Atmósfera 19(4), 267-274 (2006)

A new reconstruction of total solar irradiance since 1832

J. M. VAQUERO
Departamento de Física, Escuela Politécnica, Universidad de Extremadura,
Avda. de la Universidad s/n, 10071 Cáceres, España
Corresponding author e-mail: jvaquero@unex.es

M. C. GALLEGO
Departamento de Física, Facultad de Ciencias, Universidad de Extremadura,
Avda. de Elvas s/n, 06071 Badajoz, España

R. M. TRIGO
Centro de Geofísica da Universidade de Lisboa, Portugal, Departamento de Engenharias,
Universidade Lusófona, Lisboa, Portugal

F. SÁNCHEZ-BAJO
Departamento de Electrónica e Ingeniería Electromecánica, Escuela de Ingenieros Industriales,
Universidad de Extremadura, Badajoz, España

M. L. CANCILLO, J. A. GARCÍA
Departamento de Física, Facultad de Ciencias, Universidad de Extremadura,
Avda. Elvas s/s 06071 Badajoz, España

Received July 1, 2005; accepted April 21, 2006

RESUMEN

Diferentes autores han propuesto que las variaciones de la irradiancia solar total y espectral son magnitudes que pueden influir en el clima. El objetivo de este artículo es reconstruir la irradiancia solar total desde 1832 hasta el presente. Las contribuciones de las regiones activas y del "sol quieto" se modelan separadamente usando el método de Solanki y Fligge (1999). El área de las manchas solares desde 1832 es utilizada para calcular la contribución de las regiones activas a los cambios en la irradiancia.

ABSTRACT

Variations of solar irradiance (total and spectral) are quantities purported to have an influence on climate. The aim of this paper is to reconstruct the total solar irradiance from 1832 to the present. The contributions of active regions and the quiet sun are modelled separately using the method developed by Solanki and Fligge

(1999). The areas of sunspots observed since 1832 are used to compute the contribution of active regions to the irradiance changes.

Keywords: Total solar irradiance, solar forcing on climate, solar-terrestrial physics.

1. Introduction

Some studies by both the astrophysical and the meteorological communities have shown the fingerprint of solar activity in our climate (Eddy, 1976; Friis-Christensen and Lassen, 1991; Kodera, 2002). However, the exact physical mechanisms responsible for this influence are as yet barely understood. One of the mechanisms proposed is the change in the total solar irradiance. However, accurate measurements of total solar irradiance (TSI), with sufficient precision to show its variability have become available only since 1978. A recent comprehensive review on solar irradiance variability is given in Solanki and Krivova (2004). Solar activity is now widely accepted to have played a major role over the last millennium and, in particular, during the significant warming (positive trend) observed in late 19th and early 20th centuries (IPCC, 2001). In fact, recent works have clearly detected the impact of solar variability in both stratospheric (Labitzke, 2005) and tropospheric circulation patterns (Kodera 2002; Baldwin and Dunkerton, 2005), in particular the shape and intensity of the major Northern Hemisphere atmospheric circulation mode, the North Atlantic Oscillation (Ogi *et al*., 2003; Gimeno *et al*., 2003; Bochnícek and Hejda, 2005). Unfortunately, the exact physical mechanisms responsible for this associationship are not yet well understood, despite some early attempts to describe such mechanisms (Shibata and Kodera, 2005). Readers looking for recent substantial summaries are refereed to the books by Benestad (2003) and by Pap and Fox (2004).

The reconstruction of solar activity is very important for climatologists and solar physicists because it allows extending into the past reliable time-series much required by both communities. There are a number of different methodologies to assess solar variability throughout the last four centuries. Some of these are based on observations of aurorae (Krivský, 1984; Silverman, 1992) or the shape of the solar corona during eclipses (Vaquero, 2003). However, the majority of these reconstruction techniques are based on sunspots characteristics. Vaquero *et al*. (2004) realized a contribution in this sense in order to reconstruct the monthly sunspot area since 1832. In recent years, several reconstructions of the total solar irradiance have been proposed (Foukal and Lean, 1990; Hoyt and Schatten, 1993; Zhang *et al*., 1994; Lean *et al*., 1995; Solanki and Fligge, 1998, 1999; Lockwood and Stamper, 1999; Fligge and Solanki, 2000; Lean, 2000; Foster, 2004). Here we intend to obtain a different reconstruction of solar activity based in sunspot areas since 1832, for this purpose we will use extensively the data provided by Vaquero *et al*. (2004).

2. Method and data

The majority of the reconstruction of the Total Solar Irradiance (S_{rec}) is based on the following model

$$S_{rec} = S_0 + \Delta S_{act} + \Delta S_{qs} \qquad (1)$$

where S_0 is just a constant which is added in order to produce the correct absolute value of the observed irradiance. The term ΔS_{act} is the contribution to the TSI of the solar active regions, while term ΔS_{qs} corresponds to the contribution of the quiet-Sun. Thus, the contributions from the three different components of surface magnetism are included, namely: sunspots, faculae and the network. It is a well known fact that sunspots lead to a darkening of the Sun while faculae result in a brightening. The combined contributions of these two phenomena are reflected in the irradiance variations term (ΔS_{act}), which is the main responsible for irradiance variations over time scales equal or smaller than the solar cycle. Finally, the network component provides the main contribution to irradiance variations on time scales longer than the solar cycle (ΔS_{qs}).

Solanki and Fligge (1999) used the relationship between modern satellite measurements of solar irradiance and sunspot numbers in order to estimate the contribution of the solar active regions (ΔS_{act}) to the TSI. We should stress that, due to the relatively short length, the contribution of the quiet-sun term (ΔS_{qs}), during the period of availability of modern satellite data, is virtually zero. The sunspot area time-series reconstructed by Vaquero *et al*. (2004) is based on the Group Sunspot Number, hereafter R_G (Hoyt and Schatten, 1998). Several studies have pointed to the advantage of using the R_G instead of the Wolf Sunspot Number as it probably guarantees a better assessment of the real solar variability, particularly before 1880 (Usoskin and Kovaltsov, 2004). In fact, the R_G can be easily adopted to obtain a different reconstruction of the ΔS_{act} term. Using the approach presented by Solanki and Fligge (1999) to reconstruct the TSI, one could estimate ΔS_{act} using the relationship between modern satellite measurements of solar irradiance (Fröhlich, 2000) and contemporaneous sunspots area values. Figure 1 shows precisely the relationship between these two quantities using annually averaged data. The constant S_0 can be calculated as the TSI value when the sunspot area tends asymptotically to zero.

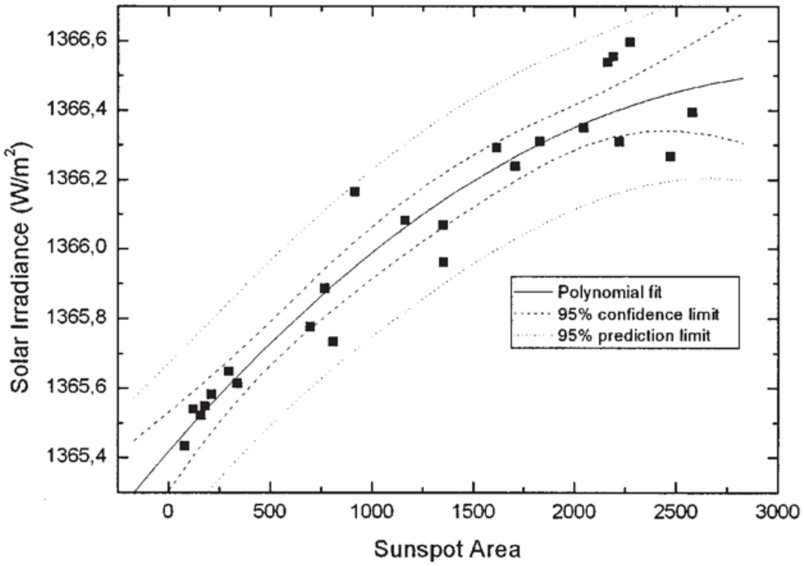

Fig. 1. Relationship between the annual average sunspot area and the corresponding measured solar irradiance. The fit of a polynomial of degree 2 to the data is included as a solid line. The 95% prediction and confidence limits are included as dotted and dashed lines.

This relationship will be used for estimating the contribution to the TSI of the solar active regions, ΔS_{act}, from sunspot area measurements since 1832. We have fitted a quadratic function to obtain the relationship between modern satellite measurements of solar irradiances and sunspot area A values during the period 1979-2002. The best quadratic fit to the data is given by:

$$S = (1365.42 \pm 0.05) + (6.8 \pm 1.1) \times 10^{-4} A + (-1.0 \pm 0.4) \times 10^{-7} A^2 \tag{2}$$

therefore, the contribution of the solar active regions (ΔS_{act}) to the TSI will be estimated based on the equation

$$\Delta S_{act} = (6.8 \pm 1.1) \times 10^{-4} A + (-1.0 \pm 0.4) \times 10^{-7} A^2. \tag{3}$$

The estimated standard error of S and ΔS_{act} is 0.1 W/m². These values correspond to relative errors of about 0.007% and 10%, respectively. Thus, using the values of sunspot area A, since 1832 reconstructed by Vaquero *et al*. (2004), one can obtain the contribution of the solar active regions (ΔS_{act}).

The following step in the reconstruction is to utilize estimations of the long-term quiet-Sun irradiance variations, ΔS_{qs}. Two slightly different approaches have enabled Solanki and Fligge (1999) to obtain two different estimates of the term ΔS_{qs}. These two time series, hereafter identified as A and B (Fig. 2), were kindly provided to us by Solanki and Fligge (1999). Series A is based on the amplitudes of the group sunspot number R_G (Hoyt and Schatten, 1998), while series B is based on the length of the solar cycle (Lean *et al*., 1992; Baliunas and Soon, 1995).

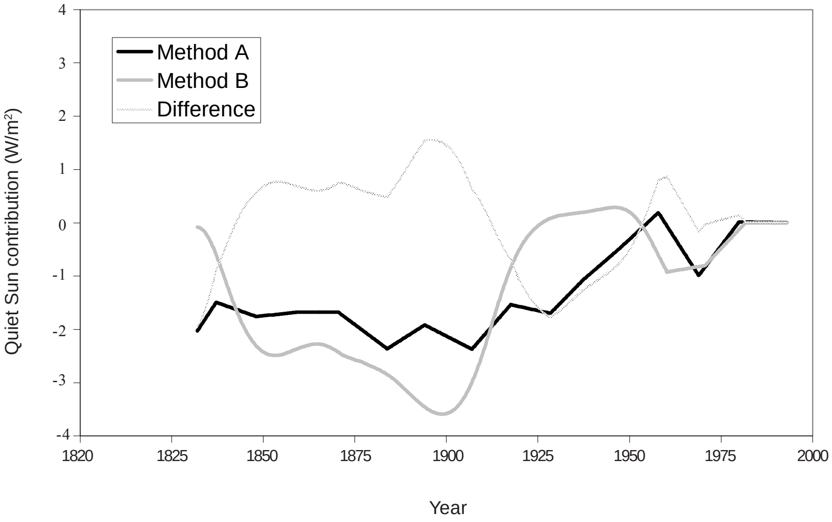

Fig. 2. The two series of quiet-Sun contribution to solar irradiance used by Solanki and Fligge (1999). The difference between the two methods is also shown.

Adding the contribution to the TSI of solar active regions and the contribution of the quiet-Sun, ΔS_{act} and ΔS_{qs}, we can obtain a reconstruction of the TSI since 1832.

3. Results and conclusions

Figure 3 shows our two different TSI time series reconstructed since 1832. As expected, the dominant term in both curves is due to the quiet-Sun contribution. The contribution of the active regions, although of smaller amplitude, causes clearly an 11-years cycle in the series reconstructed. Moreover, both reconstructions show an increase of the TSI during the 20th Century, albeit more intense in model B.

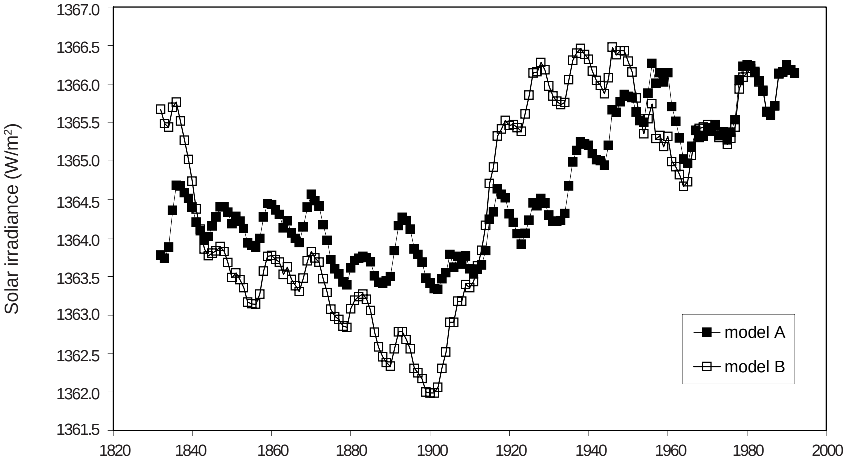

Fig. 3. Reconstruction of total irradiance with both models since 1832.

Figure 4 shows the annual differences between the reconstructions of ΔS_{act} derived by Solanki and Fligge (1999) and the one obtained in this work. We should stress that taking into account the procedure developed here, the difference between ΔS_{act} values obtained with these two reconstruction techniques is independent from which model we consider. The maximum difference between the reconstructions can reach 0.5 W/m^2, although the average value of these differences is only 0.02 W/m^2 and the standard deviation is 0.12 W/m^2. Moreover, Figure 4 shows a structural change between the two reconstructions after 1880. In fact, throughout most of the 19th century there is a clear periodicity that, after 1880, is mostly absent, particularly after the beginning of the 20th century. This change is explained by the different sunspot number used in the two reconstructions. Solanki and Fligge (1999) used the Wolf or Zurich Sunspot Number (R_Z) and Group Sunspot Number (R_G). Two records of ΔS_{act} were created using R_G and R_Z. The final ΔS_{act} record is an average of the two. However, Vaquero *et al*. (2004) used in the reconstruction procedure the Group Sunspot Number (R_G). The indexes R_Z and R_G are very similar from 1880 onwards, however before 1880, the amplitude of solar cycles using R_G is lower than using R_Z. Thus, there is a pattern –highly correlated with the solar cycle– before 1880, in the differences between the reconstructions of ΔS_{act} derived by Solanki and Fligge (1999) and the one obtained in this work.

We can conclude that the use of the sunspot area as the unique element to compute the contribution of the solar active regions to the changes of irradiance agrees considerably well with the prior results obtained using the sunspot number (Solanki and Fligge, 1999).

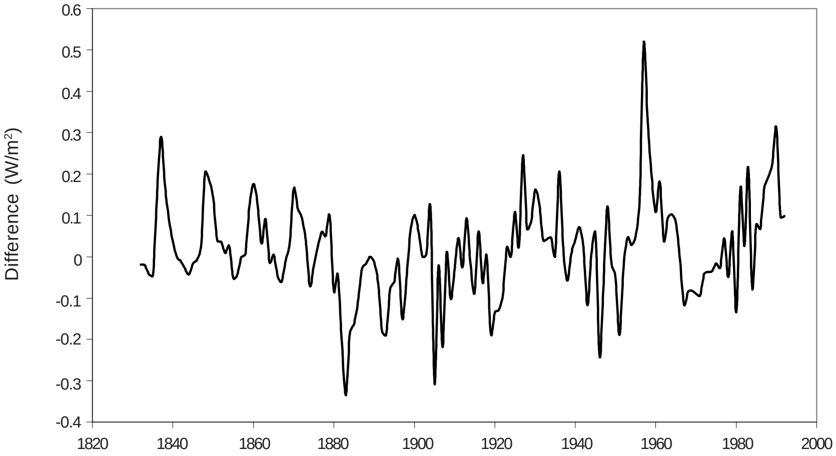

Fig. 4. Differences between the reconstruction of ΔS_{act} obtained by Solanki and Fligge (1999) and the reconstruction attained in this work.

Acknowledgements

The authors would like to thank Dr. Solanki and Dr. Fligge for providing the long-term quiet-Sun irradiance variations. We are also in debt with PMOD/WRC (Davos, Switzerland) for supplying the irradiance composite data.

References

Baliunas S. and W. Soon, 1995. Are variations in the length of the activity cycle related to changes in brightness in solar-type stars? *Astrophys. J*. **450**, 896-901.

Baldwin M. P. and T. J. Dunkerton, 2005. The solar cycle and stratosphere–troposphere dynamical coupling. *J. Atmosph. Solar-Terrestrial Phys.* **67**, 71-82.

Benestad R. E., 2003. *Solar activity and Earth's climate*. Springer Praxis Books, 287 p.

Bochnícek J. and P. Hejda, 2005. The winter NAO pattern changes in association with solar and geomagnetic activity. *J. Atmos. Solar-Terrestrial Phys.* **67**, 17-32.

Eddy J. A., 1976. The Maunder Minimum. *Science* **192**, 1189-1202.

Fligge M. and S. K. Solanki, 2000. The solar spectral irradiance since 1700. *Geophys. Res. Let*. **27,** 2157-2160.

Foster S., 2004. Reconstruction of solar irradiance variations for use in studies of global climate change: Application of recent SOHO observations with historic data from the Greenwich Observatory. Ph. D. thesis, University of Southhampton, Faculty of Science, School of Physics and Astronomy, 430 p.

Foukal P. and J. Lean, 1990. An empirical model of total solar irradiance variation between 1874 and 1988. *Science* **247**, 556-558.

Friis-Christensen E. and K. Lassen, 1991. Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science* **254**, 698-700.

Fröhlich C. 2000. Observations of irradiance variability. *Spa. Sci. Rev*. **94**, 15-24.

Gimeno L., L. de La Torre, R. Nieto, R. García, E. Hernández and P. Ribera, 2003. Changes in the relationship NAO-Northern Hemisphere temperature due to solar activity. *Earth and Planetary Science Letters* **206**, 15-20.

Hoyt D. V. and K. H. Schatten, 1993. A discussion of plausible solar irradiance variations, 1700-1992. *J. Geophys. Res.* **98**, 18895-18906.

Hoyt D. V. and K. H. Schatten, 1998. Group Sunspot Numbers: A new solar activity reconstruction. *Solar Physics* **179**, 189. Reprinted with figures in *Solar Physics* **181**, 491.

IPCC, 2001. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (Eds.), Climate Change 2001: The Scientific Basis – Contribution of Working Group I to the 3rd Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (UK), 881 p.

Kodera K. 2002. Solar cycle modulation of the North Atlantic Oscillation: Implication in the spatial structure of the NAO. *Geophys. Res. Lett*. **29**, 1218, doi:10.1029/2001GL014557.

Krivský L., 1984. Long-term fluctuations of solar activity during the last thousand years. *Solar Physics* **93**, 189-194.

Labitzke K., 2005. On the solar cycle–QBO relationship: a summary. *J. Atmos. Solar-Terrestrial Physics* **67**, 45–54.

Lean J., 2000. Evolution of the Sun’s spectral irradiance since the Maunder Minimum. *Geophys. Res. Lett.* **27**, 2425-2428.

Lean J., A. Skumanich, and O. White, 1992 Estimating the sun’s radiative output during the Maunder Minimum. *Geophys. Res. Lett*. **19**, 1595-1598.

Lean J., J. Beer and R. Bradley, 1995 Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophys. Res. Lett*. **22**, 3195-3198.

Lockwood M. and R. Stamper, 1999. Long-term drift of the coronal source magnetic flux and the total solar irradiance. *Geophys. Res. Lett.* **26**, 2461-2464.

Ogi M., K. Yamazaki and Y. Tachibana, 2003. Solar cycle modulation of the seasonal linkage of the North Atlantic Oscillation (NAO). *Geophys. Res.Lett*. **30**, 2170, doi: 10.1029/2003GL018545.

Pap J. M. and P. Fox (Eds.), 2004. Solar variability and its effects on climate. Geophysical Monograph Series, **141**.

Shibata K. and K. Kodera, 2005. Simulation of radiative and dynamical responses of the middle atmosphere to the 11-year solar cycle. *J. Atmos. Solar-Terrestrial Phys.* **67**, 125-143.

Silverman S. M., 1992. Secular variation of the aurora for the past 500 years. *Rev. Geophys*. **30** , 333-351.

Solanki S. K. and M. Fligge, 1998. Solar irradiance since 1874 revisited. *Geophys. Res. Lett*. **25**, 341-344.

Solanki S. K. and M. Fligge, 1999. A reconstruction of total solar irradiance since 1700. *Geophys. Res. Lett*. **26**, 2465-2468.

Solanki S. M. and N. Krivova, 2004. Solar irradiance variations: from current measurements to long-term estimates. *Solar Physics* **224**, 197-208.

Usoskin I. G. and G. A. Kovaltsov, 2004. Long-term solar activity: direct and indirect study. *Solar Physics* **224**, 37-47.

Vaquero J. M., 2003. The solar corona in the eclipse of 24 June 1778. *Solar Physics* **216**, 41-45.

Vaquero J. M., M. C. Gallego and F. Sánchez-Bajo, 2004. Reconstruction of a monthly homogeneous sunspot area series since 1832. *Solar Physics* **221**, 179-189.

Zhang Q., W. H. Soon, S. L. Baliunas, G. W. Lockwood, B. A. Skiff and R. R. Radick, 1994. Long-term drift of the coronal source magnetic flux and the total solar irradiance. *Astrophys. J. Lett.* **427**, L111-L114.