Modelling Solar Irradiance: Values and Uncertainties

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Abstract— Solar irradiance variations, along with anthropogenic effects, are an essential component of global climate change, and need to be included in attempts to model the climatic variations expected to occur over the next century or so. There is a wide diversity of models: some are based upon the assumption that irradiance modulation arises below the solar photosphere ("surface"); others that it is strictly a surface phenomenon. In all cases though, the complexity of the modelling task and paucity of data other than empirical indices such as sunspot number, require the use of proxies and fitting. The result is that all the models fit the time-series of irradiance measurements since 1978, but diverge in their estimates of the history of irradiance variations. If we confine our interest to the interval 1800 AD to (say) 2100 AD, a simple, totally empirical model using the 10.7 cm solar radio flux or sunspot number should be a useful means for estimating solar irradiance.

I. Introduction

Global climate change is the change in climatic response to the energy received from the Sun. Although there is a strong and possibly domiant anthropogenic component driving current changes in climate, variations in solar irradiance need to be included in climate modelling. The climate machine is almost certainly highly non-linear, may vary through a series of metastable states rather than continuously, and may be chaotic in at least some regimes. Moreover, in the current situation, where increasing amounts of solar energy are being trapped and then stored in the atmosphere and oceans, the sensitivity of the climate to even small changes in solar energy input rate needs to be considered.

There is ample historic evidence of a relationship between solar variability and climate in the recent, mediaeval and geological records [1]. The more obvious recent ones were drops in solar activity known respectively as the Wolf (1280-1350 AD), Spörer (1420-1540 AD), Maunder (1645-1715 AD) and Dalton (1795-1825 AD) minima. The connection between these periods of low solar activity and anomalous periods of climatic cooling were first pointed out by Eddy [2], [3], [4], [5], [6].

In considering global climate change, models for solar irradiance fulfil three important roles: (i) they can be used in estimating irradiance in the past, where irradiance records are unavailable, before anthropogenic influences upon the climate and atmosphere became significant, (ii) they can be used in bridging gaps in the observations of irradiance and as a means of checking the internal consistency of the time series of irradiance measurements. This is important because the database contains contributions from several instruments and there are inevitable uncertainties in bridging data gaps between instruments, and (iii) as part of modelling future climate change as needed for programme planning.

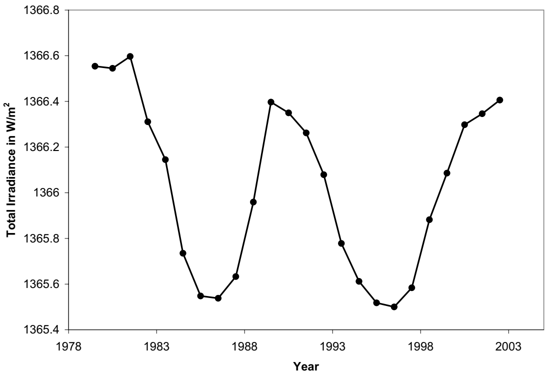

Fig. 1. Annually averaged irradiance values derived from the integrated series of irradiance measurements.

II. The Data

A. Irradiance: I

Through a succession of instruments, irradiance measurements have been made over almost three solar activity cycles so far, from 1978 to the present. The integration of the these separate data sets into a single, consistent and calibrated record is described by Pap and Fröhlich [15], [16]. This integrated irradiance database was obtained from PMOD/WRC, Davos, Switzerland. The irradiance values used in this paper are annual averages, and are shown in Figure 1. The modulation of the total irradiance by the solar activity cycle is clearly visible.

B. Sunspot Number: N_s

Sunspot number values are manual counts of the number of sunspots visible on the solar disc. There are empirical

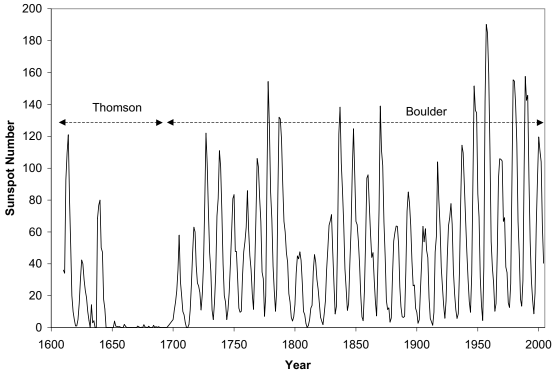

Fig. 2. Annually averaged irradiance values derived from the integrated series of irradiance measurements.

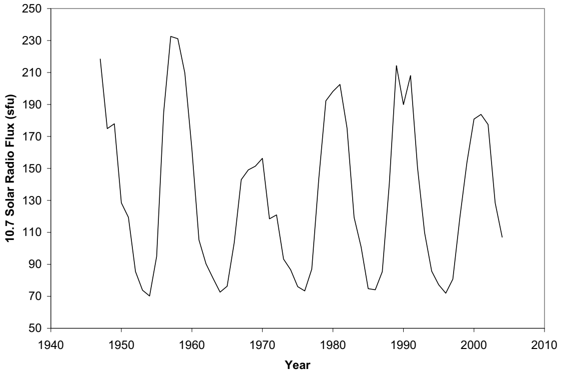

Fig. 3. Annually averaged values of the 10.7 cm solar radio flux from 1947 to the present.

procedures for estimating the number of spots in a group, and correction factors for integrating contributions made through a multiplicity of observers, instruments and observatories over more than three centuries. Considering the possibilities of inconsistencies entering the database, the time-series of sunspot number measurements has proved a remarkably durable and useful record of solar activity. The main database of sunspot numbers is maintained by the Solar Influences Data Centre (SIDC) in Belgium, but available through a number of sources worldwide. The sunspot number data used in this paper, covering the period 1700 to the present, were obtained from the National Geophysical Data Center, Boulder, Colorado. To extend the date series to before the Maunder Minimum, David Thomson (Queen's University, Kingston, Ontario - private communication), using research by Hoyt and Schatten [17], [18], [19], [20], [21] made estimates of sunspot number from 1610 onwards. The integrated data set is shown in Figure 2.

C. 10.7 cm Solar Radio Flux: $F_{10.7}$

The 10.7 cm solar radio flux values are measurements of the slowly-varying (S-) component of solar radio emission, which comprises the total emission from all structures on the solar disc, with the exception of flares. It is thermal in origin, originating in trapped plasmas in the solar chromosphere and corona, mainly concentrated over active regions. It can be observed at wavelengths ranging from about 50 to 1 cm, but it is brightest at wavelengths around 10 cm. A more detailed discussion of the S-component and its origins are given in monographs by Kundu [23] and Krüger [22], and the 10.7 cm solar radio flux more specifically in Tapping [24] and Tapping and Harvey [25]. The 10.7 cm solar radio flux is given in solar flux units (1 solar flux unit (sfu) $\equiv 10^{-22}\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$). The annually-averaged flux values are shown in Figure 3.

III. Modelling Solar Irradiance

This section comprises two sections: a brief overview of aspects of irradiance models, and then a simple approximation that can be used within the context of studying climate change at least over the interval 1800-2100 AD.

A. Models

In a very general form, the solar irradiance (solar energy flux per square meter falling on the top of the Earth's atmosphere) can be described using the equation:

$$I(t) = W(t).M(t).S(t).D(t), \tag{1}$$

where $W(t)$ is the rate at which energy is produced in the Sun's core, $M(t)$ is the modulation of energy flow as it flows from the core to the "surface" (photosphere), where it flows into space, $S(t)$ is modulation of the emission into space due to the changing distribution over the surface of darker (e.g. sunspots) and lighter features (e.g. faculae), and $D(t)$ describes changes in the irradiance observed at the Earth due to changes in the distance between the Earth and Sun. The function $W(t)$ varies only over timescales of millions of years, and can be ignored over century timescales, $D(t)$ varies over the year, as the Earth pursues its elliptical orbit around the Sun. Long-term changes in $D(t)$ have been proposed as one explanation for the occurrence of ice ages. However, within the context of this discussion, and averaging data over a year, $D(t)$ can be assumed to be constant, so the irradiance model simplifies to (absorbing constants into the functions): $I(t) = M(t).S(t)$.

There are two main schools of thought in modelling irradiance. Some workers [7], [8], [9] suggest that observed irradiance variations can be explained purely in terms of surface phenomena, that is, we need only to consider $S(t)$. On the other hand, other workers [10], [11] invoke changes in the Sun's internal structure to produce small changes in the mean surface temperature ($M(t)$). That the solar interior might be involved is supported by helioseismological studies [12], [13], [14].

In almost all cases, these models are compared with the time-series of irradiance measurements starting in 1978 and then used to estimate irradiance back in time, usually to the Maunder Minimum, which marks the start of the continuous record of sunspot number. The complexity of the physics, which leads to a need for approximations and empirical fits, and the need to estimate other solar quantities from sunspot number, lead to estimating modelling parameters by fitting the model to the data. It is not therefore surprising that all the models fit the observations well. However, there is significant divergence as the models are extrapolated back in time, particularly when fits to a 30-year data sequence are used to extrapolate 300 years back into the past. For example, irradiance estimates for the Maunder Minimum range from 0.3 W.m^{-2} lower than present [28] to as much as 2 W.m^{-2} lower than present [27]. At this point, because of the inability to avoid fits, extrapolation (both back in time and outside the parameter space in which the models were developed) and proxies, and it is not clear that this divergence will be improved in the foreseeable future.

In examining the Sun's role in global climate change, it is desirable to reliably estimate solar irradiance back at least to before the industrial revolution, before anthropogenic contributions to atmospheric greenhouse gases became significant, but not so far back in time that the divergence between models becomes too great a problem. We therefore consider the interval 1800 AD, and the possibility of forecasting and extrapolation to 2100 AD.

B. A Simple, Empirical Tool

In 1800 AD, the divergence decreases to 0.5 W.m^{-2} lower than present [28] to 1 W.m^{-2} lower than present [27]. A usable (simple) modelling tool should produce an irradiance estimate that falls within that range at 1800 AD, fit irradiance measurements and not show divergent behaviour that would make it less useful in modelling future irradiance.

In solar irradiance variability, when averaging over entire years, the rhythm of the solar activity cycle dominates the more complex interplay between the different magnetic structures. The 10.7 cm solar radio flux is an excellent index of the total amount of magnetic flux in those structures, and also changes in disc temperature if any. Therefore, if the relationship between all the structures remains the same on average, we can use the 10.7 cm solar radio flux as a proxy for solar irradiance. The plot is shown in Figure 4. A fitted line has the equation $I = 0.0072F_{10.7} + 1365$, where $R^2 > 0.9$.

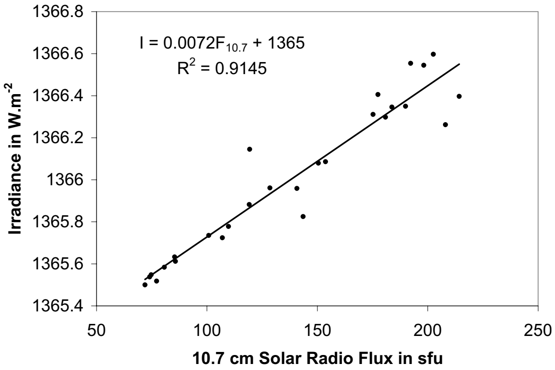

Fig. 4. Annual averages of irradiance plotted against similarly averaged values of the 10.7 cm solar radio flux.

This simple linear model is usable from the beginning of the record of 10.7 cm solar radio flux in 1947. Before that we have only sunspot number. This is an essentially empirical index of solar activity. Its relationship with the magnetic flux components is problematic, but it is strongly correlated (although non-linearly) with the 10.7 cm solar radio flux. The relationship between the two quantities is shown in Figure 5. Increases in radio flux per unit sunspot number are lower when activity is low. The empirical formula,

$$F_{10.7} = \frac{N_s}{2}\left(2 - \exp(-0.01N_s)\right) + 68 \qquad (2)$$

which gives the solar radio flux value in solar flux units, fits well, as evidenced by the modelled values (solid circles), passing through the centre of the measured values (open circles).

Combining the two equations, sunspot number can be used to model irradiance (in W.m^{-2}) using the equation

$$I = 0.0072\left(\frac{N_s}{2}\left(2 - \exp(-0.01N_s)\right) + 68\right) + 1365 \qquad (3)$$

Irradiance values since 1800 AD estimated using this simple model are shown in Figure 6.

This equation fits the observed irradiance values as well as the more complex, less empirical models. It is much simpler, and gives an irradiance for 1800 AD that is about 0.4 W.m^{-2} lower than present, which certainly fits within the range estimated using more complex models. The model fits current values and should be a well-behaved predictor usable to 2100 AD or so, depending upon the availability of predicted values of sunspot number or 10.7 cm solar radio flux.

IV. Forecasting Future Irradiance

Sunspot number forms a continuous, reasonably homogenous data set. It is therefore possible it is possible to estimate current and future values of sunspot number

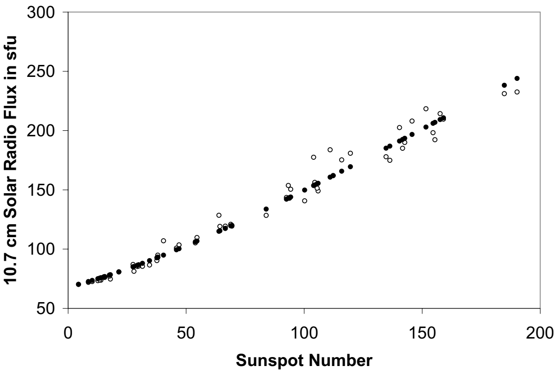

Fig. 5. Annually averaged values of the 10.7 cm solar radio flux plotted against annually-averaged sunspot number. The open circles are the data values and the solid circles are 10.7 cm solar radio flux values estimated using sunspot number by means of the empirical relationship given in the text.

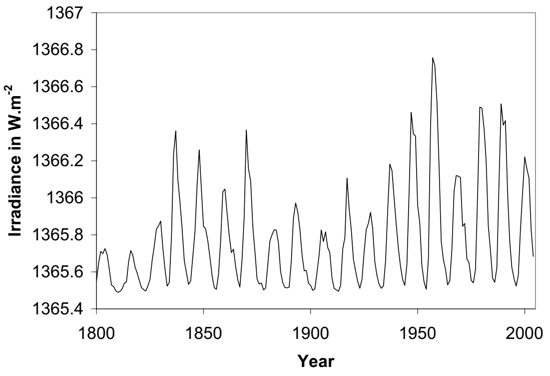

Fig. 6. Irradiance values since 1800 AD made using the simple model described in the text.

from previous values. Expressing this in a general way, with no a priori assumptions,

$$N_n = \Psi\left(N_{n-1}, N_{n-2}, N_{n-3} \cdots N_{n-n}\right) \tag{4}$$

where Ψ is a non-linear, autoregression function. In this form, without simplifications, the equation is very difficult to solve. However, it can be addressed using neural networks and genetic algorithms. Valdés ([26]) applied this technique in a manner that made no assumptions about the homogeniety or continuity of the data set, and used the sunspot number record from 1700 to 1978 AD to forecast sunspot number from 1978 to the Present. The observed and predicted values are shown in Figure 7.

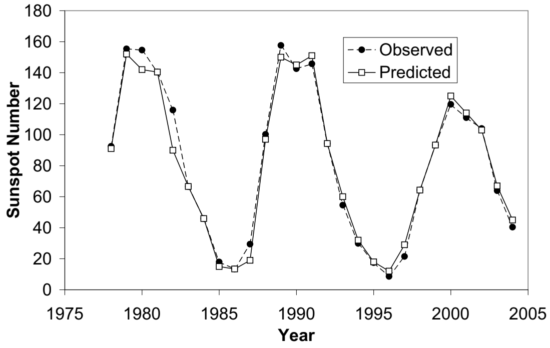

Fig. 7. Observed sunspot number 1978-Present (dashed line and filled circles), compared with the values predicted by Valdés ([26] (solid line and open squares).

We are currently using this method to attempt to predict sunspot number for the next 30 years, and use it to predict irradiance for the same period.

V. Discussion and Conclusions

The climate is a complicated, non-linear system, possibly varying through a series of metastable states rather than continuously, and maybe chaotic. Although anthropogenic effects are very likely to be the major cause of climate change, the effect of solar irradiance variations upon the climate machine may be significant, either as a direct modifier of climate or as a changer/triggerer of transitions between metastable states. There is certainly evidence that in the past, changes in the Sun's enmergy output produced signficant climatic responses. Drops in the general level of solar activity were accompanied by episodes of significant climatic cooling. Therefore, in assessing the level of climate change with which we will be faced in future, it is necessary to include solar variability.

The objective of this paper is not to be a detailed discussion of irradiance modelling, but more to provide enough background for those including solar irradiance variation in climate change models. The models explore a range of approaches, but all encounter the same difficulty, namely that the physics is complex and not all the required parameters are known. Therefore they all use proxies and fits with observed data. The result is that they all fit the time series of irradiance measurements since 1978 quite well, but produce increasingly different results as one extrapolates the model back in time. If we limit the extrapolation back in time to about 1800, which antedates the industrial revolution and the concomitant anthropogenic emission of greenhouse gases, a simple empirical model can be used, which fits observational data and falls within the irradiance range estimated using the more sophisticated models.

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