



Solar activity and climate

Measurements in terrestrial ice cores and in biological sediments provide information on past variations of the tropospheric temperature as well as on those of past solar activity. It appears that both are correlated, although not strongly. Never in the past ten thousand years has the sun been as active as in the past half century. The climate has been extreme too in that same period of time. The question of the causal relationship is of interest.

Solar activity is driven by the solar dynamo. Helioseismology has provided us with good information on the internal solar conditions and processes, especially those in the tachocline, which is important as the seat of magnetic fields.

Solar variability has two aspects: a regular variation of the solar irradiance and the emission of magnetised plasma clouds. Both vary in pace with the sunspot (Schwabe) cycle and they are (loosely) correlated. Both may be a cause for influencing terrestrial climate but presently available data seem to favour the first mechanism.

The sun varies with at least six semi-periods. The dynamo is a non-linear process that shows chaotic elements. Phase catastrophes do occur. Therefore it is basically not possible to forecast future solar variability

1. Past variations in solar activity and climate

Measurements in ice cores (Greenland and Antarctica) but also those in biological sediments, have provided us with very useful information on the variations in the past, both of the tropospheric temperature as well as in solar activity. Information on the variation of tropospheric temperatures over the years is derived from a comparison of the $^{16}\text{O}/^{18}\text{O}$ contents in air bubbles included in ice cores, while that on solar activity is given by deposits of cosmogenic radionuclides, such as ^{10}Be in sediments and ice cores. The cosmogenic radionuclides are produced by cosmic radiation interacting with upper atmospheric molecules. In turn, the flux of cosmic radiation received on earth is modulated by the magnetic fields in plasma surrounding the Earth and filling the heliosphere. The magnetized plasma is emitted by the Sun, and the amount emitted depends on the degree of solar activity. The more active the Sun, the more plasma emitted, the smaller the cosmic radiation flux on Earth and the consequent number of deposited ^{10}Be particles.

Figure 1 presents the variation of solar activity over the past 12,000 years, as measured through ^{10}Be and ^{14}C deposits. The upper frame shows that during the past 2000 years the Sun has not been as active as it was during the past half century, while the lower

frame shows that this statement even applies to the past 11,000 years. We note that while speaking in this connection of solar activity we refer to the emission of magnetized plasma clouds, because these affect the production of cosmogenic radionuclides through modulation of cosmic rays. This statement is important because there are other manifestations of solar activity. They are mostly correlated with the emission of plasma clouds but the correlation is not in all cases strong and there are indications of time delays between the maxima of sunspot activity and of the frequency of Coronal Mass Ejections (CMEs). The *Energetic Emissions Delay* (de Jager 2005) of about one to two years is the average time difference between maxima of sunspot activity and of CME ejections.

Figure 2 gives the variation of average Northern Hemisphere temperatures with time over the past 2000 years as published by Moberg et al. (2005). Note that there appears to be some correlation between this curve and those of Fig. 1; note also that over the past half century the average Northern Hemisphere temperature was higher than ever in the past 20 centuries. The similarity between the curves of Figs. 1 and 2 is suggestive and asks for an explanation, or at least for further study.

In this connection we have to add a few critical notes. First, that there are clear indications that the variation of average temperatures is not the same

over the whole Earth. Some regions have higher temperature increases than others, and there are even geographical areas where the temperature variation was opposite in sign (cf. Coughlin & Tung 2004; Matthes et al. 2004; Langematz et al. 2005). Next, that satellite measurements have hardly shown any temperature increase over the past decades, contradiction ground based observations. There are also clear indications (De Laat & Maurellis 2004) that the observed temperature increase of the past few decades is just restricted to global industrialized areas such as Western Europe and parts of the US. For references to the lively and far from finished discussions on these problems we refer to De Jager (2005, Ch. 7).

Partly for these reasons we restrict the remainder of this paper to a discussion of the observed variations of tropospheric temperature and of solar activity from before 1960, a period over which good information is available.

2. Solar activity and the solar dynamo

We briefly recapitulate the various well-known aspects of solar activity. The Centres of Activity (CAs) are surrounding the sunspots with their strong magnetic fields. The CAs surround the spots; their sizes are of order 40,000 (longitude) to 20,000 km (latitude). They are the seats of weaker, scattered fields that present themselves near the limb as facular fields. Their limb visibility is due to the fact that their temperature increases with height, due to dissipation of magnetic energy. *Solar flares* in CAs are ascribed to reconnection of magnetic flux tubes and in their

initial phase high temperatures (~ 50 MK, but occasionally much higher) are briefly observed. *Coronal Mass Ejections* are magnetized clouds of plasma emitted from CAs. Also the coronal holes, the ephemeral active regions and the polar faculae emit magnetized plasma. Such clouds leave the Sun with small velocities but the speed increases underway to values of order 500 to 1000 km/sec. They disperse over the heliosphere and thus finally fill the heliosphere with magnetized plasma. That way they can influence the cosmic ray flux received on Earth.

The number of spots varies during the 11-years cycle, often called the Schwabe cycle. The first spots of a cycle appear at latitudes around 30°, while over the following years during the cycle the spot zone appears gradually at lower latitudes (Carrington's law). During the following cycle all polarity configurations change sign (Hale's polarity laws). Hence actually there is rather question of a 22-years cycle, the *Hale cycle*.

At latitudes above ~ 40° the activity is manifested by polar faculae (Makarov & Makarova 1996), ephemeral active regions (Harvey & Martin 1973) and unipolar active regions (Priest

1981). The polar faculae and the connected seats of emission of high latitude plasma clouds move pole-ward during the Schwabe cycle. They reach maximum intensity some 5 years after spot maximum (Makarov et al. 2005).

A remarkable feature is that the most energetic flares and associated phenomena tend to appear one to two years after spot maximum: the Energetic Emissions Delay (Fig. 3).

The various aspects of solar variability are thought to be driven by the solar dynamo. Dynamo theory has to explain five elements: the Hale cycle, Carrington's law of equator-ward drift of the spot zone, the origin of the poloidal field elements including the pole-ward motion of the polar prominence zone and of the ephemeral active regions; Hale's polarity law and the Energetic Emissions Delay. Below we give a brief and necessarily incomplete description of a possible scenario.

Starting feature is an assumed poloidal magnetic field, hence extending from pole to pole. Helioseismologic observations have provided us with accurate data on the internal solar rotation (Fig. 4). The

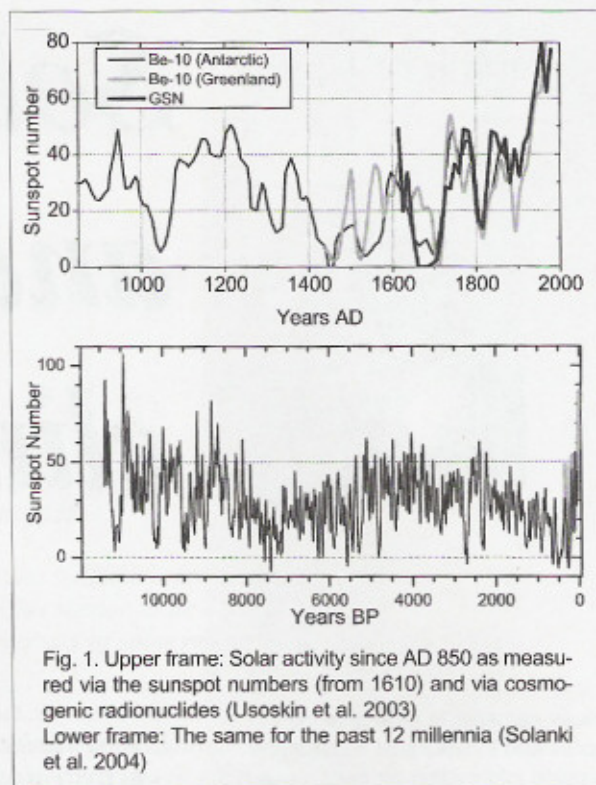


Fig. 1. Upper frame: Solar activity since AD 850 as measured via the sunspot numbers (from 1610) and via cosmogenic radionuclides (Usoskin et al. 2003) Lower frame: The same for the past 12 millennia (Solanki et al. 2004)

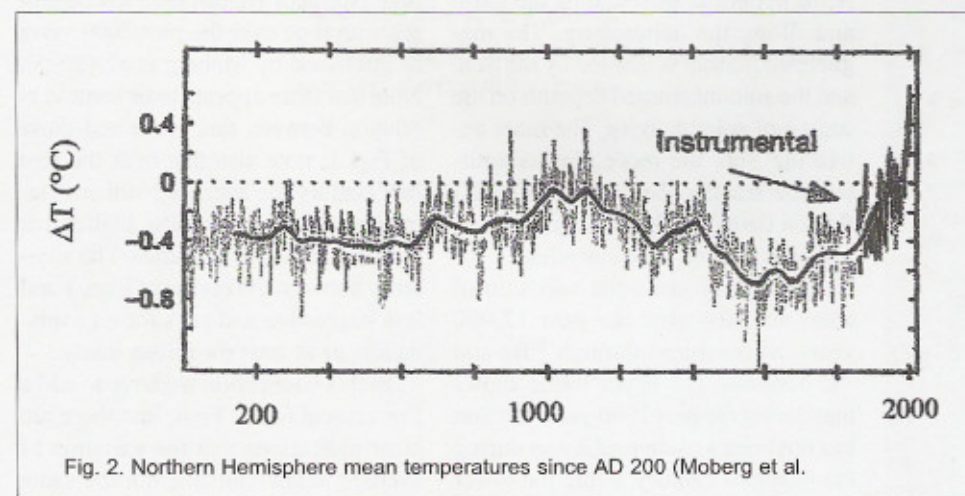


Fig. 2. Northern Hemisphere mean temperatures since AD 200 (Moberg et al.

main feature is that in the upper 200,000 km (the convection zone) the equatorial regions have a higher angular rotation rate than the polar ones. By this differential rotation the polar fields are stretched. That process happens primarily in the tachocline, which is the level at the basis of the convection zone. As a result the fields obtain a toroidal component and they are amplified. When locally the magnetic fields obtain values of order 10^5 Gauss, they become buoyant and consequently they move upward. Accordingly, sunspots arrive at the surface. In their upward motion they drag weaker fields along and so Active Regions arrive at the surface, surrounding the spots.

To this feature we have to add the existence of slow Hadley cell circulation in the convection zone: along the lower part of the zone there is an equator-ward streaming while at higher levels the motion is directed pole-ward.

Weaker dynamo action and field amplification occurs higher up in the convection zone. Combination of the uprising motions with the necessary Coriolis forces make two things happen: fields are amplified and these fields eventually obtain an important poloidal component. By the influence of the Hadley cell circulation, which is pole-ward near the upper part of the convection zone, these fields move pole-ward. At the end of the Schwabe cycle a new, but oppositely directed, poloidal field is thus created; after that the second part of the Hale cycle starts.

3. The two aspects of solar variability that may influence climate

The total solar irradiance appears to vary during the solar cycle. The amplitude is small, about 0.1%. Figure 5 compares the irradiance variation over the period 1979 through 2000, as compared with the total magnetic field variations and the sunspot number. The parallelism is obvious. There is also some indication of the Gnevyshev Gap: two successive maxima that appear one to two years after each other. This is caused by the fact that the activity in the two solar hemispheres does not reach maximum at the same time.

Closer study of the irradiance variations, including the wavelength dependences shows that the variation is ma-

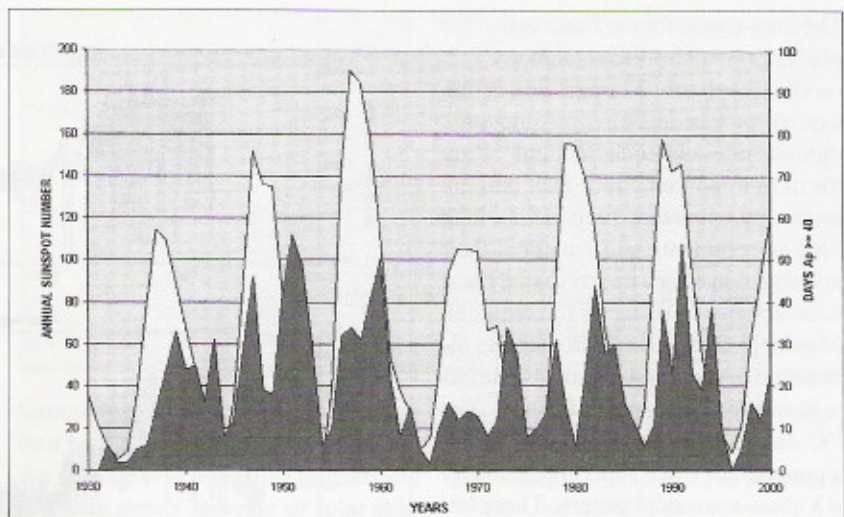


Fig. 3. Annual number of geomagnetically disturbed days with A_p index > 40 (dashed line and hatched area) and annual sunspot number (solid line) for cycles 17–23. Courtesy J.H. Allen, NOAA National Geophysical Data Center, Boulder Co.

inly situated in the UV part of the spectrum with a small additional contribution from the IR part. This is so because the amplitude of the UV flux variation during the cycle equals that of the total irradiance. Since the relevant part of the UV flux is emitted by low-chromospheric parts of the sun, the conclusion must be that the photosphere proper does not change during the cycle (detailed discussion in De Jager 2005). This result was already found by Woodard & Libbrecht (2003). That conclusion seems to counter the finding by Gray & Livingston (1997) that the photospheric temperature varies during the cycle with an amplitude of 1.5 K. But if that result were true then the total irradiance would already change by the observed amount of 0.1% only by the photospheric contribution, not including the variation of the same order of the UV radiation flux, which is a contradiction.

The variation of the solar irradiance can not directly influence terrestrial tropospheric temperatures because the UV flux is mainly absorbed in stratospheric levels. Indirectly it can, through large-scale atmospheric meridional circulation.

The other aspect of solar variability that may influence climate is the emission of magnetised plasma. The main contributions are from Coronal Mass Emissions and the plasma stream from coronal holes. A smaller contribution is from ephemeral active regions. A measure for their importance at Earth distance is the open solar flux (Lockwood et al. 1999), which is the activity-connected magnetic flux in interplanetary space. The magnetised plasma remains in the heliosphere with a dissipation time that is estimated at 3 to 5 years. Hence, at any time, also during solar minimum activity, there is magnetized plasma in the heliosphere.

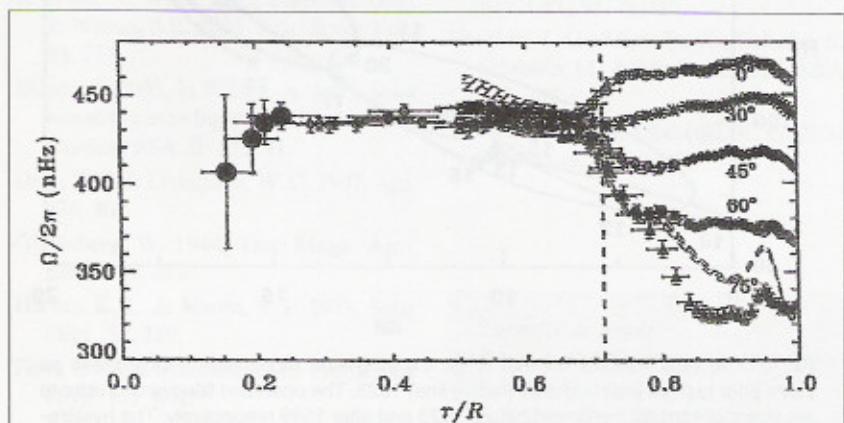


Fig. 4. Solar interior rotation frequencies as function of depth and latitude. The tachocline is at $0.69 R_{\odot}$. (Thompson et al. 2003)

The importance for the Earth is that the plasma modulates the cosmic ray flux received on Earth. The past flux is measured by the deposited cosmogenic radionuclides of which ^{10}Be and ^{14}C are the most important. Since their half life time is such that they remain for a long time in sediments and ice cores their investigation offer a means to study past solar activity in so far as the emission of solar plasma is concerned. In the discussion of such measurements one has to be aware of non-solar influences. The ^{14}C record over the Holocene shows a gradual slope and superimposed over it a quasi-sinusoidal pattern. These latter variations are thought to be of terrestrial origin. For a part they are due to variations in the Earth's magnetic field with time.

The cosmic ray particles ionize the Earth's atmosphere. At altitudes of a few km cosmic rays are the main source of ionisation. Ions, electrically charged aerosol particles and charged water droplets may then act as condensation nuclei for water droplet formation and so an enhanced cosmic ray flux may cause increased cloud formation in the atmosphere at km heights. Several authors have studied these problems. Svensmark & Friis-Christensen (1997) and Dergachev et al. (2004) found correlation between solar activity and cloud formation: stronger activity is correlated with reduced cloudiness as may be expected.

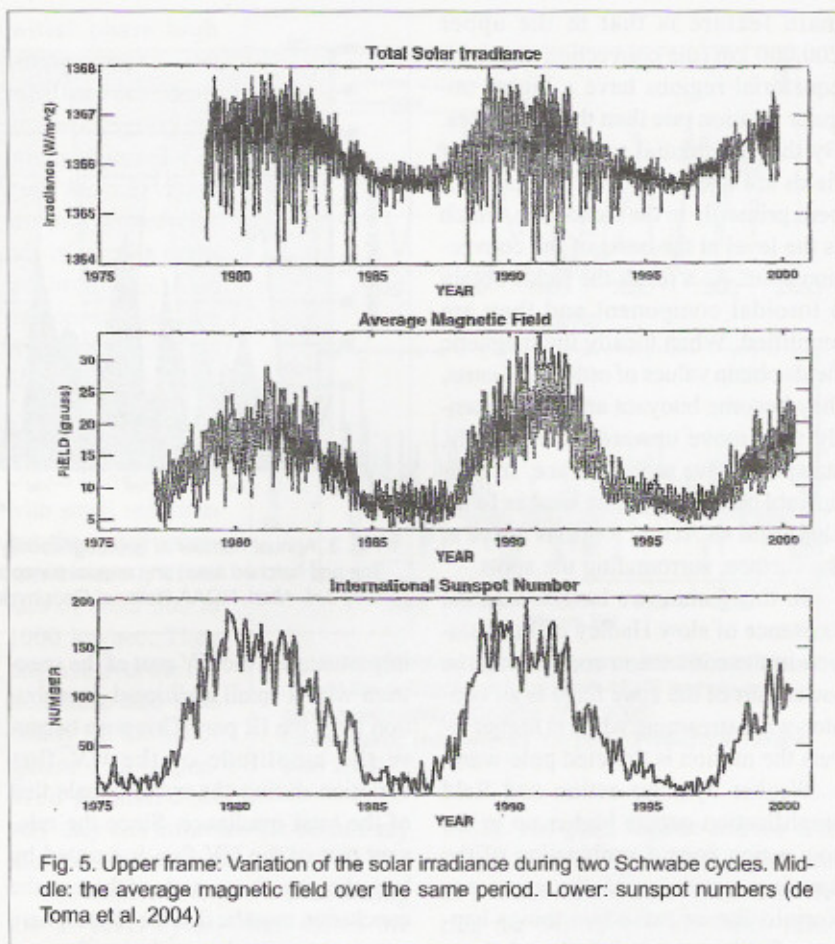


Fig. 5. Upper frame: Variation of the solar irradiance during two Schwabe cycles. Middle: the average magnetic field over the same period. Lower: sunspot numbers (de Toma et al. 2004)

4. Which of the two, or both?

The next obvious question is which of the two mechanisms (UV heating or plasma clouds) is the most important in influencing climate. We may translate this question in solar terms. Since

the sunspots and the associated facular regions are originating from the toroidal magnetic fields while the most important part of the emitted plasma is related to the poloidal fields, the question may be reformulated: are toroidal solar fields or rather poloidal fields important in influencing climate?

A hint to the possible answer is found by studying the correlation of Moberg et al.'s Northern Hemisphere temperatures with either the Group Sunspot Number (Hoyt & Schatten 1998) and with the solar source function, as derived from the flux of deposited cosmogenic radionuclides (Solanki et al. 2000). Since Group Sunspot numbers are only available for the years after 1610 we took that year as our starting year. We did not use radionuclide data from after 1960 because of possible human influence. The data were smoothed with a triangular profile with half width of 9 years, in order to eliminate the strong variations in the sunspot numbers due to the Schwabe cycle. A correlation analysis shows higher correlation between temperatures and Group Sunspot Numbers than between temperature and source

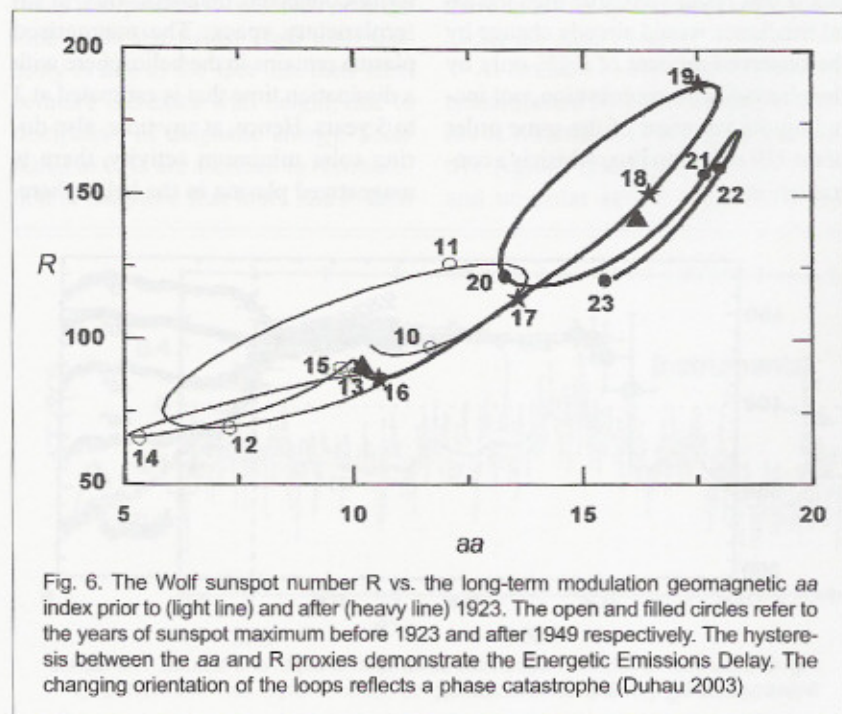


Fig. 6. The Wolf sunspot number R vs. the long-term modulation geomagnetic aa index prior to (light line) and after (heavy line) 1923. The open and filled circles refer to the years of sunspot maximum before 1923 and after 1949 respectively. The hysteresis between the aa and R proxies demonstrate the Energetic Emissions Delay. The changing orientation of the loops reflects a phase catastrophe (Duhau 2003)

function. A preliminary conclusion may be that terrestrial temperature variation correlates best with that of the UV fluxes and are hence caused by variations in the strength of the toroidal magnetic fields. A reserve is that this result does not exclude that both effects are active at the same time.

5. The chaotic solar dynamo

Subsequent authors have found many periodicities or quasi-periodicities in solar variability, measured either by the time variation of the sunspot number or by variations in the fluxes of cosmogenic radionuclides. We list them in Table 1.

In the literature more possible periods have been mentioned, but it is not sure if these are really solar. They may be due to other, possible terrestrial causes. The periods listed in Table 1 are pretty firmly determined. Their values are not fixed, though, and vary over time. During the past century the Schwabe cycle was 10 years rather than 11. Ogurtsov et al. (2002) describe the wide frequency band of the Gleissberg period: there are two maxima, one of 50–80 years and another of 90 to 140 years. Lee & Wang (2003) found average periods of 53 and 101 years.

It seems attractive to use such data for forecasting solar activity for coming years. Most authors, who did so, concluded that solar activity may decrease in the course of the 21st century. But such attempts may be questioned because the solar dynamo is a non-linear system that moreover shows phase jumps. The latter effect was shown first by Duhau (2003), cf. Fig. 6, by plotting the lower envelope of the geomagnetic *aa* index, which may be taken as a proxy for the strength of the poloidal fields (Ruzmaikin & Feynman 2001) against the smoothed sunspot numbers, taken as a proxy for the variations in the toroidal fields. The plot shows closed loops that show hysteresis: the Energetic Emissions Delay. Moreover there is a clear jump in orientation after 1923. This was the phase jump that initiated the extraordinary increase in solar activity of the past century.

Another way to study the behaviour of the solar dynamo is by plotting the fraction of the source function that is due to the poloidal field, versus the

Table 1: periodicities in solar activity

Period (years)	Name	Main ref.
1.3	—	Basilevskaya et al. 2000
11	Schwabe	
22	Hale	
88	Gleissberg	Gleissberg 1944
205	De Vries (Suess)	Ogurtsov et al. 2002
2300	Hallstadt	Clilverd et al. 2003

Group Sunspot Numbers, assumed to be a proxy for the toroidal component. An important aspect is the gradual and virtually steady increase of solar activity from the years of the Maunder Minimum (1652–1704) till 1950. During part of the Maunder Minimum, when sunspots were virtually absent, the poloidal field and its consequent emission of magnetised plasma were still active, because the measured ¹⁰Be flux was significant. In some years the relation shows a discontinuous jump. The, in my view, most important feature is the chaotic and virtually unpredictable character of the dynamo.

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