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Solar Forcing of Climate

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Abstract Solar activity is evident both in the equatorial activity centres and in the polar magnetic field variations. The total solar irradiance variation is due to the former component. During the extraordinarily long minimum of activity between sunspot cycles 23 and 24, the variations related to the equatorial field components reached their minimum values in the first half of 2008, while those related to the polar field variations had their extreme values rather at the end of 2009 and the first half of 2010. The explanation of this delay is another challenge for dynamo theories. The role of the open solar flux has so far been grossly underestimated in discussions of Sun-climate relations. The gradual increase in the average terrestrial ground temperature since 1610 is related both to the equatorial and polar field variations. The main component (0.077 K/century) is due to the variation of the total solar irradiance. The second component (0.040 K/century) waits for an explanation. The smoothed residual increase, presumably antropogenic, obtained after subtraction of the known components from the total increase was 0.31 K in 1999.

Keywords Solar forcing · Climate · Total and spectral solar irradiances

1 Introduction

The discussions in the workshop underlined the complexity of the Earth's atmosphere of which essential aspects are still far from being understood. This is in contrast to the simple and transparent structure of that of the Sun. But these thoughts made me remember a colloquium once held in an astronomical institute during which the lecturer claimed "A star is a very simple structure." Whereupon a voice from the audience interposed "You sir,

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would be a very simple structure too, at a distance of ten light-years." The Sun is at only eight light-minutes. That makes it the most complicated star that we know of, but along this line of reasoning, its atmosphere is still quite simple as compared to that of the Earth. In the following, I will discuss some of the essential elements and the resulting discussions of the presentations made at the workshop in session 3, which was devoted to solar forcing of climate.

2 Measuring Total Solar Irradiation and its Spectra

The energy received on Earth from the Sun relative to the non-solar energy (geothermal energy, tidal energy and waste heat from fossil fuel) stands as 1–0.0004. The primary components of the varying parts of the total solar radiation are the facular radiation and the sunspot darkening. These vary while the Sun rotates. Attempts to model that variation by Unruh show good agreement between model and observations. The contribution of the chromospheric network[1] is still to be examined.

So far, we possess data on the total solar irradiance (TSI) over three solar cycles. The observations, when performed simultaneously, show virtually the same time-dependent shapes, but they differ in the absolute values. This is a characteristic of absolute intensity measurements. Performing these is one of the most difficult experimental techniques. The resulting curves show a small degree of variability. Essentially, the shape of the Schwabe cycle of sunspot number variability is well reproduced in that of the TSI.

The variability is mainly due to the variation of the solar area covered with faculae, the brighter and hotter magnetic regions around sunspots that together constitute the activity centres. The size of the area covered with faculae and the number of such areas on the solar disc are, to a good approximation, proportional to the number of sunspots on the disc. While the spectrum of the non-magnetic part of the disk has its maximum intensity in the visual spectral range, the radiation from the activity centres has its maximum rather in the violet and ultraviolet parts. A substantial percentage of the enhanced radiation from the facular fields is emitted in the wavelength range below 400 nm. This is so because of the higher facular temperatures, about 10,000 K. This stands in contrast to the non-magnetic parts of the solar disk, of which the temperature is close to the solar effective temperature, $T_{eff} \approx 5{,}800$ K. All other magnetic parts of the Sun, such as the network, have higher temperatures. An important part of the far UV radiation is from the Lyman α line. It originates from higher parts of the chromosphere than all other contributions mentioned here. During Schwabe cycles, its amplitude varies by about 50 % (Lean and Woods 2010).

Dissipation of magnetic energy, transported towards the solar surface by the lower situated convective motions, is the main cause for the higher temperatures of the magnetic parts. Solar variability is mainly concentrated in the activity centres of which the main visual marking is the sunspots in their centres. It should be remarked, though, that a spot as such is a thoroughly inactive part of the Sun. The real variability, as presented in faculae, solar flares, flare surges, coronal mass ejections and the like, is concentrated in the surroundings of the spots. A still open problem is that of the emission by the network, whereby one should distinguish between the general solar network that covers the whole surface and the enhanced network that appears in the aftermath of the facular fields during their decline.

[1] A web-like pattern easily seen on the solar disk in the emissions of the red line of hydrogen (H-alpha) and in the ultraviolet due to the concentration of bundles of magnetic field lines under the effect of fluid motions.

3 The Recent Extreme Solar Minimum

Conspicuous is the very long-lasting recent minimum that we have witnessed in the past few years. The times, at which the various solar activity indicators reached their minimum values, ranged between early 2008 and late 2010. Interestingly, indices such as the UV flux and the MgII line core emission had their minima nearly at the same time (early 2008) as the sunspot number. This is understandable since the facular emission correlates well with sunspots. On the other hand, the galactic cosmic rays had their extreme values in the second part of 2009 and even as late as in 2010. The association with the cosmic ray flux suggests a physical cause related to the open solar flux (cf. "The Open Solar Flux" below) and the related emission of magnetic plasma.

A diagram presented by Lockwood, and referred to herewith as Fig. 1, best summarizes the above. It shows that indices related to the activity centres reached minimum values around the first half of 2008, while those related to coronal activity, the open solar flux and galactic cosmic rays, variables that are partly related to the polar activity and to solar particle fluxes had their extreme values around the end of 2009 and early 2010. Hence, contrary to the conventional picture that the polar magnetic fields reach their maximum simultaneously with minimum values of the equatorial fields, there was a time lag of nearly two years during the past sunspot minimum period. These observations must have their implication for our views on the physical mechanisms of the solar dynamo.

The extended minimum of 2008–2010 lasted longer than previous minima during the past century, and this associated with the very low polar magnetic field strengths during that period leads—on the basis of the Gnevyshev-Ohl rule—to the conclusion that the next solar activity maximum will be as late as 2013–2014 and fairly low ($\sim$60 in sunspot numbers; De Jager and Duhau 2009; Duhau and De Jager 2010). In this connection, we refer to Nandy et al. (2011) who found that a long-lasting minimum may be related to a situation in which the solar meridional sub-surface plasma streaming has an initial high velocity during the time before the preceding sunspot maximum and is followed by a strongly reduced velocity. I may remark, though, that the large variations in the meridional

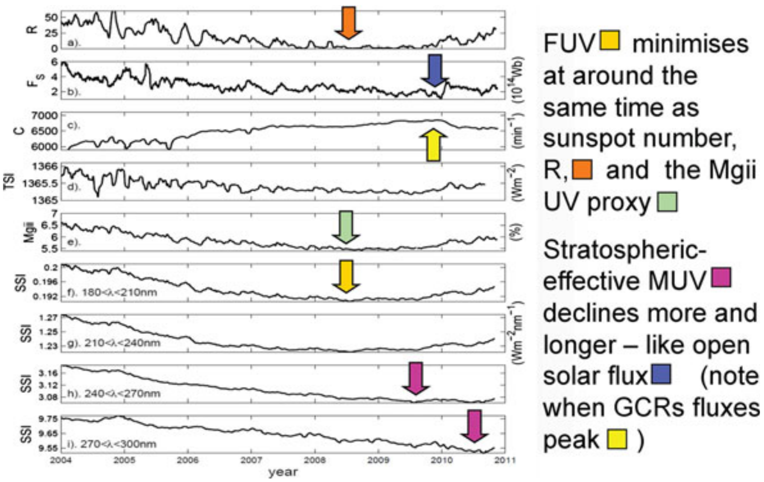

Fig. 1 Indices related to the activity centres (source and SOLSTICE data) shown by Lockwood during the workshop

velocities that are needed for explaining the observations were not observed in helioseismic observations.

Fröhlich drew attention to his observation that the TSI during the past solar minimum was lower than during the previous two minima. The difference with the earlier minima can be expressed in effective temperatures and is as small as 0.25 K. It is about equal to twice the mean error of the observed values and, understandably, this fact gives rise to dispute. Criticisms of the reality of the deep minimum are indeed implied in the contribution by Unruh. Also, Krivova et al. (2011) do not agree with this result. On the other hand, both Barnard et al. (2011) and Ball et al. (2012) confirm the low minimum between cycles 23 and 24.

The above observation may be compared with those of spectral irradiance. During the workshop, Unruh showed that the observed spectra, including their variability, could well be represented by numerical modelling during a full solar rotation. Although this would show that we well understand solar spectral variability, there is a remarkable recent development. Remarkable, because of its contrast with earlier observations, is the spectrum obtained by the SORCE-SIM team (Haigh et al. 2011). In the visual spectral range, the intensity appears to be less than in earlier minima while it is relatively higher in the ultraviolet part of the spectrum. These observations provoked discussion, since they were thought not to correspond with usual conjectures. Particularly, they are not confirmed in Unruh's analysis. An offhand explanation may be that these observations, if correct, are related to a yet to be explained very minor enhanced density of the upper photosphere and the chromosphere.

For the TSI, the situation is clearer, as the VIRGO observations agree well with the ACRIM-II/III data. Essentially, the differences between UV and visual spectral irradiance would be important for climate modelling (cf. Haigh et al. 2011).

4 The Open Solar Flux

The presentation by Rozanov at the workshop showed the results of the influence on climate of varying solar activity indices, especially the UV radiation but also the varying particles fluxes. Discussions during the workshop underlined the importance of the open solar flux (OSF) for the topic of Sun–Earth relations, as well as the need to include that notion in the relevant investigations. The OSF is usually defined as the magnetic flux emerging quasi-radially from a sphere around the Sun's centre situated at a distance of 2.5 solar radii, but this value does not receive unanimous agreement.

An important remark that emerged during the workshop was that instead of looking for correlations of the Earth's average surface temperature with the polar magnetic field variation, it may appear to be more rewarding to correlate average terrestrial surface temperatures with the open solar flux. Lockwood found that it correlates better with terrestrial surface temperatures than other indices do. An indication that the OSF is related to the polar magnetic fields may be extracted from a finding by Fröhlich that a good correlation is found when the comparison of TSI and the flux is restricted to the solar minima—at these times, the polar flux has maximal values.

In discussions during the workshop, Dudok de Wit showed a way to disentangle the open solar flux from the geomagnetic *aa* data. Over the past grand maximum of solar activity, the OSF shows a steady increase with time and, while the sunspot data reached their largest values during the extreme maximum of 1957–1958, the OSF had its maximum values only after 1980 according to Lockwood's presentation at the workshop. A recent attempt to link the open solar flux with total solar irradiance is based on the observations of cosmogenic radionuclides measured in ice cores (Steinhilber et al. 2009). The measurements cover a period of 9300 years.

If part of the Earth's temperature variation is related to the open solar flux then the conclusion seems unavoidable that part of the terrestrial warming must depend on particle emission, either from the Sun or else activated by the Sun. This aspect was discussed by Rozanov (cf. "Sun-Atmosphere Relationships"). The role of particles in Sun–climate relations has been discussed many times in the scientific literature, but in order to play a significant role, it should involve strong amplification mechanisms. An overlooked topic is the chemistry induced by precipitating particles and the role of aerosol formation by cosmic ray particles. An experiment called "CLOUD" is now under development at CERN which aims at simulating the processes of the interactions between cosmic ray particles and an experimental model simulating the Earth atmosphere with a blend of sulphuric acid and ammonia.

5 Sun-Atmosphere Relationships

Solar incoming radiation interacts with the atmosphere at various heights, depending on the wavelength and the character of the radiation (continuum versus lines). Particles of different kinds and energies are absorbed at different heights in the Earth's atmosphere. Rozanov discussed the energy deposition in the atmosphere, both electromagnetic and particle radiation. The heating rate in the atmosphere varies with height and with solar activity. The depth to where particles penetrate and the consequent atmospheric ionization are likely to vary. As to the charged particle inflow, it is only the galactic cosmic rays that are able to penetrate down to the troposphere. UV radiation is absorbed in stratospheric layers. The precise height and degree of absorption depend both on the wavelength and on the chemistry of the stratosphere. The resulting terrestrial surface temperature variation depends on the degree of coupling between the stratosphere and the lower layers. The forcing is not yet well defined, and the physical explanation of the solar effects is still beset with uncertainty.

Lockwood investigated periods of severe winters in England. A relative lack of cold winters appears to occur for periods of high solar activity. This correlation is associated with the occurrence of 'blocking events', which are large long-lived anticyclones that deflect the jet stream and thus may cause the occurrence of cold eastern winds over Europe.

Several authors have discussed the observed more or less gradual rise of the Earth's surface temperature since the last stages of the deep Maunder Minimum of solar activity, in around 1700 A,D. This was usually done by correlating the Earth's average surface temperature, or that of part of the Earth such as the Northern Hemisphere, with the total solar irradiance. Since the latter is only known for the last three Schwabe cycles, it is usually extended to earlier times by correlating it with the sunspot number. It is habitually found that these variations in TSI are too small to contribute effectively to terrestrial temperature variation.

By only considering the TSI and the sunspot number, the assumed solar variability that would influence climate is restricted to the sunspot belt, but the solar dynamo, which governs solar variability, is an intricate interplay between the toroidal sunspot belt's magnetic field and the poloidal (polar) field. The latter's principal manifestations are the solar wind emerging from coronal holes, the radiation from polar bright points and polar faculae and the like. Although the polar field does not show strong concentrations comparable with the sunspots, the total polar flux is comparable with that of the toroidal field. This is understandable because the one originates from the other. De Jager described an attempt to disentangle both correlations by studying seven recent average temperature data files and found that the average temperature increase over the period 1610–1970 (hence before the period of significant antropogenic warming) can be split in three components (cf. de Jager et al. 2010). Correlated with the equatorial field is an average increase of 0.077 K/century; the polar field component is 0.040 K/century, and a remaining part of 0.051 K/century is not of solar origin. The first is explained by the variation of the TSI provided one includes a positive water vapour feedback of a factor 2. The feedback effect was discussed by Rozanov, who showed that there is a fair amount of coupling between stratospheric warming and the resulting tropospheric effects. It was, though, not quantified.

The second component has not yet found a physical explanation, while the third must be due to atmospheric effects. After having subtracted the above-mentioned components from the recent average surface temperature values, a smoothed residual for 1999 was left of 0.31 K. A value derived relative to the average residuals for the period 1800—1950, and the total excess with regard to the period 1650–1750 would be 0.62 K (de Jager et al. 2010), while Lockwood found a value of 0.86 K for the excess of 2000–2009 with regard to 1650–1750. If both sets of data would be forming a homogeneous set, this would imply an increase for the period 1999–2009 of 0.24 K, but this increase is not supported by observations. The difference is most probably due to the use of different data sets.

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Appendix: Pilewskie's Comments on Solar Spectral Irradiance Forcing on Climate

Measurements of solar spectral irradiance (SSI) during the last solar cycle (cycle 23) from the NASA SORCE mission (Harder et al. 2009) have received considerable attention for suggesting that the Sun's output varies in ways not previously considered. SORCE data published to date shows that spectral irradiance in the ultraviolet region of the spectrum varied by a factor of 3–10 times more than it did in the previous cycles. However, this was compensated by bands in the visible and near-infrared where irradiance *increased* during the declining phase of the cycle. These new modes of spectral variability have been implemented in a number of climate and atmospheric model simulations (see, for example, Haigh et al. 2011). Although it has been suggested that modelled atmospheric response to the SORCE spectral variability agrees better with observations than simulations forced with Naval Research Laboratory (NRL) spectral irradiance reconstruction (Lean 2000), there are some inconsistencies among the models and with empirical evidence of solar cycle-induced temperature response. Perhaps, more importantly, however, it should be noted that validation of the SORCE spectral irradiance trends can only be provided by other irradiance measurements. Some papers (DeLand and Cebula (2012), Lean and DeLand (2012)) have called into question the consistency of the observed trends with other present and past measurements and with solar activity. Therefore, it is premature to speculate on the validity of the SORCE SSI trends until a thorough validation, now underway, is completed. Furthermore, the measurements published to date cover only part of a solar cycle and must be extrapolated over the full cycle for model analysis, adding additional uncertainty to the simulations (Garcia 2010). Until the SORCE SSI validation is complete, uncertainties in the measured irradiance and their trends are better quantified, and a full solar cycle has been observed, caution is urged in the interpretation of climate response to the recent observed trends in solar spectral irradiance.

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