# Solar Changes and the Climate

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## Timescales

The sun affects our climate in direct and indirect ways. The sun changes in its activity on timescales that vary from 11, 22, 80, and 180 years and more. A more active sun is brighter due to the dominance of faculae over cooler sunspots; in this way, the irradiance emitted by the sun and received by the Earth is higher during active solar periods than during quiet solar periods. The amount of change of the total solar irradiance (TSI) during the course of an 11-year cycle, based on satellite measurements since 1978, is about 0.1%. This was first discovered by Willson and Hudson (1991) from the results of the SMM/ACRIM1 experiment, and was later confirmed by Fröhlich and Lean (1998). This finding has caused many to conclude that the solar effect on climate is negligible; however, many questions still remain about the actual mechanisms involved and the sun's variance on century and longer timescales.

The irradiance reconstructions of Hoyt and Schatten (1997); Lean et al. (1995); Lean (2000); Lockwood, Stamper, and Wild (1999); and Fligge and Solanki (2000) assumed the existence of a long-term variability component in addition to the known 11-year cycle, such that, during the seventeenth century, Maunder Minimum total irradiance was reduced in the range of 0.15%–0.6% below contemporary solar minima.

The cumulative energy of even the most dramatic solar-energetic events during a solar cycle is miniscule compared with TSI. The largest flare during the past 30 years was barely identifiable as a small variation in TSI data. TSI comprises so many orders of magnitude greater in total energy transfer to the Earth that even tiny variations can cause climate swings like the "Little Ice Age." Special amplification mechanisms must be postulated to produce measurable climate forcings by high-energy solar events like flares, solar wind, and coronal mass ejections (CMEs).

Wang, Lean, and Sheeley (2005) used a solar reconstruction model that simulated the eruption, transport, and accumulation of magnetic flux during the past 300 years using a flux-transport model with variable meridional flow. They suggested a radically different picture of the long-term variation of solar output, most notably an increase since 1700 of only 27% on the lower end of the previously estimated range (0.037%). In its Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC) has embraced this finding to support its claims that there is only a small solar influence on recent climate change. This result contrasts sharply with other estimates mentioned above, as well as Lockwood, Stamper, and Wild (1999), who showed how the total magnetic flux leaving the sun has increased by a factor of 2.3 since 1901. Moreover, as the AR4 itself states in chapter 2, long-term trends in geomagnetic activity and cosmogenic isotopes, together with the range of variability in sun-like stars (Baliunas and Jastrow, 1990), suggested that the sun is capable of a broader range of activity than witnessed during recent solar cycles.

In addition, the AR4's conceptualization of solar forcing does not account for the sun's eruptional activity (e.g., flares, solar wind, bursts from CMEs, and solar wind bursts from coronal holes), which may have a magnifying effect on the basic TSI variances through indirect means. Labitzke (2001) and Shindell et al. (1999) have shown how ultraviolet radiation, which changes as much as 6–8% even during the 11-year cycle, can produce significant changes in the stratosphere that propagate down into the mid-troposphere. The work of Svensmark and Friis-Christensen (1997), Palle Bago and Butler (2000), Tinsley and Yu (2004), Shaviv (2005), and many others have documented the possible effects of the solar cycle on cosmic rays, and through them the amount of low cloudiness. It may be that, through these other indirect factors, solar variance is a much more important driver for climate change than is currently assumed. It may be that solar irradiance measurements are useful simply as a surrogate for the total solar effect.

## Correlations with total solar irradiance

In recent years, satellite missions designed to measure changes in solar irradiance, though promising, have produced their own set of problems and conflicts. Fröhlich and Lean (1998) noted the problem that no one sensor collected data over the entire time period from 1979, "forcing a splicing of data from different instruments, each with their own accuracy and reliability issues, only some of which we are able to account for." Their assessment suggested no increase in solar irradiance had occurred in the 1980s and 1990s.

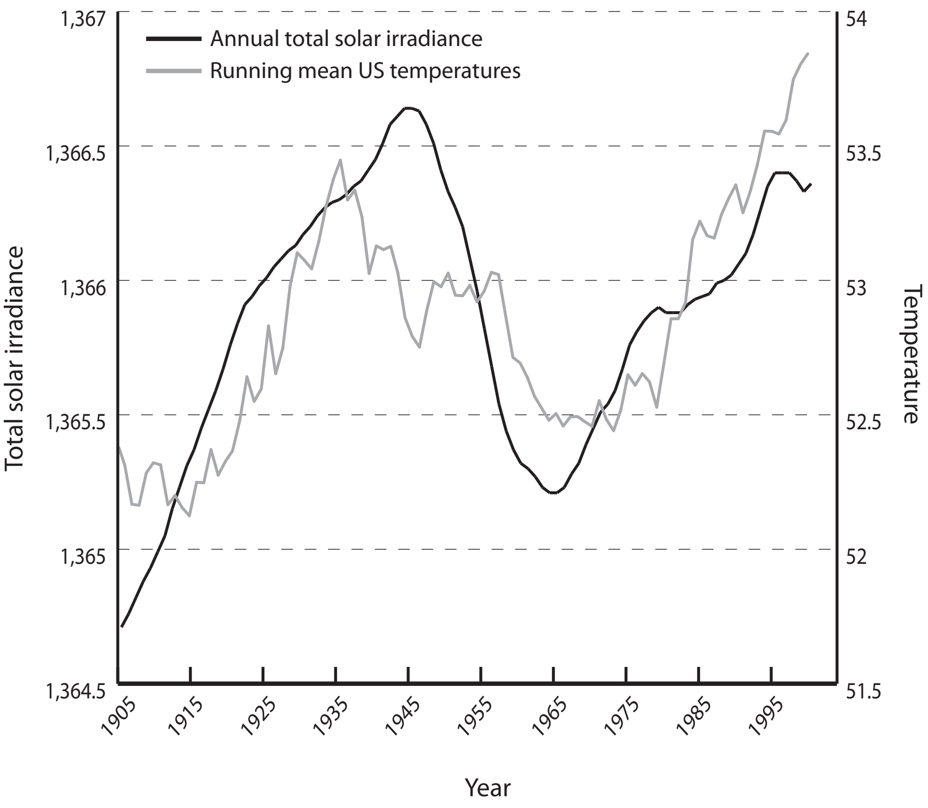
There are three TSI composites available, denoted Active Cavity Radiometer Irradiance Monitor (ACRIM), Physikalisch-Meteorologisches Observatorium Davos (PMOD), and Institut Royal de Météorologie (IRMB) (Royal Meteorological Institute of Belgium, Brussels), each originating from the same underlying data but differing based on analysis techniques (Fröhlich, 2006). Willson and Mordvinov (2003) found a TSI trend of 0.04% per decade during solar cycles 21–23. Further, they found specific errors in the dataset used by Lean and Fröhlich to bridge the "ACRIM Gap" between the ACRIM1 and ACRIM2 satellite experiments (1989–1991). Lean and Fröhlich's results arose from modifying the published results from the Nimbus7/ERB, ERBS/ERBE, and SMM/ACRIM1 experiments instead of making algorithm improvements and reprocessing raw satellite data.

Lean and Fröhlich added degradation corrections to the results of Nimbus7/ERB and ACRIM1 results, which had the effect of lowering their TSI results during the solar cycle 21 maximum and conforming the TSI time series to the predictions of Lean's solar proxy model. Their method is not consistent with the degradation analyses published by the ACRIM1 science team. Fröhlich and Lean chose overlapping ERBS/ERBE results to relate ACRIM1 and ACRIM2 results across the crucial "ACRIM Gap." Willson has argued that the ERBS/ERBE results are inferior to those of the Nimbus7/ERB in general, and specifically during the "ACRIM Gap," when uncorrected sensor degradation of the ERBS/ERBE results causes lower results after the "Gap" and the absence of a trend in the Lean-Fröhlich composite TSI time series (Willson and Mordvinov, 2003).

Not surprisingly, given the uncertainty on the decadal scale, studies vary on the importance of direct solar irradiance on the longer century timescale. Wang, Lean, and Sheeley (2005) suggest that long-term solar forcing is 70% smaller than earlier thought, with no significant effect in the last half-century. Lockwood, Stamper, and Wild (1999) estimated that changes in solar luminosity can account for 52% of the change in temperatures from 1910–1960, and 31% of the change from 1970–1999. Scafetta and West (2007) argued that total solar irradiance accounted for up to 50% of the warming since 1900 and 25–35% since 1980. The authors noted the recent departures may result "from spurious non-climatic contamination of the surface observations such as heat-island and land-use effects [Pielke et al., 2002; Kalnay and Cai, 2003]."

The United States Historical Climatology Network (USHCN) database, though regional in nature, provides a useful check on these findings, as it is more stable, has less missing data, and has better adjustments for changes to location and urbanization. Figure 1 shows the 11-year running mean of USHCN mean temperature data over the period from 1895–2005, and the total solar irradiance (TSI) data for the same interval obtained from Hoyt and Schatten (1997, updated in 2005). The Hoyt-Schatten TSI series uses five historical proxies of solar irradiance, including sunspot cycle amplitude, sunspot cycle length, solar-equatorial rotation rate, fraction of penumbral spots, and decay rate of the 11-year sunspot cycle. It confirms a strong correlation (r-squared of 0.59). The correlation increases to an r-squared value of 0.64 if temperature is lagged three years, close to the five-year lag suggested by Wigley (1988) and used by Scafetta and West (2006).

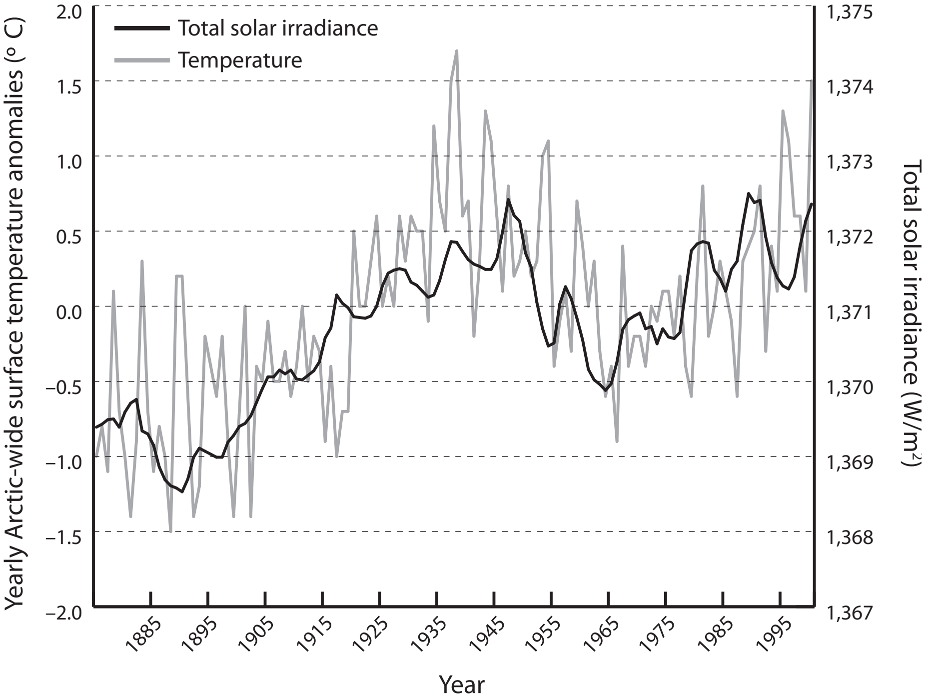
***Figure 1: Running mean of USHCN mean annual temperature (° F) versus total solar irradiance, 1900–2000***



Source: National Climate Data Center, 2007; total solar irradiance data up to 2005 supplied by Doug Hoyt, personal communication, 2006.

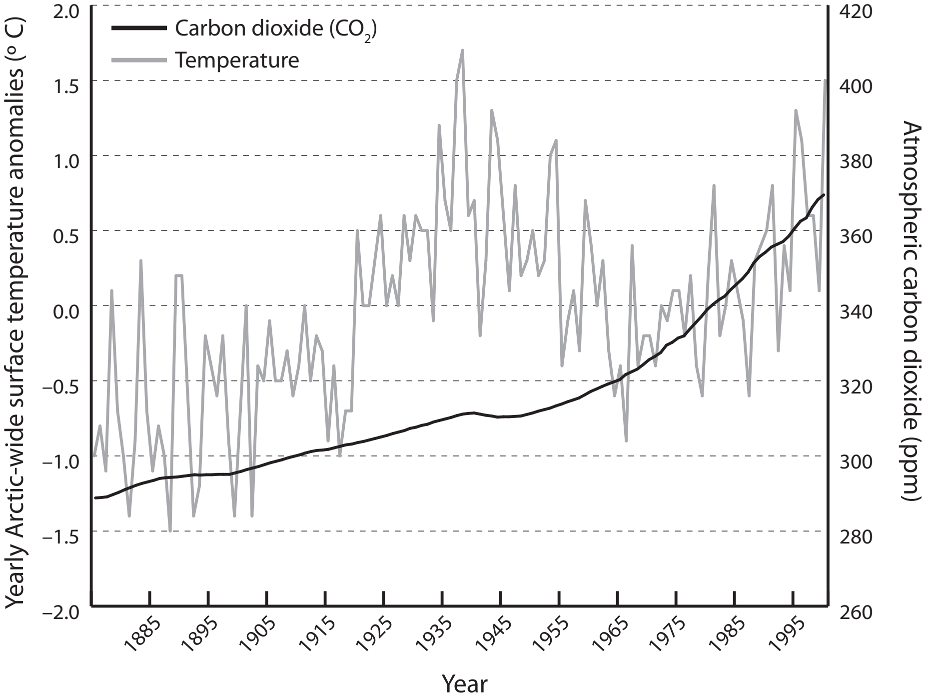
Two other recent studies that have drawn clear connections between solar changes and the Earth's climate are Soon (2005) and Kärner (2002). Soon (2005) showed that Arctic air temperatures correlated with solar irradiance far better than with greenhouse gases over the last century (figures 2a, 2b). For the 10-year running mean of total solar irradiance (TSI) compared to Arctic-wide air temperature anomalies (Polyakov et al., 2003a), he found a strong correlation—r-squared of 0.79—compared to an r-squared correlation with greenhouse gases of just 0.22.

### Figure 2a: Correlation between solar output and Arctic air temperature anomalies



Source: Soon, 2005.

### Figure 2b: Much weaker correlation between atmospheric $CO_2$ and Arctic air temperature anomalies



Source: Soon, 2005.

Kärner (2002) studied the time-series properties of daily total solar irradiance and daily average tropospheric and stratospheric temperature anomalies. He showed that average temperature anomalies exhibit a temporal evolution characterized by antipersistency, in which the variance expands as the observed sample length increases on all timescales, but at a diminishing total rate. $CO_2$ forcing is not antipersistent; instead, it has a steadily increasing trend, implying persistency. But Kärner showed that total solar irradiance is antipersistent, implying a discriminating hypothesis: the dominant forcing mechanism will endow the atmospheric temperature data with its time-series property. Since the temperature series is antipersistent, this implies that solar forcing dominates. The test supported this finding on all available timescales, from daily to decadal. He concluded that:

> The revealed antipersistence in the lower tropospheric temperature increments does not support the science of global warming developed by IPCC [1996]. Negative long-range correlation of the increments during last 22 years means that negative feedback has been dominating in the Earth climate system during that period. The result is opposite to suggestion of Mitchell (1989) about domination of a positive cumulative feedback after a forced temperature change. Dominating negative feedback also shows that the period for $CO_2$ induced climate change has not started during the last 22 years. Increasing concentration of greenhouse gases in the Earth atmosphere appeared to produce too weak forcing in order to dominate in the Earth climate system. (Kärner, 2002)

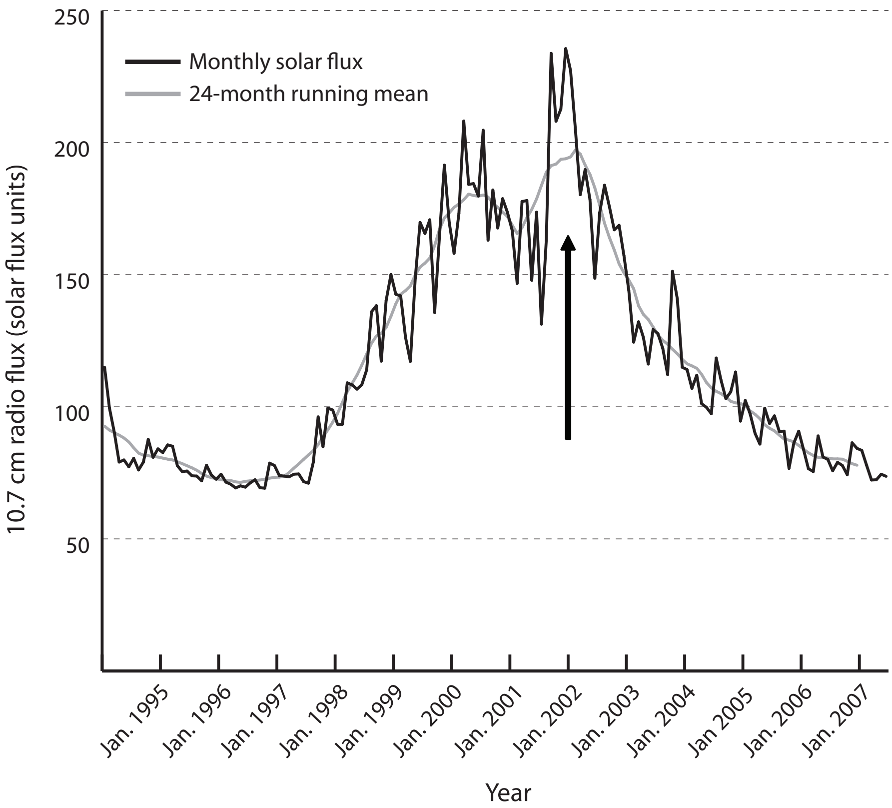
## Warming due to ultraviolet effects through ozone chemistry

Though solar irradiance varies slightly over the 11-year cycle, radiation at longer ultraviolet (UV) wavelengths are known to increase by several percent with still larger changes (factor of two or more) at extremely short UV and X-ray wavelengths (Baldwin and Dunkerton, 2004). Palamara (2003) reports that, during a solar flare, extreme ultraviolet can increase by a factor of 10 (Foukal, 1998).

Ozone in the stratosphere absorbs this excess energy and converts it to heat, which has been shown to propagate downward and affect the general circulation in the troposphere. Shindell et al. (1999) used a climate model that included ozone chemistry to reproduce this warming during high flux (high UV) years. Labitzke and Van Loon (1988), and later Labitzke in numerous papers, have shown that high flux (which correlates very well with UV—she notes changes 6–8% over the 11-year cycle) produces a warming in low and middle latitudes in winter in the stratosphere, and then penetrates down into the middle troposphere.

The winter of 2001/02, when cycle 23 had a very strong high-flux second maxima, provided a good test of Shindell and Labitzke and Van Loon's work.

***Figure 3: Solar cycle 23, strong high-flux second maxima around January 2002***



Source: National Oceanic and Atmospheric Administration, Space Environment Centre, 2007.

## Geomagnetic activity, weather, and climate

As early as 1976, Bucha speculated on the variations of geomagnetic activity, weather, and climate. In recent years, Bochnicek et al. (1999), and Bucha and Bucha (1998), have shown statistically significant correlations between geomagnetic activity and the atmospheric winter circulation patterns in high and mid-latitudes, as controlled to a large degree by the Northern and Southern Annular Modes (NAM and SAM) and modulated by the Quasi-Biennial Oscillation (QBO). They have found the tendency for the modes to be cold during the east QBO at solar minimum and during the west QBO at solar maximum, and for the modes to be warm at the west phase during the solar minima and warm at the east phase during solar maxima. This relates to the strength of the stratospheric vortex, which Baldwin and Dunkerton (2004) showed controls the tendencies in the middle and lower atmosphere for the phase of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). Since the QBO alternates east and west approximately every year, this would suggest a tendency for winters to alternate cold and warm near solar maxima or minima, but would not argue for long-term changes.

## Helio- and geomagnetic activity, solar winds, cosmic rays, and clouds

A key aspect of the sun's effect on climate may well be the indirect effect on the flux of Galactic Cosmic Rays (GCR) into the atmosphere. The hypothesis is that cosmic rays have a cloud-enhancing effect through ionization of cloud nuclei. As the sun's output increases, the solar-wind-induced atmospheric magnetic field shields the atmosphere from GCR flux. Consequently, the increased solar irradiance is accompanied by reduced cloud cover, amplifying the climatic effect. Likewise, when solar output declines, increased GCR flux enters the atmosphere, increasing cloudiness (and thus planetary albedo) and adding to the cooling effect associated with the diminished solar energy.

In an excellent treatise on the geomagnetic solar factors, Palamara (2003) noted how Forbush was the first to conclude that there was a relationship between geomagnetic activity and cosmic ray decreases (called the "Forbush decrease"). Ney (1959) proposed a chain of events whereby solar activity influences atmospheric temperatures via cosmic rays and ionization, with the greatest effects in polar regions. Dickinson (1975) proposed that cosmic rays could modulate the formation of sulphate aerosols which could serve as cloud nuclei. In a series of papers, Tinsley and coauthors proposed instead that cloud-cover changes could relate to changes in atmospheric electricity brought about by ionization (Tinsley and Yu, 2004). These theories were points of contention among researchers concerning the mechanisms proposed. There was little evidence to support any of them until Svensmark and Friis-Christensen (1997) found changes of 3–4% in total cloud cover during the solar cycle 21.

This paper was also quickly challenged. Among the challenges, Kristjansson and Kritiansen (2000) and Jorgensen and Hansen (2000) disputed the theoretical mechanisms linking cosmic rays to clouds, the latter arguing the changes in clouds might be explained by the El-Nino Southern Oscillation (ENSO) or volcanic eruptions. Kernthaler et al. (1999) repeated Svensmark's work but included the polar regions, where it was thought the effects would be greatest because that is where the cosmic ray attenuation was greatest. They found that by including the polar regions the correlations were weakened. Friis-Christensen (2000) reported this latter work was based on data subject to instrument calibration problems and that, with the adjusted cloud data, Kernthaler's work could not be reproduced. Though they acknowledged some effect on cloudiness could be attributed to ENSO, they could not rule out the influence of cosmic rays.

Svensmark's work received support from papers by Tinsley and Yu (2004), and Palle Bago and Butler (2001). The latter showed that low clouds in all global regions changed with the 11-year cycle in inverse relation to the solar activity extending over a longer period than the original Svensmark and Friis-Christensen (1997) study. Usoskin et al. (2004) found a significant correlation between the annual cosmic ray flux and the amount of low clouds for the past 20 years. They found that the time evolution of the low cloud amount can be decomposed into a long-term trend and inter-annual variations, the latter depicting a clear 11-year cycle. They also found that the relative inter-annual variability in the amount of low cloud increases polewards and exhibits a highly significant one-to-one relation with inter-annual variations in the ionization over the latitude range 20–55° S and 10–70° N. This latitudinal dependence gives strong support for the hypothesis that the cosmic-ray-induced ionization modulates cloud properties.

The conjectured mechanism connecting GCR flux to low cloud formation received experimental confirmation in the recent laboratory experiments of Svensmark et al. (2006) and Svensmark (2007), which demonstrated that cosmic rays trigger the formation of water droplet clouds.

Le Mouel et al. (2005) showed a strong correlation of geomagnetic indices and global temperature over the last century with some departure after 1990, perhaps indicating anthropogenic effects.

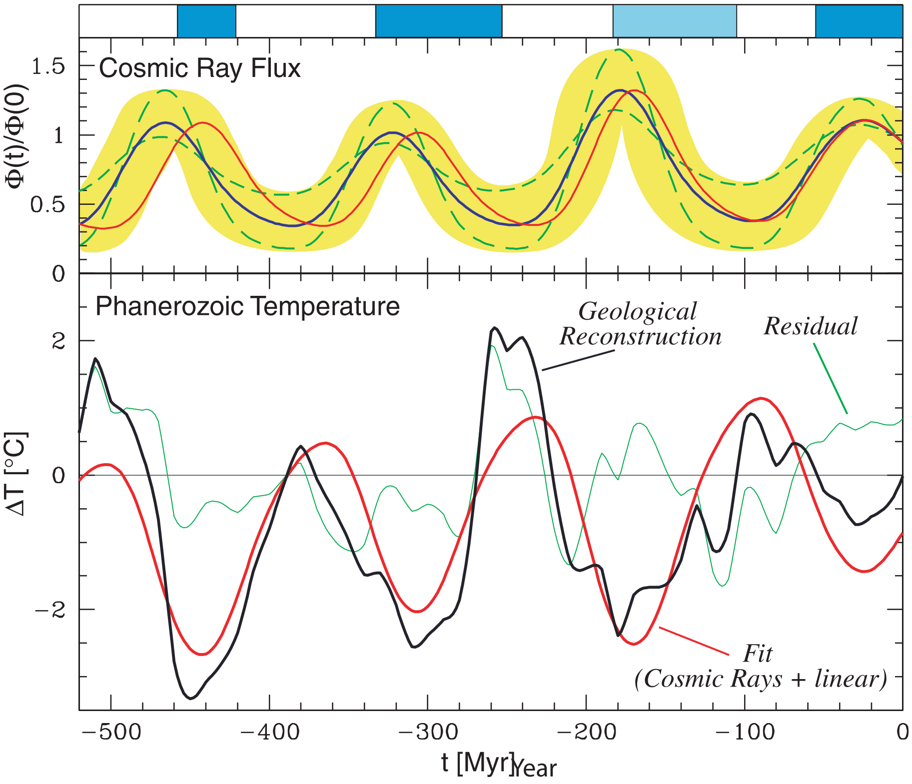
Shaviv (2005) found that when including the changes in cosmic rays over the last century, the total solar influence could be responsible for 0.47° C (±0.19° C), or roughly 77% of the total reported warming.

This issue is yet to be resolved but may indeed turn out to be an important solar-climate link, considering the plethora of correlations of climate trends with the GCR proxies (e.g., cosmogenic nuclides; Solanki et al., 2004) over a multitude of timescales, as compiled in Veizer (2005) and Scherer et al. (2006). Svensmark (2007) integrated the results of a dozen studies by him and other colleagues over a decade in a new theory he called "cosmoclimatology" that may help explain changes on the century and longer-term timescales.

## Long timescales

The review in the IPCC Fourth Assessment Report (AR4) of million-year-timescale climate change also overlooks the work of Veizer et al. (2000), showing greenhouse periods were asynchronous with high $CO_2$, as modeled by Berner and Kothavala (2001). This research was undertaken independently of, but almost simultaneously with, research by Shaviv (2002), who demonstrated a variable flux of cosmic rays impinging on our solar system. The intensity of this cosmic ray flux, which originates from supernovae, follows the 140-million-year cycle of our solar system's migration through the spiral arms of the Milky Way Galaxy. These independent reconstructions show that climate over the past 600 million years is highly synchronous with cosmic radiation. As proposed for modern climate variability, the mechanistic connection between these records is that of ionization and cloud nucleation in the atmosphere, leading to an increase in cloudiness. However, on these long timescales of the Phanerozoic Eon, high frequency variability in solar activity and attenuation of cosmic radiation is negligible. The impact of cloudiness on both long- and short-term climate cycles is significant. Change in cloudiness of only a few percent can engender, through changes in albedo, a climatic forcing greater than the entire IPCC-proposed anthropogenic "greenhouse effect." Further, cloudiness is recognized by the IPCC's AR4 as one of the greatest sources of uncertainty in climate modeling.

***Figure 4: Cosmic ray flux (upper diagram) and tropical ocean temperature anomaly variations over the past 500 million years***



Source: Shaviv and Veizer, 2003. The upper curve is based on meteorite exposure ages from Shaviv, 2002. The lower curves show the fit of cosmic rays with temperature anomaly reconstruction from Veizer et al., 2000.

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