INTERPLAY OF PERIODIC, CYCLIC AND STOCHASTIC VARIABILITY IN SELECTED AREAS OF THE H-R DIAGRAM
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Cycles and cyclicities of the Sun

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Abstract. The solar activity cycle is discussed in the broader context of solar variability. It is pointed out that the Sun exhibits periodic, cyclic, chaotic and stochastic phenomena. The origins of solar variability are mentioned and the importance of secular variations of the solar cycle for a putative influence of the Sun on the Earth's climate is briefly discussed.

1. Introduction

The Sun can hardly be classified as an early-type star. As such, the source of any cycles, cyclicities and periodicities exhibited by the Sun is quite distinct from the sources of such phenomena in early type stars, which are the main subject of the current volume. Nevertheless, cyclic solar variability may be of some interest for studies of hot stars, since the Sun's behaviour has been studied very extensively and the possibility of resolving the Sun's surface allows details to be resolved that are not accessible on stars. Here we give a brief introduction to the solar cycle, but also touch upon other properties of the variable Sun, such as the periodic solar oscillations and secular variations.

2. Solar variability

The Sun varies on all time scales accessible to observations, from a fraction of a second to centuries (Solanki, 2002), and is expected to change also on longer time scales right up to its main-sequence life time. The way the variability manifests itself, its sources and its statistical properties (periodic, cyclic, chaotic, stochastic) all depend on the time scale of interest. Variability of different types can also co-exist at a given time scale. For example, on a time scale of minutes periodic, chaotic and stochastic phenomena are found. Chaotic signals at this time scale are observed in solar radio bursts (Isliker & Benz, 2001). In addition, the Sun exhibits a rich spectrum of non-radial oscillations with periods of around 5 minutes. In Fig. 2. the period of the solar oscillations is plotted versus horizontal wavelength. Such a representation of these highly non-radial oscillations is only possible because the Sun's surface can be resolved. Many distinct ridges of power are visible, which are in turn composed of myriads of individual peaks, as indicated by the inset of Fig. 2.. These p-mode oscillations are thought to be excited by the turbulent motions present in the solar convection zone, i.e. by stochastic 'noise' (see e.g., Gough & Toomre, 1991; Brown & Gilliland, 1994; Gough et al., 1996).

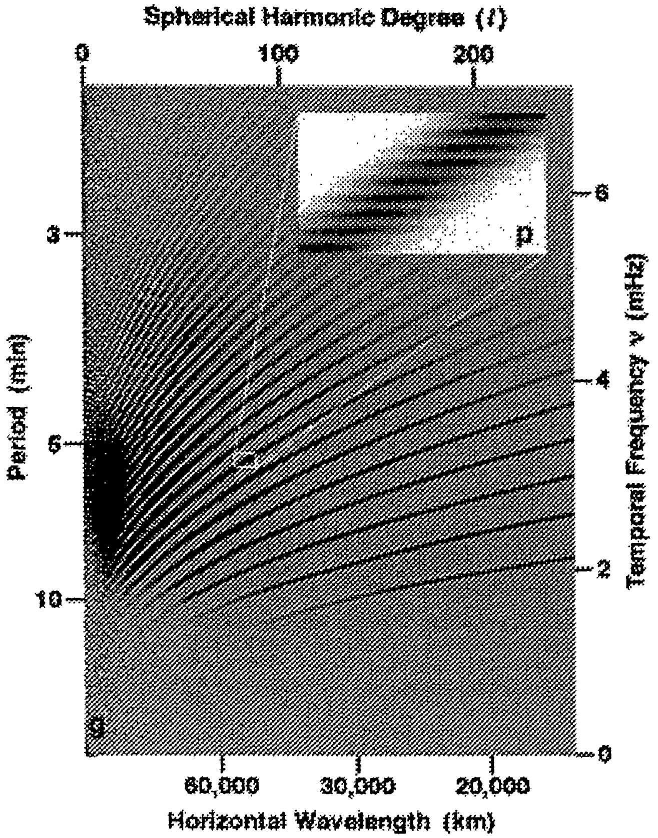


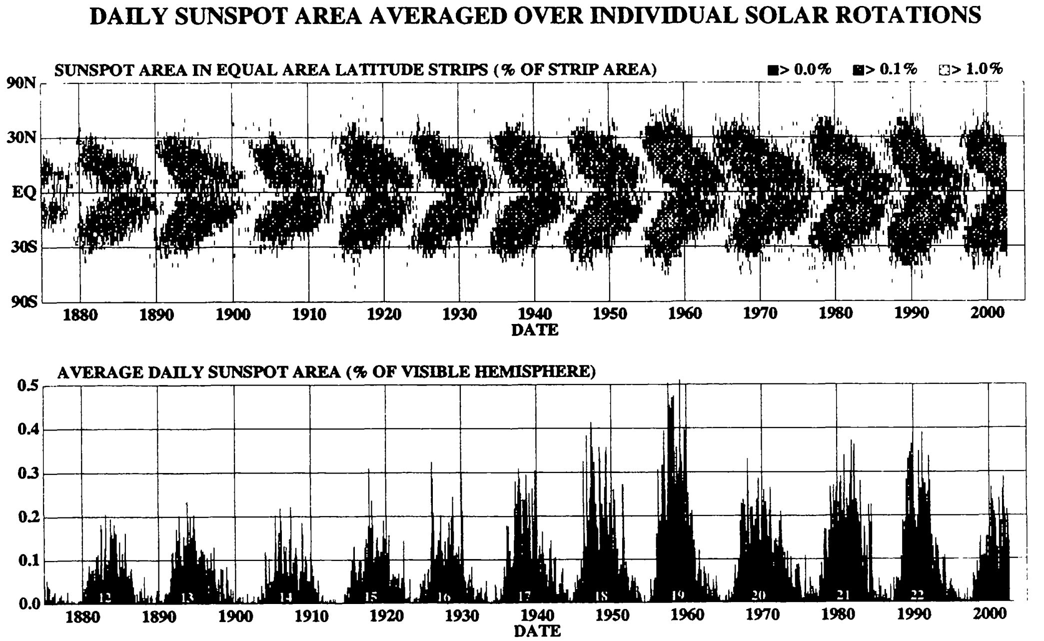
Figure 1. The $l - \nu$ (period versus horizontal wavelength) diagram obtained by the Michelson Doppler Imager (MDI) on the SOHO spacecraft. Since only waves with specific combinations (related to the Sun's interior structure) of period and horizontal wavelength resonate within the Sun, they produce the fine-tuned 'ridges' of greater power.

At longer time scales of days to centuries the source of solar variability is in one way or another the magnetic field. It produces both stochastic and cyclic variability. The major exception is the period of 27.2573 days due to solar rotation (the Carrington rotation period; although different latitudes rotate at different rates). Solar rotation modulation is clearly seen, e.g. in the EUV radiation of the Sun, as solar active regions, which are prodigious sources of EUV radiation, rotate in and out of view. The modulation due to rotation is often distorted, however, because the active regions evolve and decay and are replaced by new ones at nearly random longitudes relative to the old ones.

The stochastic variability on minutes to months time scales produced by the magnetic field is, on the one hand, related to the solar dynamo, which leads to the seemingly random emergence of magnetic flux (which forms active regions containing sunspots) and on the other hand to the interaction of the magnetic field with convection, which leads to the evolution and destruction of active regions and also produces such spectacular and dynamic phenomena as solar flares or coronal mass ejections.

3. The solar cycle

The most prominent solar time-dependent phenomenon is the sunspot cycle or, more generally, the solar activity cycle with a period of roughly 11 years. Within this period of time the area covered, for example, by sunspots increases by over an order of magnitude before dropping again. This area is plotted as a function of time over an interval containing 11 cycles in the lower frame of Fig. 2.


DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)

AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)

http://science.nasa.gov/ssl/pad/solar/images/bfly.ps NASA/NSSTC/HATHAWAY 08/2002

Figure 2. *Top:* The butterfly diagram shows the latitudes of sunspots as a function of time, in particular exhibiting the evolution of these latitudes over the solar cycle. Sunspots appear mainly at high solar latitudes at the beginning of a new cycle but move closer to the Sun's equator when the cycle progresses. *Bottom:* Daily sunspot area record.

Over the activity cycle many more observables change than just the number of sunspots or the area covered by them. For example, the latitudes at which the sunspots are present evolve over the solar cycle, producing the so-called butterfly diagram shown in the upper panel of Fig. 2. This point is also illustrated in Fig. 3. There the Mg II core-to-wing ratio (Fig. 3b) describes the disc integrated brightness (radiative flux) in the core of Mg II at 280 nm, relative to the flux in the line wing. This index is a measure of the chromospheric response to the change in solar magnetic flux. The 10.7 cm flux (Fig. 3d), although at the other end of the spectrum, also reflects the upper solar atmosphere's response to the magnetic field. Obviously, emission in a number of spectral bands (including the total solar irradiance, Fig. 3c, which is the wavelength integrated flux of the Sun measured above the Earth's atmosphere) changes in step with the sunspots, as do many more indices and features (e.g., the frequencies of solar p-modes).

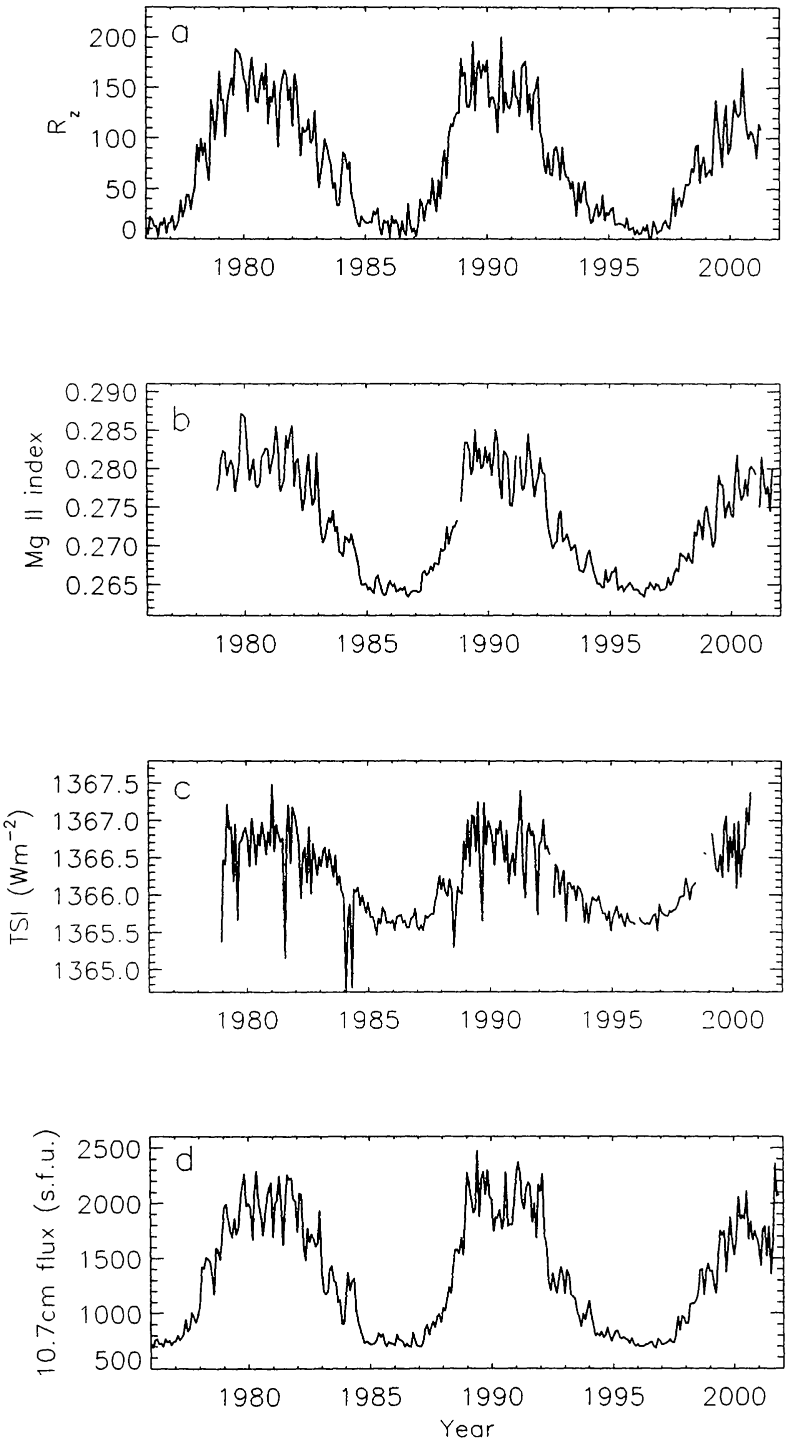


Figure 3. Monthly averages of different indicators of solar magnetic activity for the last 2.5 cycles. **a)** Zürich sunspot number; **b)** Mg II core-to-wing ratio (NOAA; Viereck & Puga 1999); **c)** Total solar irradiance (PMOD/WRC, Davos, Switzerland; Fröhlich & Lean 1998); **d)** Solar radio flux at 10.7 cm in solar flux units, where 1 s.f.u. = 10^{-22}Wm^{-2}Hz^{-1} (NRC, Canada).

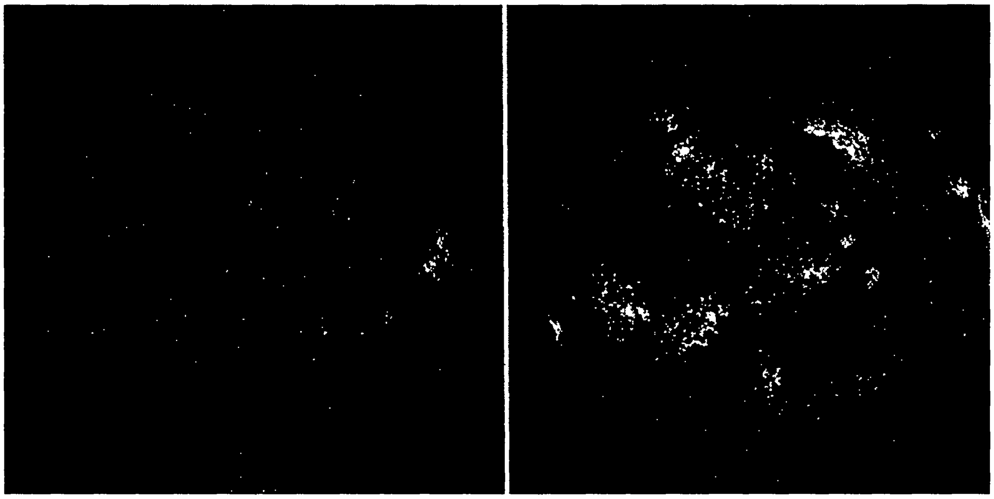


Figure 4. Magnetograms of the full solar disc obtained by the MDI instrument (Scherrer et al., 1995) on SOHO in December 1996 (left) and May 2001 (right) and averaged over 20-minutes.

From solar activity minimum to maximum the face of the Sun changes completely if it is observed at the appropriate wavelengths (e.g., cores of strong lines, radio, EUV and X-rays). Underlying all these changes is the magnetic field, which itself evolves strongly from activity minimum to maximum. In Fig. 4 we plot 2 magnetograms one recorded near minimum, the other near maximum of activity of solar cycle 23. White and black patches denote the presence of positive and negative polarity flux, respectively. Obviously, many more active regions, seen here as large bipolar patches of field, are present at activity maximum. Not so clearly visible in this figure but nonetheless present is a network of field covering the whole Sun with a salt-and-pepper pattern at all times during recent cycles. Thus the Sun changes its total magnetic flux only by a factor of 2 between activity minimum and maximum (Krivova et al., 2002).

Figure 5 provides an illustration that it really is the magnetic field which produces the observed variability in the solar irradiance measured by the VIRGO instrument on SOHO (solid line) over roughly half a solar cycle. Over-plotted on the measurements are the results of model calculations that are based on the assumption that all the solar irradiance changes are due to the evolution of the magnetic field on the Sun's surface (stars). Only a single free parameter is available to the model, which also simultaneously reproduces a whole set of further observations. The excellent correspondence between the two time series suggests that the assumption underlying the model is correct and also demonstrates that on time scales up to the solar cycle our understanding of the sources of solar irradiance variations is relatively advanced.

4. Secular change of the solar cycle and climate

A look at Fig. 2 reveals that in spite of many similarities each cycle is distinct from the others, most obviously in amplitude, less obviously in the cycle length, the maximum latitudes at which sunspots are seen, and in other parameters. The length of the solar cycle during the last roughly 150 years is plotted in Fig. 6. It changed by approximately 20% in this period of time.

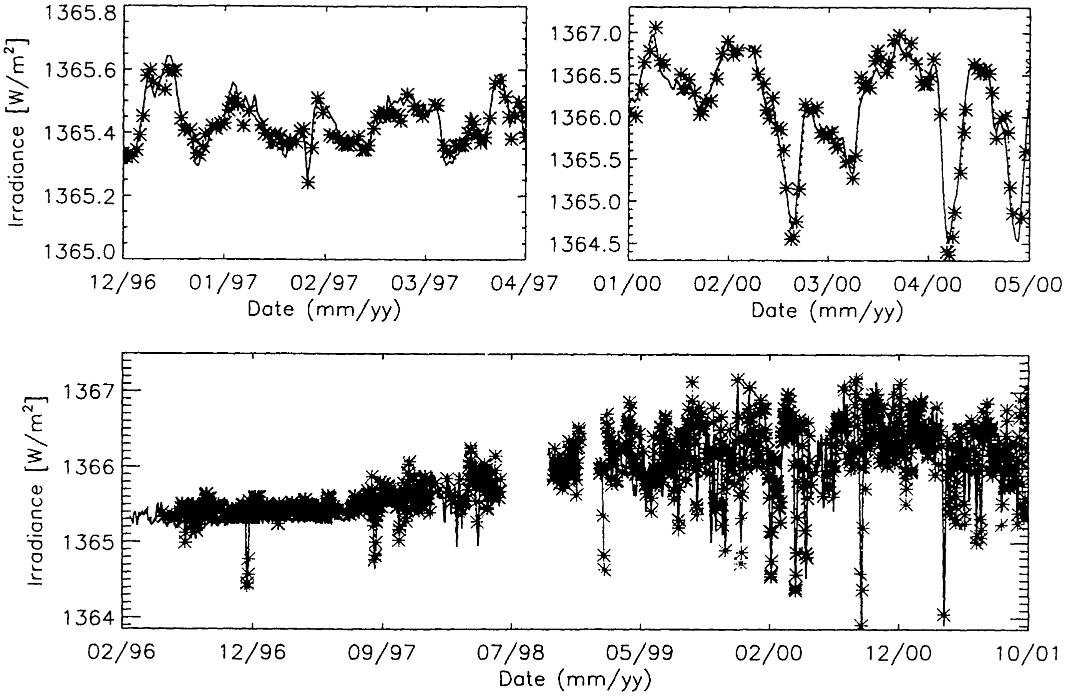


Figure 5. Reconstruction (asterisks) of total solar irradiance from MDI magnetograms for about 1500 individual days between 1996 and 2001, i.e. the minimum of cycle 23 and its maximum. The irradiance record measured by VIRGO is represented by the solid line. The two panels on the top show a zoom-in to two shorter intervals during low and high activity periods. These periods are indicated by darker symbols in the lower panel.

A much more drastic change than shown in Figs. 2 or 6 happened in the 17th century, when hardly any sunspots were seen during more than 50 years. This period is called the Maunder minimum. The coincidence of the Maunder minimum with the little ice age, as well as the excellent correlation of solar cycle length with Northern hemisphere air temperature over land masses (Fig. 6), suggests that solar variations have an effect on the Earth's climate, although chance correlations cannot be ruled out. This is particularly strong caveat since a priori neither the number of sunspots nor the cycle length are expected to directly influence climate.

Since the signature in the climate record of the solar cycle is extremely weak, even undetectable, it is the secular variation of the cycle and associated slow

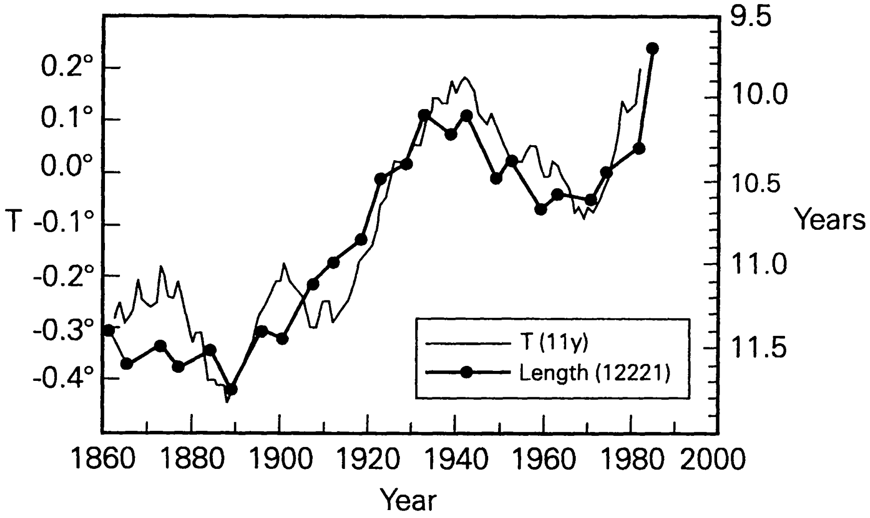


Figure 6. 11-year running mean of the annual average northern hemisphere land-air temperature relative to the average temperature 1951–1980 and the filtered length of the sunspot cycle (from Friis-Christensen & Lassen, 1994).

changes of other quantities which are the most important possible contributors.

Of more direct potential relevance for the climate are the Sun's irradiance and the quantity underlying all solar activity, the magnetic field. Unfortunately, regular and detailed measurements of the Sun's surface magnetic field are only available for a few decades, not long enough for comparison with climate. Records of the solar irradiance are available for an even shorter length of time. However, much longer records exist for proxies of the Sun's open magnetic flux such as the geomagnetic *aa* index (Lockwood et al., 1999) and the concentration of the cosmogenic isotope ^{10}Be in ice cores (Beer et al., 1990). At the same time the sunspot number record, which goes back to 1610, provides a measure of the magnetic flux emerging from the solar interior to the surface. Using it Solanki et al. (2000, 2002) were able to reconstruct the Sun's open and total magnetic flux. The open flux reconstructed in this manner is plotted in Fig. 7 (thick solid curve) and compared with the open flux reconstructed by Lockwood et al. (1999; light shaded curve starting in 1860) and the ^{10}Be record in Greenland ice (dotted curve). Obviously, the 3 curves agree very well with each other. It is noticed that the open magnetic flux, although following the cycle, stays at a high level even at recent activity minima. Also, it exhibits a strong secular trend, being almost zero at the end of the Maunder minimum and increasing to high levels at current times. This secular variation depends on both the maximum rate of flux emergence (the sunspot cycle amplitude) and the length of the cycle. The latter dependence is of particular interest given the excellent correlation between cycle length and a climate indicator found by Friis-Christensen & Lassen (1991; see Fig. 6).

Finally, knowledge of the magnetic flux allows the solar irradiance to be reconstructed. This has not been done as yet employing the models of Solanki

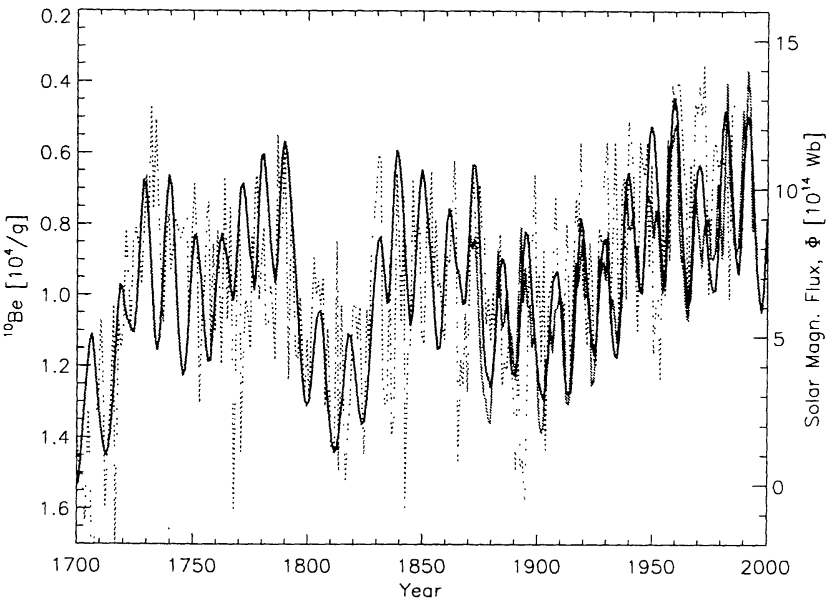


Figure 7. Evolution of the open magnetic flux at the solar surface since the end of the Maunder minimum in 1700. Model predictions by Solanki et al. (2000) are represented by the thick solid curve, reconstructions by Lockwood et al. (1999) based on geomagnetic indices by the light shaded curve beginning around 1860 and the ^{10}Be concentration in ice cores (corresponding to the inverted scale on the left y-axis, Beer et al., 1990) by the dotted curve.

et al. (2002). However, other, more indirect indicators also point to a strong secular change in solar irradiance (e.g., Baliunas & Jastrow, 1990; White et al., 1992). Using the various indications models have already previously been constructed (e.g., Hoyt & Schatten, 1993; Lean et al., 1995; Solanki & Fligge, 1998, 1999).

In Fig. 8 the irradiance reconstructions of Solanki & Fligge (1999), combined with direct measurements wherever available, are compared with records of the Earth's temperature. All curves have been subjected to an 11-year running mean. Clearly, prior to 1980 the irradiance reconstruction runs parallel to or ahead of the climate curves. This is consistent with a solar cause of a considerable fraction of the temperature variations prior to that date. This does not mean, however, that other sources, e.g. the natural variability of the Earth's atmosphere, did not contribute (see Bengtsson, this volume). It is highly likely, however, that after 1980 the Sun has not contributed in any significant way to global warming.

5. Conclusions

Like most stars, the Sun is variable, with variations being observed on a wide range of time scales and by many observables. The main cause of these variations, apart from solar evolution, rotation and eigen oscillations, is the time-

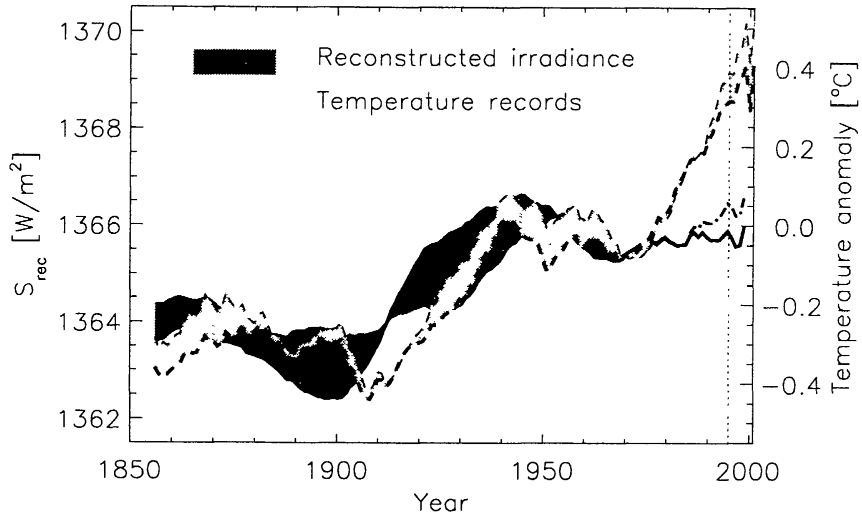


Figure 8. Total solar irradiance and terrestrial temperature vs. time for irradiance reconstructions with an increase in the 11-year averaged irradiance between 1700 and 1980 of 4 Wm^{-2} (Solanki & Fligge, 1999; Fligge & Solanki, 2000). The solid curves prior to 1985 represent irradiance reconstructions (thick curve: cycle-length based, thin: cycle-amplitude based). From 1985 onwards they represent total irradiance measurements (solid: composite of Fröhlich & Lean 1998; dot-dashed: composite following Willson 1997). The dashed curves represent global (thick) and northern hemisphere (thin) temperatures. All curves have been smoothed by an 11-year running mean. After the epoch marked by the vertical dotted line the averaging period has been successively reduced.

dependent magnetic field of the Sun. The most prominent example of this variability is the 11-year cycle seen in many proxies of solar activity. Such cyclic activity turns to be typical among late-type stars, but the possibility to resolve the Sun's surface makes it by far the best studied example. Studies of other stars and their evolution in turn furnish insights into the mechanisms of solar variability on longer time scales, which is of great importance for understanding the causes of changes of the Earth's climate.

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Discussion

Andronov: Besides the solar cycle of 11 years (and longer) and the rotation period (and shorter scales), are there any preferred time scales of solar variability? Does the spectrum obey a power law, resembling a fractal variability?

Solanki: The spectrum basically obeys a power law, with some strong local peaks (e.g. around 5 minutes due to p-mode oscillations) and some broader, gentle bumps whose origin is not yet clear. According to the textbooks the variations on time scales of minutes to days are caused by the evolution of different types of convection cells, but this needs to be checked and understood.