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Total solar irradiance and climate

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Abstract

The solar radiation is the fundamental source of energy that drives the Earth's climate and sustains life. The variability of this output certainly affects our planet. In the last two decades an enormous advance in the understanding of the variability of the solar irradiance has been achieved. Space-based measurements indicate that the total solar irradiance changes at various time scales, from minutes to the solar cycle.

Climate models show that total solar irradiance variations can account for a considerable part of the temperature variation of the Earth's atmosphere in the pre-industrial era. During the 20th century its relative influence on the temperature changes has descended considerably. This means that other sources of solar activity as well as internal and man-made causes are contributing to the Earth's temperature variability, particularly the former in the 20th century.

Some very challenging questions concerning total solar irradiance variations and climate have been raised: are total solar irradiance variations from cycle to cycle well represented by sunspot and facular changes? Does total solar irradiance variations always parallel the solar activity cycle? Is there a long-term variation of the total solar irradiance, and closely related to this, is the total solar irradiance output of the quiet sun constant? If there is not a long-term trend of total solar irradiance variations, then we need amplifying mechanisms of total solar irradiance to account for the good correlations found between total solar irradiance and climate. The latter because the observed total solar irradiance changes are inconsequential when introduced in present climate models.

Keywords: Total solar irradiance; Earth's climate; Earth's temperature; Global warming; Solar variability

1. Introduction

The Sun expels several products of its activity to the interplanetary medium, namely electromagnetic radiation, energetic particles, and solar wind and transient ejecta with a frozen in magnetic field. The bodies embedded in the heliosphere react to the impact of solar activity according to their characteristics, i.e., whether or not they have intrinsic magnetic fields, ionosphere or neutral atmosphere. In particular the Earth responds to solar variability through geomagnetic activity, variations of the high atmosphere, and possibly changes of weather, climate and biota.

The solar electromagnetic radiation that arrives to the Earth changes because of three main mechanisms: planetary orbital parameter variations (inclination and eccentricity of the orbit, inclination of the rotation axis), changes of the albedo (due for instance to variations of cloudiness or atmospheric composition and changes in the distribution of land and ocean masses) and intrinsic variations of the solar irradiance. Some of these mechanisms produce variations that are evident on time scales of thousands or even millions of years, but in particular the observed changes of the solar irradiance are occurring from minutes to decades, the time scales that matter to human beings.

The observations of the global warming of the Earth since the beginning of the 20th century and claims that the increasing concentration of greenhouse gases is the

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cause, have naturally lead to the question of whether or not the Sun is playing an active role in this temperature rise. The coming sections shall focus on the total solar irradiance variability and its influence on the climate of the Earth.

2. The total solar irradiance

The total solar irradiance (TSI) is the value of the integrated solar energy flux over the entire spectrum arriving at the top of the terrestrial atmosphere at the mean Sun–Earth distance (the astronomical unit, AU). The TSI at the Earth's orbit can be calculated knowing the Sun's radius, the photospheric temperature and the value of the AU, the result is approximately 1367 W/m^2. Satellite observations indicate an average value of 1367 ± 4 W/m^2.

Before the launch of satellites changes of the TSI were difficult to detect by ground-based observatories due to the lack of knowledge of the selective absorption of the Earth's atmosphere and the insufficient radiometric precision. From those measurements a constant solar output was assumed, in fact it was called the "solar constant". Satellite measurements of the TSI started with NIMBUS-7 launched in November 1978 and have been carried out by their successors. Although the various instruments disagree at the 0.2% level in the absolute value of the TSI, the relative change within each dataset are accurate to better than 0.01%. Fig. 1 presents the results of several observations.

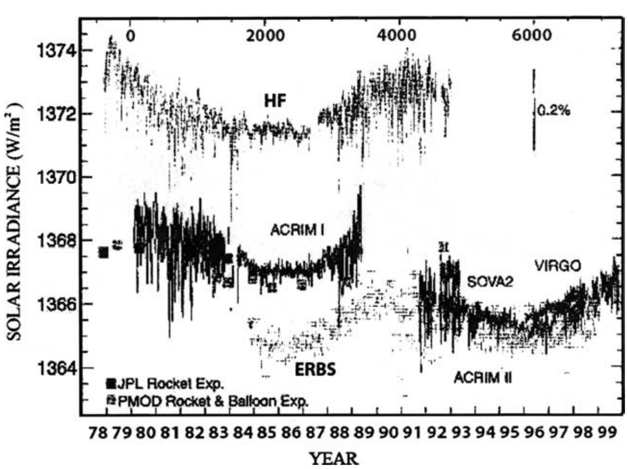

Fig. 1. Daily average values of the solar irradiance from different radiometers measured from space since 1978. Hickey–Frieden cavity radiometer (HF) on NIMBUS 7, Active Cavity Radiometer (ACRIM I) on the Solar Maximum Mission (SMM), Earth Radiation Budget Experiment (ERBE) on the Earth Radiation Budget Satellite (ERBS), ACRIM II on the Upper Atmosphere Research Satellite (UARS), Solar Variability (SOVA2) experiment on the European Retrievable Carrier (EURECA) and Variability of Irradiance and Gravity Oscillation Experiment (VIRGO) on the Solar and Heliospheric Observatory (SOHO). Also plotted are results from rockets and balloons (taken from Fröhlich, 2000).

From the observations the following TSI variations and sources have been identified:

(1) Changes of minutes to hours related with granulation, meso and supergranulation. In particular fluctuations on the 5 min range are due to solar oscillations (e.g., Fröhlich et al., 1997; Wolff and Hickey, 1987).
(2) Short-term changes of few days to weeks are dominated by sunspots. The sunspot-related dips produce changes of ∼0.3% in TSI (e.g., Chapman, 1987).
(3) Over the solar cycle, variations of ∼0.1% have been observed in consonance with sunspot activity (e.g., Willson and Hudson, 1991; Lee III et al., 1995). This modulation is mainly due to the interplay between sunspots and faculae and the changing emission of bright magnetic elements tracing the chromospheric network borders (Fontenla et al., 1999). For instance, faculae can enhance the total flux by 0.08% (Hudson et al., 1982). This is the most unexpected discovery concerning the TSI variation.
(4) Space-based observations exist only for about 20 years, therefore, variations on time scales longer than the 11-year cycle are uncertain.

The existence of several TSI time series allow the construction of composite time series. Willson (1997) and Willson and Mordvinov (2003) constructed a composite series using the Nimbus 7/ERB results to relate the non-overlapping ACRIM I and ACRIM II data sets, while Fröhlich and Lean (1998) and Fröhlich (2000) have produced such composite series using ERBS to relate ACRIM I and ACRIM II. For instance, in their composite series Fröhlich and Lean (1998) found a prominent 11-year cycle of amplitude 0.085% of difference between September 1986 and November 1989 monthly means. Fig. 2 shows the composite TSI series from Fröhlich (2000).

3. Total solar irradiance spectrum and its interaction with the Earth's atmosphere

Fig. 3 shows the spectrum of radiation incident at the top of the atmosphere, it resembles closely the curve of black body radiation at 5770 K, mainly for the visible and longer wavelengths. It has a maximum level near 500 nm and decreases to more than six orders of magnitude in the X-ray (not shown) and radio spectral regions. Around 50% of the TSI is at visible and near-infrared wavelengths from 400 to 800 nm, while between 300 and 10,000 nm occurs the 99% of the solar output (e.g., Fligge et al., 2001) These parts of the spectrum

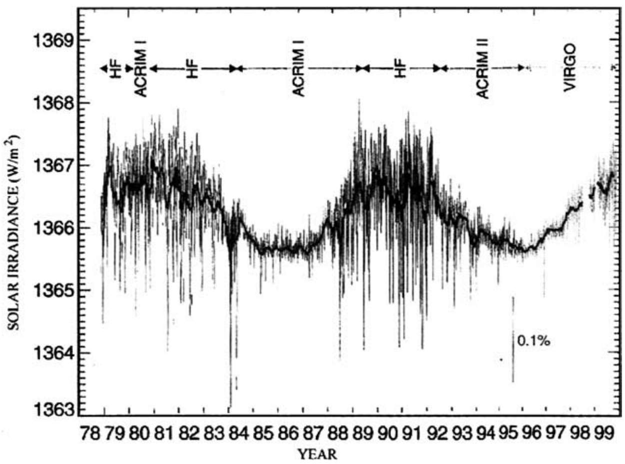

Fig. 2. Composite TSI from Fröhlich (2000) using different time series at different times as indicated on the figure.

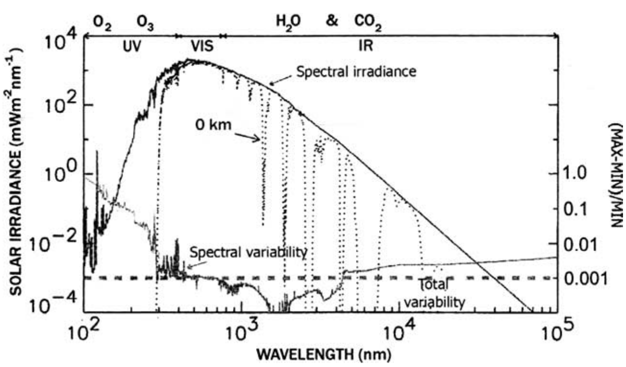

Fig. 3. Observed spectral solar irradiance at the top of the atmosphere and its estimated variability along the 11-year solar cycle. Also shown are the irradiance spectrum at the Earth's surface (0 km) and the main gases absorbing solar radiation (taken from Lean, 2000). The horizontal dashed line corresponds to the TSI variability observed along the solar cycle.

emerge from the solar photosphere where sunspots and faculae are. The spectrum at both longer and shorter wavelengths mostly originates at greater solar heights.

The amplitude of the variations of the Sun's light output depends on the wavelength. At shorter wavelength the fractional variation in the solar spectrum becomes larger (see Fig. 3), as a consequence of the Planck radiation law: For the UV wavelength, the measurements indicate solar cycle irradiance changes of 20% near 140 nm, 8% near 200 nm and 3% near 250 nm (Lean et al., 1997; Rottman, 2000). According to Fig. 3, most of the spectral irradiance variations occur below 500 nm.

Spectral irradiance variability at visible and infrared wavelengths is not well known mainly because of the lack of long-term space based measurements. For this reason in Fig. 3 the spectral irradiance changes at wavelengths larger than 400 nm are theoretical estimates (e.g., Solanki and Unruh, 1998). Nevertheless, Fligge et al. (2001) in their review of the observations indicate a variability of ~0.1% along the solar cycle closely related to the evolution of sunspots and faculae.

Also in Fig. 3 the TSI reaching the surface (0 km) is shown. Considerable absorption is evident in the ultraviolet (UV) and near infrared regions due to the atmospheric O_2, O_3, H_2O and CO_2. Table 1 indicates the layers of the Earth's atmosphere where the TSI according to its wavelength is absorbed. It is clear that solar radiation below 300 nm are absorbed in the stratosphere and above.

4. Empirical models of TSI variations

Of the several processes proposed for TSI variations (e.g., photospheric temperature changes, Kuhn and Libbrecht, 1991; changes in solar diameter, Sofia and Fox, 1994; changes in convective strength, Hoyt and Schatten, 1993) the changes in the amount and distribution of magnetic flux on the solar surface is the best established (Foukal and Lean, 1988; Lean et al., 1998).

Most recent reconstructions of the TSI assume that all variations have been driven by surface magnetic changes. The field on the solar surface is organized into flux tubes of different sizes, the largest being the sunspots and the smallest the magnetic elements forming the bright network and the faculae. The time evolution of these features indicates the variation of the magnetic solar activity, and therefore the

Table 1
Interaction of the TSI with the Earth's atmosphere

λ (nm)	Name of radiation	Effect	Height (km)	Atmos. layer
Up to 10	γ-rays X-rays	Ionizes all gases	70–100	Mesosphere Thermosphere
10–100	XUV	Ionizes N_2, O, O_2	100–300	Thermosphere
100–120	EUV	Ionizes O_2	80–100	Thermosphere
120–200	VUV	Dissociates O_2	40–130	Stratosphere and thermosphere
175–200	VUV and UV	Dissociates O_2 forms O_3	30	Stratosphere
200–240	UV	Dissociates O_2, O_3	20–40	Stratosphere
240–300	UV	Dissociates O_3	<40	Stratosphere

1 nm = 1×10^{-9} m; XUV = X-ray and ultraviolet; EUV = extreme ultraviolet; VUV = vacuum ultraviolet; UV = ultraviolet.

variations in brightness, and constitute indices of solar activity. Conspicuous instances of solar activity indices are the sunspot number, the plage area, the 10.7 cm radio flux, or the chromospheric global index derived form Mg, He or Ca emissions. Indirect indices of solar activity have also been developed, such is the case of the cosmogenic isotopes Be^{10} and C^{14} that are proxies of cosmic rays, in turn modulated by solar activity.

The solar activity indices are used to construct irradiance indices such as the facular brightening (e.g., de Toma et al., 1997) and sunspot darkening (Lean et al., 1998). Using different solar irradiance indices, models of the solar irradiance variations have been developed even beyond the observational period. These models are phenomenological, as opposed to physically base upon fundamental radiative principles.

The short-term models, developed for the time scales of the solar cycle, use as inputs the facular brightening and the sunspot darkening (e.g., Fröhlich and Lean, 1998; Solanki and Fligge, 1998). In particular these models have reproduced ~80% of the TSI irradiance variability of the space observation time span (e.g., Solanki and Fligge, 2002; Fröhlich, 2002). In Fig. 4, we see a model developed by Fröhlich and Lean (1998).

Long-term TSI changes are speculative. Reconstructions of long-term TSI variability use besides the facular brightening and the sunspot darkening along the solar cycle, an index of long-term variability such as the smoothed sunspot group number or the cycle length (e.g., Lean et al., 1995; Solanki and Fligge, 1999). Fig. 5 shows a model for the long-term total solar irradiance by Lean et al. (1995) where the long-term contribution was obtained from the smoothed sunspot group number. When this long-term variation is considered the results indicate a large variation of TSI for the Maunder minimum (1645–1710) with a change of 0.24%, another variation ~1800 during the Dalton minimum (1795–1823), and increasing irradiance from 1900 onwards.

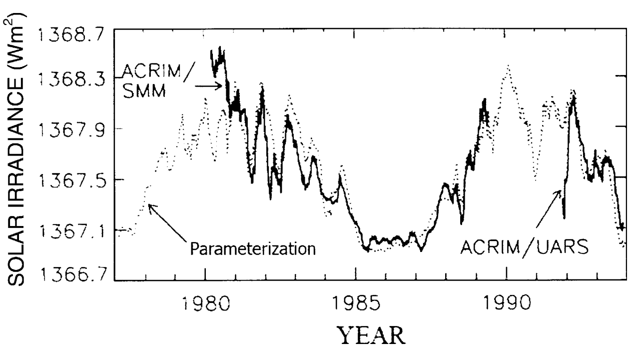

Fig. 4. A model of TSI variability based on sunspot and faculae compared with the measured TSI (taken from Lean et al., 1995).

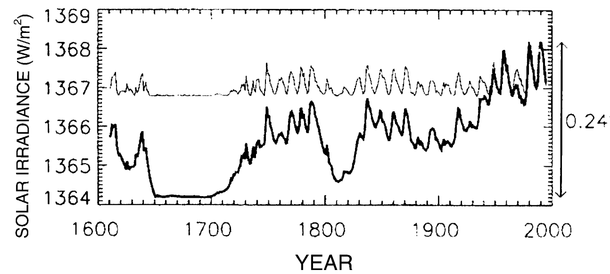

Fig. 5. Long-term TSI using as long-term component the smoothed sunspot group number (taken from Lean et al., 1995).

5. Correlations between TSI and climate

Changes in the TSI produce changes in the energy input into the Earth's atmosphere where weather and climate occur and the biosphere exists. Since the 18th century it has been suggested that the Sun affects the Earth's climate. Many correlations between climate variations and solar phenomena have been proposed, but these correlations did not stand statistical validity or appear and disappear according to the length of the climate time series used. Therefore this has been a controversial issue of the Sun–Earth relations (see review by Hoyt and Schatten, 1997).

An average global warming of 0.6 ± 0.2 °C has been measured along the 20th century (e.g., IPCC TAR, 2001). It has been attributed preponderantly if not solely to the anthropogenic influence on climate. The current interest of the role of the Sun in climate change stems from the possibility that solar activity is also contributing to the observed temperature increase.

The 1367 W/m^2 of solar irradiance arriving to the Earth's orbit is distributed over the planet, then the average solar radiation at the top of the atmosphere is 1/4 of this: ~342 W/m^2. As the Earth has a planetary albedo of 0.3, the incoming radiation is further reduced to 239 W/m^2. Also, as mentioned before, upon entering the atmosphere solar irradiance wavelengths shorter than 300 nm are absorbed in the stratosphere and above. And as we have seen it is at shorter wavelengths that the TSI varies the most. For the last two solar cycles, the portion of the TSI that actually arrives at the troposphere presents a change with the solar cycle of ~0.1% that seems too small to have an appreciable effect on surface climate.

Several attempts have been made to estimate the impact of TSI changes on global climate. Linear correlations between temperature records and solar irradiance reconstructions for secular time scales have been carried out. For instance Lean et al. (1995) use a reconstruction of total irradiance from 1610 to the present. They use for the TSI variations two separate components: an 11-year cycle plus a slowly varying background related with the amplitude of the group sunspot cycle. For the temperature record they use the decadal averages of North

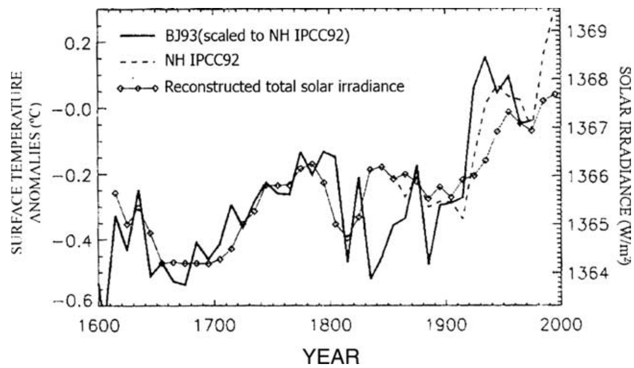

Fig. 6. Decadal averages of a reconstructed TSI and North Hemisphere temperature anomalies to the present (taken from Lean et al., 1995).

Hemisphere (NH) temperature anomalies. The result is presented in Fig. 6; the authors concluded that from 1610 to 1800 there is a high correlation between both series ($r = 0.86$). They indicate that from 1860 to the present half of the observed surface warming is attributable to direct solar forcing, but 65% of this warming has occurred since 1970 and solar forcing can account for less than a third of this. More recently, Solanki and Krivova (2003) have used a TSI irradiance reconstruction for 1856–1999 taking into account the composite solar irradiance of Willson (1997) and Fröhlich and Lean (1998); for the extended irradiance record back in time they used as long-term component both the length and the amplitude of the solar cycle. Also they work with global and north hemisphere surface temperatures. The 11-year running means show a good correlation of $r = 0.83$ and $r = 0.97$ for the global and NH temperatures respectively for the years before 1970. They point out that the contribution of total solar irradiance before 1970 is substantial but after 1970 is at most 30% coinciding with Lean et al. (1995).

6. Models of the influence of TSI variability on Earth's climate

The solar cycle variation of 0.1% observed in TSI in the last 20 years corresponds to changes of ~0.24 W/m^2 in the low atmosphere. Models of secular TSI variations indicate changes from 0.24% to 0.30% (e.g., Lean et al., 1995, 1997) corresponding to 0.5–0.75 W/m^2, with an extreme value during the deepest phase of the Maunder minimum of 1.23% decrease corresponding to 2.9 W/m^2 (Mendoza, 1997). Then the solar forcing has been most of the time small compared with estimates of the anthropogenic forcing by greenhouse gases of 2.4 W/m^2 during the 20th century (Houghton et al., 1996).

Several calculations with energy balance models (e.g., Crowley, 2000) and three-dimensional coupled ocean-atmosphere models (e.g., Cubasch and Voss, 2000) indicate that relatively small solar irradiance changes could cause changes of surface temperature of the order of several tenths of °C. In particular Cubasch and Voss (2000) used a version of the ocean-atmosphere general circulation model and two reconstructions of solar irradiance based on the amplitude and the length of the sunspot cycle respectively for the period 1770–1992 (Lean et al., 1995; Hoyt and Schatten, 1993). The result indicates that the 11 year cycle is not present in modelled temperature but the warming trend of the last 100 years is clear. They compared their simulation with a reconstruction of the NH temperature (see Fig. 7). The simulations represent well the temperature reconstruction between 1700 and 1800, however, we observe that during the 18th century the temperature reconstruction and the simulation tend to behave oppositely. During the last 100 years, the simulations have linear increasing trends of 0.17–0.19 K, while the observed one is 0.6, which means that TSI is contributing moderately to the observed warming.

A recent model by Shindell et al. (2001) examined the climate response to TSI changes between the late 17th century and the late 18th century. They used a version of the general circulation model which included a parameterization of the response of the complete stratospheric ozone to TSI. They worked with the Lean et al. (1995) irradiance reconstruction and a temperature reconstruction. Global changes of 0.3–0.4 °C were obtained coinciding with temperature reconstructions. However, regional temperature changes as large as 1–2 °C in the NH winter are obtained. The 20th century simulations show that TSI together with ozone variations and climate feedbacks change the temperature by ~0.19 °C, almost a third of the warming trend.

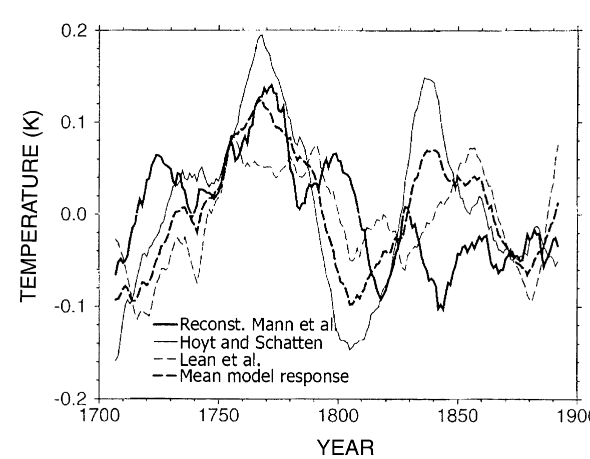

Fig. 7. Reconstructed temperature change for the northern hemisphere and model simulations using different TSI forcings (taken from Cubasch and Voss, 2000).

7. Other forcings of climate

7.1. Some solar forcings of climate

The broad conclusion reached from the studies mentioned above is that before 1970 although reproducing well the observed temperature, the TSI variations cannot account for all the temperature changes, and that after 1970 its influence has conspicuously descended. Even more, as the TSI cannot account for all temperature changes other sources of solar variability and/or sources different from solar variability must be present. Besides the TSI changes, two more mechanism have been proposed for the Sun-climate relations: variations in the UV, and the solar wind flux and energetic particles.

Solar UV irradiance has been used as a forcing because this radiation is absorbed by the stratospheric ozone raising the temperature there, warming of the lower stratosphere produce stronger winds, and penetration of these winds into the troposphere alters the Hadley circulation which then affects the equator-to-pole energy transport and the lower atmosphere temperature (Haigh, 1999; Shindell et al., 1999). The models show the observed 11-year variation in the stratosphere but the amplitude of the simulated changes is still too small compared to the observations (e.g., Larkin et al., 2000). Even more, Foukal (2002) compared his reconstructed UV solar irradiance with global temperature along 1915–1999, finding a poor correlation of $r = 0.46$. This result suggests that the interaction of UV irradiance and climate could be indirect.

The solar wind modulates the galactic cosmic rays, the precipitation of relativistic electrons and the ionospheric potential distribution in the polar cap, each of these affects the ionosphere-Earth current density. The variations of the current density change the charge of aerosol particles that affect the ice nucleation and production rate and hence the cloud microphysics and climate (e.g., Tinsley, 2000). Charged aerosol particles are more effective than neutral aerosol particles as ice nuclei (electrofreezing) and the enhanced collections of charged evaporation nuclei by supercooled droplets enhance the production of ice by contact ice nucleation (electroscavenging). Both electrofreezing and electroscavenging involve an increase in ice production with increasing current density.

After finding a good correlation between cloud cover changes and cosmic rays along 1983–1994 Svensmark and Friis-Christensen (1997) suggested that cosmic rays modulate the production of clouds on time scales of decades and longer. Further work seemed to confirm this for low level clouds (Marsh and Svensmark, 2000; Pallé-Bagó and Butler, 2000), however, serious criticisms have been raised concerning the handling of the data (Laut, 2003). Ramirez et al. (2004) worked with a thermodynamic climatic model for the years 1984–1990 and showed that responses of the order of few tenths of degrees can be obtained in the NH temperature using as the only forcing the change in total and cloud cover modulated by cosmic rays. Moreover, Pudovkin and Veretenenko (1995) have shown that Forbush decreases can produce short-term variations in the amount of high altitude cloudiness mainly in the latitudinal belt of 60–64°.

7.2. Some models including man-made and natural non-solar forcings

Simulations that take the greenhouse gases as prescribed according to observations but without the influence of the Sun simulate a linear trend of 0.43 K for the 20th century. When taking both, the greenhouse gases increase and the TSI according to Hoyt and Schatten (1993), the linear trend is of 0.6 K, which is very close to observations (Paeth et al., 1999); however, the aerosol cooling effect, neglected in the model, should lower the temperature below the 0.6 K.

Studies such as that of Crowley (2000) for the last millennia forced an energy balance model with TSI from Lean et al. (1995), indices of volcanism and changes in greenhouse gases. Explosive volcanic eruptions emit sulphur rich volatiles; these gases result in sulphuric acid aerosols being produced in the stratosphere, such aerosols are known to be important in reducing solar radiation at the surface as they affect the atmospheric albedo (Toon and Pollack, 1980; Bradley and Jones, 1992) and therefore there is less solar energy available for evaporation/convective precipitation processes; then volcanic eruptions perturb the rainfall regime. The authors found that for this time span the combination of the TSI and volcanism before ~1850 reproduces between the 41% and 64% of the total temperature variations. He also points out to the unusual increase in temperature in the late 20th century compared with the last 1000 years. Finally, at most 25% of the temperature increase in the late 20th century is due to natural variability, the remaining augment is consistent with the increase in greenhouse gases.

Obviously to have reliable temperature time series is crucial for all these studies. We would like to point out that the reconstructed temperature series for the last millennium are based on different data sets, different calibrations and different assumptions, and although similarities exist between the series there are also large differences (Briffa et al., 2001). This point becomes particularly relevant when claiming that the rise in temperature of the 20th century is the largest in the last 1000 years, as it seems that other periods in the past have shown even larger warmings (Soon and Baliunas, 2003).

8. Discussion

The direct observations of the TSI during the past 20 years have produced an enormous advance in the understanding of its variability. However, these results open new questions, and some of them are addressed below.

For instance, Willson (1997), Willson and Mordvinov (2003) in his composite series found a secular upward trend of 0.05% per decade between the consecutive solar cycles 22 and 23, while Fröhlich and Lean (1998) and Fröhlich (2000) in their composite series do not see such change. These results are proposing either an increasing, or a constant radiative output of the quite Sun. However, the data are too short to draw any conclusion.

Most models assume that almost all solar cycle changes in TSI are due to surface solar magnetic activity. Nevertheless, de Toma et al. (2001) pointed out that although solar cycle 23 seems magnetically weaker than solar cycle 22, TSI space observations indicate a similar radiative output for both cycles. One possibility is that sunspot and facular indices may not adequately represent the TSI from cycle to cycle, pointing to the possible existence of sources of solar cycle TSI variability with importance comparable to that of sunspots and faculae.

The TSI observations of the last two solar cycles indicated an increase of TSI from the minimum to the maximum of solar activity, the explanation being that within the solar cycle, faculae and bright magnetic network elements dominate over spots at maximum times. Foukal (1993) showed that between 1874 and 1976, for the Sun at maximum faculae dominated over sunspots except for the highest activity cycle in that time span, cycle 19, when sunspots dominated over faculae. This result implies that the change of solar irradiance in consonance with solar activity may be reversed if the Sun becomes much more active than today. Even more, Mendoza and Ramirez (2001) proposed the possibility that not only the high activity Sun but also the low activity Sun can become dimmer when evolving from minimum to maximum.

As mentioned before secular TSI forcings of climate consider a long-term component. The very existence of this long-term trend in TSI is challenged by studies such as that carried out by Foukal (2002). He points out that analysis of space borne radiometry indicate that TSI variations are closely proportional to the difference between spot and facular areas, which varies from cycle to cycle, then there is little reason to expect that TSI tracks any of the familiar solar activity indices. The author then reconstructs the TSI from 1915 to 1999 with no long-term trend considered, and found that this TSI and the global temperature along this period have a very high correlation of $r = 0.91$, but the TSI variation amplitude is insufficient to influence global warming in present-day climate models.

Lean et al. (2002) point out that TSI comes mainly from closed solar magnetic flux regions that constitute most of the total solar magnetic flux. The open and total magnetic flux variations behave differently, in particular the total flux does not present a long-term trend as does the open flux. Therefore the TSI should not show a long-term change, in agreement with Foukal's (2002) study and with the composite of TSI by Fröhlich and Lean (1998) and Fröhlich (2000), and in disagreement with Willson (1997) and Willson and Mordvinov (2003).

The existence of a long-term trend in TSI is based on extrapolations to the Sun of photometric behavior of Sun-like stars: there is evidence that the Ca II H and K emission measured in solar-type stars exhibit a much wider scatter than the Sun does along a solar cycle. On the Sun Ca II brightness is well correlated with magnetic features such as faculae and the network. Many of these stars show a much weaker Ca II emission than the Sun during a minimum, such stars are supposed to be in a Maunder minimum-type of activity (Baliunas and Jastrow, 1990). Also the variation of cosmogenic isotopes (Beer, 2000) which are proxy of cosmic rays suggest that the Sun may also present a wider range of activity and therefore a wider range of irradiance changes. However, Lean et al. (2002) have argued that as the open and total (mainly closed) magnetic flux variations are not the same, we cannot expect cosmic rays, or their proxy, cosmogenic isotopes, which are modulated by the open flux to reproduce TSI that is modulated by the closed flux. The fact that cosmogenic isotopes change do not imply a change in TSI.

If long-term changes of TSI are inexistent then the solar radiative forcing of climate in long-term climate models will be reduced by a factor of $\sim$3, and those climate models will be overestimating the role of TSI variability. Then how to explain the close correlation between solar irradiance and temperature? Perhaps the answer is in some mechanisms that amplify a weak solar forcing. For instance indirect interactions of TSI with climate: a high anticorrelation between TSI and low cloud cover has been presented by Kristjánsson et al. (2002) for 1983–1999, they suggest that TSI variations are amplified by interacting with sea surface temperature and subsequently with low cloud cover in subtropical regions.

9. Conclusions

The secular reconstructed TSI variations can account for a considerable part of the temperature variations of the Earth in the pre-industrial era. But even for those times the temperature changes are not fully reconstructed from TSI. Which means that other sources of solar activity as well as internal natural causes were contributing to the Earth's temperature variability.

During the 20th century TSI produces less than half of the observed temperature changes, confirming suggestions that for this century besides natural causes, man-made activities are contributing to the Earth's temperature variability, particularly the latter.

Also, reliable temperature data are mandatory to further proceed with the assessment of the factors that contribute to climate change.

Some current challenging questions on TSI variations and climate are the following: Are TSI variations from cycle to cycle mainly represented by sunspot and facular changes? Does TSI variations always parallel the solar activity cycle? Is there a long-term component of the TSI? Closely related to the former, is the TSI output of the quiet Sun constant? If there is not a long-term trend of TSI variations, then we need amplifying mechanisms of TSI to account for the good correlations found between TSI and climate.

Acknowledgments

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