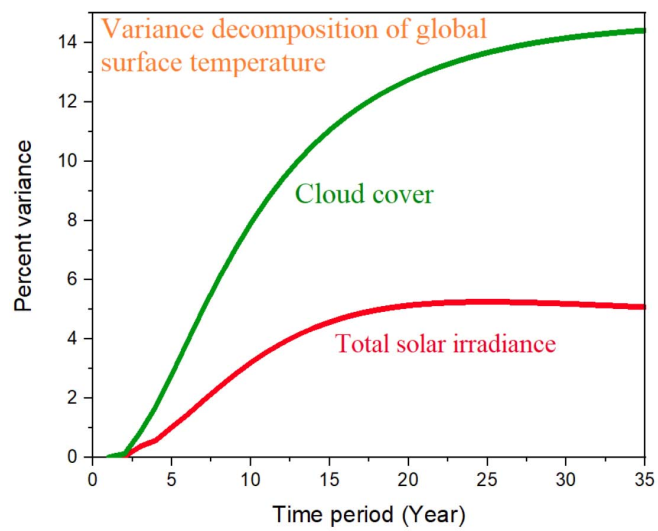

Figure 15: Percentage variations of the TSI and cloud cover responsible for variation in global surface temperature anomaly obtained from the variance decomposition method (Singh and Bhargawa, [220]).

5. FUTURE SOLAR ACTIVITY PREDICTIONS AND CLIMATE

The coincidence of an unusual long and deep solar minimum around 2008 together with the occurrence of a few cold and snowy winters in Europe since 2009 revived the discussion of solar influence on climate [38]. Number of studies recently has predicted that the Sun is currently declining from a grand maximum and moving towards a new grand minimum on longer scales [7, 27, 157, 221-224]. Figure **16** shows the predicted variations (dotted lines) of the sunspot numbers, F10.7 spectral index and Lyman Alpha index for solar cycles 25 and 26 which clearly indicates for future minimum solar activity [27]. Contrary to above, model projections of the 21st century participating in the Fifth Coupled Model Intercomparison Project (CMIP5) did not account for long-term changes in solar variability in the future [225, 226]. While there is consensus on the small impact of a solar minimum on global warming, the effects on regional scales are still poorly understood. More recently, it was shown that a future grand minimum would lead to a significant reduction in the projected warming tendency over Eurasia [227, 228].

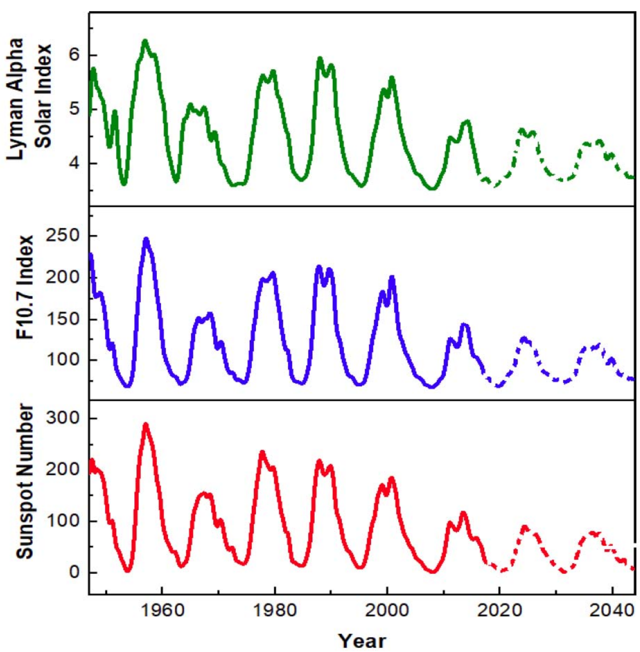

Figure 16: Predicted variations (dotted lines) of the solar activity parameters like sunspot numbers, F10.7 spectral index and Lyman Alpha index for solar cycles 25 & 26 (Singh and Bhargawa, [27]).

Based on the reconstructions of sunspots, solar forcing were possibly overestimating the amplitude of the TSI decrease during the maunder minimum relative to present-day. It has been suggested that the solar minimum in 2008–2009 could better represent the actual TSI values for the maunder minimum [167, 229]. Therefore, a feasible future scenario of solar activity may involve a decrease in 11 year variability, with smaller TSI changes. A future decrease in the 11 year solar cycle variability could be predominantly driven by changes in certain spectral regions, such as visible and UV, as supported by current observational estimates of solar spectral irradiance (SSI) forcing [181]. However, the use of different magnitudes for TSI and UV forcing in their simulations makes it difficult to accurately assess the relative contribution of visible and UV wavelengths to the model response to a given TSI perturbation.

Various predictions have already been made by various workers using different methods and the results obtained were varied in some order. Schatten and Tobiska [230] had claimed that solar activity will decrease after cycle 24 and will lead for a Maunder Minimum in the next few decades. Hathaway and Wilson [231] had predicted that the maximum number of sunspot numbers would be 70 ± 30 for solar cycle 25 while Du and Du [232] had found that the amplitude of a solar activity cycle was well correlated with the descending time three cycles earlier. Clilverd *et al*. [233] used a model for calculation of sunspot numbers using low-frequency solar oscillations. Their peak value of sunspot predictions for the cycle 25 was also significantly smaller than cycle 24. Quassim *et al*. [234] had used the neuro-fuzzy approach for the prediction of amplitudes of the upcoming solar cycle 25. They estimated the maximum sunspot numbers in the year 2021 with the value of 116. Pishkalo [235] calculated the correlation between various parameters of solar cycles 1-23. Further they used these derived regressions to make predictions of solar cycle 25. Apart from sunspot numbers Singh and Bhargawa [27] have considered F10.7cm index and Lyman alpha index for the predictions of solar cycles 25 and 26 and have inferred that the next solar cycle (cycle 25) will start in 2021 (January) and would last till the year 2031 (February) while the maxima of the cycle would reach around the year 2024 (February) with sunspot numbers, F10.7 cm index and Lyman alpha index values 89±9, 124±11 and 4.61±0.8 respectively. The solar cycle 26 will start in 2031 (March) and will last till 2043 (February) and its maxima will reach during the year 2036 (June) with the particular values of sunspot numbers, F10.7cm index and Lyman alpha index as 78±7, 118±9 and 4.41±0.02 respectively (Figure **16**). Based on the above findings if we assume that the there will be lower solar activity in future then it simply mean that there will be increased radiation from the GCRs which directly influence the terrestrial climate in future.

Galactic cosmic ray (GCR) flux in the proximity of the Earth is strongly modulated by the variable solar magnetic activity. Figure **17** shows the cosmic ray modulation which has the revere relation to solar activity analogous to 11 year solar cycles. The time profile of the sunspot numbers is shown in Figure **17a** while Figure **17b** has represented the cosmic ray flux

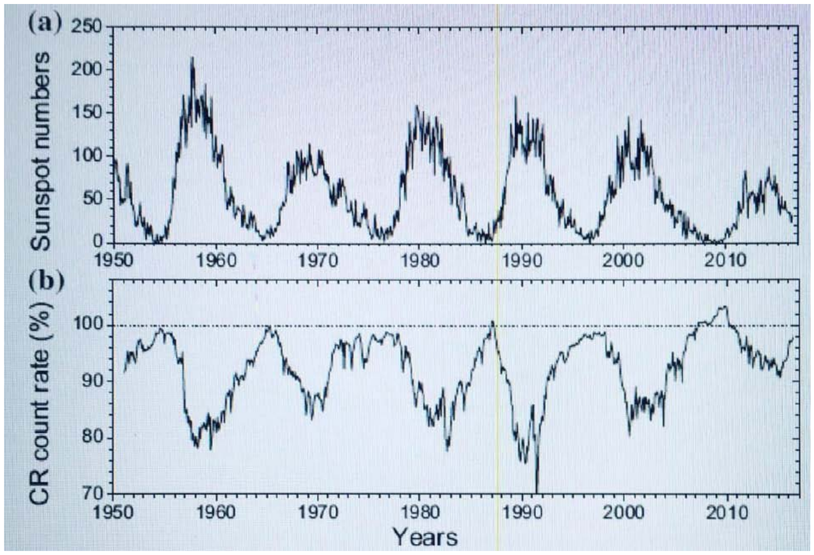

Figure 17: Cyclic variations (**a**) time profiles of International sunspot number (**b**) cosmic- ray flux as the count rate of a polar neutron monitor since 1951 (Usoskin, [60]).

measured by neutron monitor. Besides inverse relation between them, it is noticeable that short terms fluctuations are driven by interplanetary solar transients and so are indirectly related to sunspot numbers. The level of cosmic ray modulation during the solar cycle 24 is moderate in comparison to the previous solar cycles indicating the weak activity of the cycle [60]. Based on the above findings, one can infer that if there is lower solar activity in future then it simply means that there would be increased GCR radiations that impact directly to the terrestrial climate in future.

A future Maunder Minimum type grand solar minimum, with total solar irradiance reduced by 0.25% over a 50 year period from 2020 to 2070, is imposed in a future climate change scenario experiment (RCP4.5) using, for the first time, a global coupled climate model that includes ozone chemistry and resolved stratospheric dynamics (Whole Atmosphere Community Climate Model). This model has been shown to simulate two amplifying mechanisms that produce regional signals of decadal climate variability comparable to observations, and thus is considered a credible tool to simulate the Sun's effects on Earth's climate [236]. After the initial decrease of solar radiation in 2020, globally averaged surface air temperature cools relative to the reference simulation by up to several tenths of a degree Centigrade. By the end of the grand solar minimum in 2070, the warming nearly catches up to the reference simulation. Thus, a future grand solar minimum could slow down but not stop global warming [237].

6. DISCUSSION

Radiation from the Sun ultimately provides energy source for the Earth's atmosphere and changes in solar activity clearly have the potential to affect climate. There are statistical evidences for solar influence on various climate parameters on all timescales, although extracting the signal from the noise in a naturally highly variable system remains a key problem. The three broad types of suggested Sun-climate mechanism have been discussed above in order of their current state of development. Variations in solar total irradiance certainly affect climate, since the Sun's total irradiance is ultimately responsible for driving the climate system, while the effect of the 11-year cycle in total irradiance seems to have been directly observed in global sea-surface temperatures. In the case of spectral irradiance variations in the ultraviolet, general circulation models using observed 11-year variations in stratospheric ozone show that tropospheric circulation may well be affected, thereby influencing surface climate.

Changes in the total solar irradiance directly impacts the Earth's energy balance but there are some uncertainties in the historical record of TSI which mean that the magnitude of even this direct influence is to be studied properly. Variations in solar UV radiation impact the thermal structure and composition of the middle atmosphere but details of the responses in both temperature and ozone concentrations are not well established. Various theories are now being developed for coupling mechanisms whereby direct solar impacts on the middle atmosphere might influence the troposphere but the influences are complex and non-linear and many questions remain concerning the detailed mechanisms which determine to what extent, where and when the solar influence is felt. Variations in cosmic radiation, modulated by solar activity, are manifest in changes in atmospheric ionisation but it is not yet clear whether these have the potential to significantly affect the atmosphere in a way that will impact climate [238].

The most obvious mechanism for solar variations affecting the Earth's climate is due to the change in heating of the Earth system associated with varying TSI. These are found to partially explain the variations in the temperature of the oceanic mixed layer, but even in this case, it appears that modulations in the ocean-atmosphere sensible and latent heat fluxes are needed to explain the observations. Space-based radiometers have recorded TSI since 1978 and have established that it varies at the 0.1% level over the solar cycle. Solar variability is a strong function of wavelength, increasing toward shorter wavelengths and, thus, reaching a factor of two in the Lyman alpha line. Most of the irradiance variability of the Sun is produced by dark (sunspots, pores) and bright (magnetic elements forming faculae and the network) surface magnetic features, whose concentration changes over the solar cycle.

The most mature Sun-climate mechanism at this time involves the direct effect of the observed variation in solar UV radiation affecting stratospheric ozone, leading to associated temperature variations. The resulting temperature gradients lead to changes in the zonal wind, which, in turn, changes planetary wave-mean flow interactions. Inclusion of these mechanisms in fully coupled chemistry-climate models has been achieved, and many of the observed features in stratospheric temperatures, winds, and ozone distributions have been reproduced, including the maximum in ozone in the lower stratosphere, which appears to be an indirect effect associated with changes in the global circulation. The solar modulation of GCRs or the global electric circuit has also been proposed as a mechanism for Sun-climate influence on climate, through their ability to influence cloud cover. Looking towards the lower solar activity in future predictions this factor may play a bigger role in terrestrial climate change and will further need the appropriate model to understand the exact mechanism involved in the complex nature of the problem.

It therefore seems likely that solar activity has had more pronounced climate impacts at the regional scale than at the global scale, at the time scales considered here. Better reconstructions and simulations of these regional climate variations, and independently of climate forcings, are needed to understand their relationships. These studies of the last few centuries make it possible to consider the climatic impact of the Sun over the next few centuries, particularly with the hypothesis of a return to a very low level: this impact should remain low on a global scale compared to those of anthropogenic forcings (greenhouse gases, albedo), but at a regional scale it will continue to interact with climate variability. According to the IPCC [239], the current scientific consensus is that long and short-term variations in solar activity play only a very small role in Earth's climate. Warming from increased levels of human-produced greenhouse gases is actually many times stronger than any effects due to recent variations in solar activity. The last few decades were marked by considerable successes in helioclimatology may be because of both the satellite and the ground-based observations have brought a lot of new evidences for a link between solar activity and the phenomena of the lower atmosphere. The significant progress in experiment and theory/modelling has increased our knowledge of the Sun and solar-terrestrial connections, although the absolutely conclusive proof of the reality of the solar-climate link is still missing. The lack of facts and understanding about the connecting processes at work is the main cause of this shortcoming. Data obtained by experimental observation are quite precise but rather short in time scale. Paleoproxies are much longer but their uncertainty generally increases as a function of time from the present.

7. SUMMARY

This paper presents a brief review of our present knowledge of solar influence on climate, including the physics of solar variability, information on direct and proxy observations of both solar variability and climate, and some of the suggested mechanisms by which solar variability might influence climate. Observations have indicated that electromagnetic radiation from the Sun varies with the solar cycle and the Sun emits more radiation at sunspot maximum, paradoxically, when it is most covered with dark sunspots. We now understand this to be a result of the dominance of the bright faculae, which also vary over the solar cycle. In summary:

1. Considerable progress has been made in the past decade on the topic of solar variability and its influence on climate. New data and models

have revealed some new inconsistencies that will provide a challenge for the future.

2. It is an interdisciplinary field that has reverberations well beyond astrophysics, and considerable effort will be required to overcome the challenges ahead.

3. A large proportion of climate variations can be explained by the action of TSI, UV and CR on the state of the lower atmosphere and climatic parameters.

4. The trend of global surface temperature is moving towards warming despite of the role of solar signals in the 11-year variations of the Earth's climate are being expressed as several years of global temperature drop.

5. Combined effects of solar, cosmic, geophysical and human activity on climate change patterns are required to deal with the complexity of the situation.

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