The Impact of Solar Irradiance on the Maunder Minimum Climate

B. MENDOZA¹, R. GARDOÑO², and J. ADEM²,³

¹Depto. de Física Espacial, Instituto de Geofísica, Circuito Exterior CU, UNAM, México D.F., México
²Centro de Ciencias de la Atmosfera, UNAM, México, D.F., México
³El Colegio Nacional, México

(Received April 16, 1996; Revised March 18, 1997; Accepted March 24, 1997)

We estimate an average surface Northern Hemisphere temperature anomaly of around -0.3°C for the Maunder Minimum (1645–1715) using the average total solar irradiance. As various cooling effects were neglected this estimate is an upper limit and a deeper anomaly may be found. The total solar irradiance is obtained from the solar rotation rate reconstructed using observations of sunspots recorded at the Observatoire de Paris from 1660 to 1719, and is found to be lower than at present by 0.1% to 0.43%.

1. Introduction

During the Maunder Minimum (1645–1715) there was a reduction in the number of naked-eye sunspots, very low production of aurorae, faint corona at eclipses, and an increased atmospheric radiocarbon production which has been detected in tree rings (Eddy, 1980), all of which indicate low levels of activity associated with sunspots.

An explanation for such diminished activity can be given by the α-ω dynamo theory (Krause and Radler, 1980), which predicts that the azimuthal component of the magnetic field (toroidal field) is generated by stretching of the north-south magnetic field lines (poloidal field) due to a radial shear of the internal angular velocity (differential rotation rate). Sunspots are generally thought to be produced by toroidal magnetic fields below the photosphere, which erupt to the surface due to buoyant forces. The higher a star’s rotation rate, the stronger is the stretching of the poloidal field component below the star’s surface and the generation of the toroidal component. If the Sun’s rotation rate was lower during the Maunder Minimum than at present, the toroidal field may have been weaker and the production of sunspots lower than today. The toroidal field derives from the poloidal field of the previous half-solar cycle and vice-versa. Poloidal fields are large-scale and heat the star’s atmosphere (see review by Kuperus et al., 1981). A weaker field produces less atmospheric heating, and the lower temperatures manifest as reduced solar emission, e.g., in the Ca II H and K emission lines, that brighten with increasing magnetism (Howard, 1959; Leighton, 1959).

Previous works have estimated the reduction in solar luminosity during the Maunder Minimum. Lean et al. (1992) using an empirical correlation between total solar irradiance corrected for sunspot dimming and integrated Ca II emission as a surrogate for bright magnetic features, concluded that the Sun’s irradiance in the absence of magnetic bright features, i.e., during quiet Sun periods, could have been from 0.15% to 0.35% below the average present radiative output, as measured by the ACRIM radiometer on the Solar Maximum Mission satellite. More recently Lean et al. (1995) have reconstructed the annual total solar irradiance since 1610, determining separately the 11-year irradiance cycle and the longer term variability of the facular network. They found for the years 1650 to 1700 an irradiance reduction of -0.24% compared with the ACRIM average radiative output. Nesme-Ribes and Mangeney (1992) found a 0.2% luminosity decrease from comparison between differential helioliatitudinal rotation changes during the Maunder Minimum and modern time. Also Nesme-Ribes et al. (1993) found an average of 0.25% to 0.5% of decrease in luminosity, using apparent solar radius measurements for the Maunder Minimum period and assuming a constant ratio for the anticorrelation between the Sun’s diameter and its luminosity.
In this paper we make use of the relationship between a star’s rotation rate and its radiative output to estimate the total irradiance. Ribes and Nesme-Ribes (1993) find that solar rotation slowed in the Maunder Minimum. Given the lower solar rotation rates in the Maunder Minimum we estimate the total solar irradiance also to be lower.

The Maunder Minimum occurred in the second half of the 17th century, when a global cooling was observed. However, although some areas of the Earth, especially Europe, experienced coolings of up to 1°C, other regions exhibited much less cooling (Legrand et al., 1990; Damon and Jirikowic, 1994). Eddy (1976) suggested that this cold period might be caused by a reduced solar irradiance. As terrestrial surface temperature seems to correlate well with solar activity (Friis-Christensen and Lassen, 1991), models for the atmosphere-ocean-continent system have been applied to simulate the impact of solar irradiance changes on terrestrial climate (Reid, 1991; Schlesinger and Ramankutty, 1992). However these models are limited by their sensitivity and do not show significant terrestrial temperature changes unless the irradiance variation is larger than the 0.1% change observed in the recent 11-year solar cycles.

The purpose of this work is twofold: to reconstruct the total solar irradiance for the Maunder Minimum using the solar rotation rates observed at that time. Then, to estimate the impact of this lower irradiance on terrestrial climate.

The paper is structured as follows, Section 2 contains the calculations for estimating the total Maunder Minimum solar irradiance. Section 3 contains the modeling of Earth’s climate which takes the results of Section 2 as inputs. Section 4 has a discussion of the results, and in Section 5 we present our conclusions.

2. Total Solar Irradiance during the Maunder Minimum

Investigations of surface magnetic fields for stars of about 1 solar mass have shown that emission in the Ca II H and K lines (HK) varies as the stellar rotation rate $\Omega$ (Skumanich, 1972).

$$\frac{HK}{HK_0} = \frac{\Omega}{\Omega_0}$$  \hspace{1cm} (1)

where the subscript $o$ corresponds to present values.

Satellite measurements of the total solar irradiance $S$ (Willson and Hudson, 1991; Hoyt et al., 1992), and ground-based observations of the Sun’s disc-integrated Ca II emission $K$ (Lean et al., 1992) exist for several solar cycles. Lean et al. (1992) found a linear relationship between $K$ and $Sc$, the total solar irradiance corrected for sunspot deficit. The expression of $Sc$ is given by

$$Sc = S - S_{Qo} (1 + Ps)$$  \hspace{1cm} (2)

where $S_{Qo}$ is the total solar irradiance for the present quiet Sun, and $Ps$ is the sunspot dimming function (Foukal, 1981).

The linear regression between $K$ and $Sc$ (Lean et al., 1992) is:

$$Sc = -(13.6 \pm 0.5) + (160 \pm 6)K.$$  \hspace{1cm} (3)

White et al. (1992) provide a relationship between the solar $K$ measurements and the stellar HK emission:

$$HK = 0.04 + 1.53K.$$  \hspace{1cm} (4)

Substituting into Eq. (3) the value of $K$ from Eq. (4), and using Eq. (1), we may now write Eq. (3) in terms of $HK$. With this new form of Eq. (3) we obtain the total solar irradiance, given by Eq. (2), during the Maunder Minimum ($S_{QMm}$):
Here we assume for the quiet Maunder Minimum Sun that $P_S = 0$ (i.e., no sunspots).

Equation (5) is required for calculating the quiet Sun total solar irradiance for the Maunder Minimum. This equation involves the rotation rate ratio $\Omega_{Mm}/\Omega_o$. The parameters are found in Table 1, and their sources are the following: Ribes and Nesme-Ribes (1993) reconstructed sunspot numbers, solar cycle lengths and rotation rates for the period 1660–1719 using careful sunspot observations at the Observatoire de Paris. During the period that they identify as the Deep Maunder Minimum (1666–1700), they find an average rotation rate of 13.97° per day for latitudes between 2° and 14° in the southern hemisphere. Toward the end of the Maunder Minimum (1701–1719) their analysis yields a value of 14.15° per day (see columns 1 and 2 of Table 1).

The longest modern measurements of $S$ were obtained by the Earth Radiation Budget Experiment (ERB) on the Nimbus 7 satellite from November 1978 through November 1992 (Hickey et al., 1988), and by the Active Cavity Radiometer Irradiance Monitor (ACRIM) on the Solar Maximum Mission satellite from February 1980 to November 1989 (Willson and Hudson, 1991). The yearly average total solar irradiance for the solar minimum or quiet Sun in 1986 measured in these experiments is shown in Table 1 column 4. The ERB and ACRIM irradiance distributions with time are quite similar (Hoyt et al., 1992).

The magnetic activity $HK$ is usually given as the ratio of the fluxes in the $H$ and $K$ Ca II emission cores over the nearby continuum fluxes. The observed values for the Sun range between 0.164 and 0.178 as the solar cycle evolves from minimum to maximum (Wilson, 1978). The minimum value in the centers of supergranulation cells in very quiet regions on the Sun is ~0.123, associated with a nearly zero mean magnetic flux density (Schrijver et al., 1989). This low value is very close to the minimum stellar flux ratio observed for solar-type stars which is 0.120 (Baliunas and Jastrow, 1990). This information is provided in column 5 of Table 1.

Entering the values from Table 1 in Eq. (5) we obtain average total solar irradiance values for the quiet Sun during the periods in the Maunder Minimum. The results appear in Table 2, columns 2 and 3. The average quiet Sun irradiance increased towards the end of the Maunder Minimum, due to an increased rotation rate $\Omega_{Mm}$. Irradiances computed using $S_{Q_o}$ from ACRIM are lower than values using ERB measurements, because ACRIM measurements of $S_{Q_o}$ are consistently lower than ERB values. This reflects differences in absolute irradiance calibration of the two instruments.

Table 1. Parameters used to calculate the total solar irradiance during the Maunder Minimum.

| $R_z$ | $\Omega_{Mm}$ (deg/day) | $\Omega_o$ (deg/day) | $S_{Q_o}$ (W/m²) | $HK_o$ |
|------|-------------------|-------------------|-----------------|--------|
| 0.121 (a) | 13.97 (c) | 14.48 (c) | 1371.38 (f) | 0.164 (b) |
| 0.877 (b) | 14.15 (d) | | 1366.99 (g) | 0.123 (f) |

(a)Sunspot average number for 1666–1700, Ribes and Nesme-Ribes (1993).
(b)Sunspot average number for 1701–1719, Ribes and Nesme-Ribes (1993).
(c)Southern hemisphere average for 2°–14° of heliolatitude, 1666–1700, Ribes and Nesme-Ribes (1993).
(d)Southern hemisphere average for 2°–14° of heliolatitude, 1701–1719, Ribes and Nesme-Ribes (1993).
(e)Average for 2°–14° of modern rotation rate of sunspots during 1977–1984, obtained from a polynomial fitting. Ribes and Nesme-Ribes (1993).
(f)Modern average measurements for 1986 from ERB, Hoyt et al. (1992).
(g)Modern average measurements for 1986 from ACRIM, Hoyt et al. (1992).
(h)Usual Ca II H and K flux ratio observed for solar minimum times. Wilson (1978).
(i)Minimum Ca II H and K flux observed in very quiet solar regions, Schrijver et al. (1989).
Table 2. Average total solar irradiance values for the quiet Sun during the Maunder Minimum.

| Period    | $S_{QMM}$ (W/m²) | ERB     | ACRIM    |
|-----------|------------------|---------|----------|
| 1666-1700 | 1370.14*         | 1365.75*|
|           | 1366.01**        | 1361.62**|
| 1701-1719 | 1370.36*         | 1365.97*|
|           | 1366.17**        | 1361.78**|

*Estimations for the solar minimum activity $HK_o$ flux = 0.164.
**Estimations for the minimum observed $HK_o$ flux = 0.123.

Table 3. Percentage decreases of the total solar irradiance values during the Maunder Minimum with respect to modern values.

| Period    | %ERB | %ACRIM |
|-----------|------|--------|
| 1666-1700 | -0.11* | -0.13* |
|           | -0.43** | -0.43** |
| 1701-1719 | -0.11* | -0.11* |
|           | -0.42** | -0.42** |

*Corresponds to $HK_o = 0.164$.
**Corresponds to $HK_o = 0.123$.

Now let us compare the values of $S_{QMM}$ during the Maunder Minimum (Table 2) with modern average values measured from ERB: $S_A$ (1978–1993) = 1371.92 W/m² (Kyle et al., 1994), and from ACRIM: $S_A$ (1980–1988) = 1367.46 W/m² (Hoyt et al., 1992). The percentage differences appear in Table 3, columns 2 and 3.

3. Modeling the Terrestrial Climate during the Maunder Minimum

Simulations of radiative forcing on the Earth’s surface temperature applying climate-ocean energy balance models have not succeeded because the sensitivity of the models requires irradiance variabilities larger than the 0.1% change observed over the recent 11-year solar cycles. However, the results of Table 3 allow us to apply the model developed by Adem (1979, 1982, 1991). It consists of an atmospheric layer of about 9 km height, which includes a cloud layer, an oceanic layer of about 60 m in depth and a continental layer of negligible depth. It also includes an ice and snow cap. The cloud layer and the frozen cap are variable in their horizontal extents. The basic equations are those of conservation of thermal energy in this atmosphere-ocean-continent system. Monthly averages of the variables are used, and we assume that the equations of hydrostatic equilibrium, perfect gas and continuity are valid for the time-averaged variables. Also the lapse rate is assumed to be constant.

The equation for the atmosphere (clouds included) is the following (Adem, 1965):

$$ca\partial T'_m / \partial t + c\left(\int H\rho_c v dz\right) \cdot \nabla T'_m - caK\nabla^2 T'_m = E_r + G_2 + G_5. \quad (6)$$

The relation for the ocean is (Adem, 1991):

$$h\rho_s c_s \partial T'_s / \partial t = E_s - G_2 - G_3. \quad (7)$$
The Impact of Solar Irradiance on the Maunder Minimum Climate

In the continents Eq. (7) reduces to:

\[ 0 = E_s - G_2 - G_3. \] (8)

The terms and symbols in Eqs. (6), (7) and (8) mean:

- \( V \): two-dimensional horizontal gradient operator,
- \( t \): time,
- \( T'_m, T'_s \): departures of the mid tropospheric and surface ocean temperatures from constant values, respectively,
- \( c, c_v \): specific heats of air and water, respectively,
- \( a \): a constant proportional to the average air density,
- \( \rho_w \): density of water,
- \( c a \partial T'_m / \partial t, h \rho_v c_v \partial T'_s / \partial t \): local rates of change of thermal energy in the atmosphere and ocean, respectively,
- \( c(\mu \rho_v zdz) \cdot \nabla T'_m, c a K \nabla^2 T'_m \): advections of energy in the atmosphere by the mean wind and by horizontal eddies, respectively,
- \( H \): height of the model atmosphere,
- \( h \): depth of the model ocean layer,
- \( z \): vertical upward coordinate,
- \( \rho_o \): computed standard air density,
- \( v \): horizontal component of the wind,
- \( K \): horizontal a\text{ustausch} coefficient for the atmosphere,
- \( E_T, E_o \): rates at which heat is added by radiation in the atmosphere and in the ocean, respectively,
- \( G_2, G_3, G_5 \): rates at which energy is added by vertical turbulent transport by sensible heat, by evaporation (both at the surface) and by condensation of water vapor (in the clouds), respectively.

We make a semi-empirical parameterization of the heating and transport terms by combining observed data with physical laws and conservation principles. The time derivatives of the temperatures are replaced by backward finite differences. We finally obtain a second order elliptic differential equation for \( T'_m \). The equation itself is solved as a finite differential equation by the Liebmann relaxation method (Thomson, 1961). The region of integration is a polar stereographic projection of the Northern Hemisphere. The integration is performed over the low resolution NMC grid, which consists of 512 points with a constant grid distance of 817 km (Adem, 1979). In the present numerical experiments we use an implicit method of integration and a time step of one month.

The snow and ice boundary is assumed to coincide with the computed 0°C surface isotherm. For each point the model selects from two fields the value to form the surface albedo field:

- One of these fields has the permanent snow and ice, i.e., the normal values for August, when the cap is mostly reduced.
- The other field has snow and ice everywhere. For this we use the normal values for January, when the cap is mostly extended. Outside this cap, we complete the field with hypothetical snow and ice with a uniform albedo of 45%.

When the surface temperature is greater than 0°C, we take the albedo value from the first field, in the opposite case we take it from the second one.

In the annual cycle, the computed 0°C surface isotherm is used to compute the surface albedo. The computations are started in August by assuming the initial normal values of surface albedo for that month as given by Posey and Clapp (1964). With these prescribed values, an iterative process begins, in which the initial values for a given month are the surface albedo generated for the previous month. We compute the surface temperature (and other variables), and repeat the process until the difference between the computed temperatures for two consecutive computations is smaller than 0.01°C. This condition usually converges after four or five iterations and implies that the internally generated snow (and ice) boundary and the 0°C computed surface isotherm have reached stable solutions. The convergence time is 6 to 8 years.
in our formulation.

The model incorporates parameterization of an interactive IR spectrum. This allows us to compute accurately absorptivity by carbon dioxide and by water vapor, as a function of atmospheric pressure, temperature and gas content. Furthermore, the increase in water vapor is expressed as a function of the increase of surface temperature, mid-tropospheric temperature and the horizontal extent of cloudiness as computed in the model (Garduño and Adem, 1988). The model with this parameterization is being applied currently to study the climatic effect of an increase of atmospheric CO$_2$ content as well as the net effects of changes in the IR water vapor emission spectrum, changes in albedo due to clouds, snow and ice.

$E_T$ and $E_p$ are proportional to the solar irradiance $S$. We applied the model taking a total solar irradiance decrease of 0.43% below modern values, $S = 1361.62$ W/m$^2$. This decrease corresponds to a very quiet Sun, with an $HK$ flux value of 0.123. We run the model with the present values of $S$ and then with that for the Maunder Minimum. The difference between the two calculations measures the climate change, defined as the computed anomalies of the climate variables: mid tropospheric and surface temperatures, precipitation, evaporation, net radiation, etc.

The surface temperature anomaly $TSDN$ has an annual and hemispherical average of $-0.29^\circ$C. In Fig. 1 the dot-dash curve shows the annual cycle of the Northern Hemisphere average of $TSDN$, and the solid curve shows the latitudinal profile of the same variable for summer, when the effect is strongest. In modeling the climate we have several shortcomings: during the Maunder Minimum the atmospheric CO$_2$ concentration has the lower preindustrial level. This CO$_2$ decrease is an independent external forcing, which reinforces the cooling. In this experiment we do not include the three main climate feedbacks. These mechanisms involve the cryosphere (snow and ice polar caps), atmospheric water vapor and cloudiness. The modeled cloudiness feedback is based on the usual assumption of fixed relative humidity in the atmosphere (Garduño and Adem, 1993). The tree feedbacks are positive in sign; i.e., they also reinforce the cooling.

![Graph of North Latitude vs. TSDN](image)

Fig. 1. Dot-dash curve, Maunder Minimum annual cycle of the Northern Hemisphere average value of the surface temperature decrease, in $^\circ$C. Solid curve, Maunder Minimum summer latitudinal profile in the Northern Hemisphere of the surface temperature decrease, in $^\circ$C.
4. Discussion

We suggest that the reduction of the solar rotation rate was the cause of the reduced solar activity during the Maunder Minimum. One result of this would be a reduced solar emission, which would produce a decrease in the Earth's temperature.

From earlier approaches, we derived Eq. (5) which involves only the rotation rate, and estimate the total solar irradiance for the Maunder Minimum. During 1666 to 1700 we found an average change of irradiance of 0.11% to 0.43% below the modern value. From 1701 to 1719 the rotation rate increased and the average irradiance percentage changes were of 0.11% to 0.42%. These results are consistent with previous estimates. However, we would like to point out that in a recent paper by Mendoza (1997) the irradiance obtained during the Maunder Minimum by a completely different method that the one presented here is even lower than those previous calculations. For instance in 1683 it was found to be ~1.23% lower than at present.

We have also modeled the impact on the Earth's climate that this reduced irradiance may have had during the Maunder Minimum. We have found an average surface temperature anomaly of ~-0.3°C in the Northern Hemisphere, with the strongest effect during the summer months and at low and middle latitudes. Reid (1991) found that the total solar irradiance for zero sunspot numbers corresponding to the Maunder Minimum should have been about 1% below the 1980 value, producing a decrease of around 1°C in global average sea surface temperature, as compared with present times. We would like to stress that the sea surface temperature and surface air temperature distributions agree only in a very general sense from 1860 to 1980. The sea temperature can have a difference of up to ~-0.3°C with respect to the air temperature (Reid, 1991), therefore our results are not quite comparable with those obtained for the sea temperature. Furthermore, we are not considering in the modeling the effects of a preindustrial concentration of CO2, the cryosphere, the atmospheric water vapor and the cloudiness. All of them reinforce the cooling. Therefore the TSDN calculated here is in fact an upper limit and deeper cooling may be found when these effects are taken into account.

5. Conclusions

We suggest that the solar rotation rate may be a quantitatively reliable parameter for estimating total solar irradiance.

The mean total solar irradiance during the years 1666–1719 was lower than modern values by 0.11% to 0.43%.

We obtained an average surface Northern Hemisphere temperature anomaly of around ~-0.3°C for the Maunder Minimum.

As deeper cooling is expected when preindustrial concentrations of CO2 and the effects of the cryosphere, atmospheric water vapor and cloudiness are included, the anomaly obtained is an upper limit.

We thank to A. Aguilar, D. Esparza and J. Zintzun for their valuable help. This work was partially supported by CONACYT grant 3921-T.

REFERENCES

Adem, J., Preliminary model for computing mid-tropospheric and surface temperatures from satellite data, *J. Geophys. Res.*, 70, 376–386, 1965.

Adem, J., Low resolution thermodynamic grid model, *Dyn. Atmos. Oceans*, 3, 433–451, 1979.

Adem, J., Simulation of the annual cycle of climate with a thermodynamic numerical model, *Geophys. Int.*, 21, 229–247, 1982.

Adem, J., Review of the development and applications of the Adem Thermodynamic climate model, *Climate Dynamics*, 5, 145–160, 1991.

Baliunas, S. L. and R. Jastrow, Evidence for long-term brightness changes of solar-type stars, *Nature*, 348, 520–523, 1990.
Damon, P. E. and J. L. Jirikowic, in The Sun as a Variable Star, IAU Collq. 143, 382 pp., Cambridge Univ. Press, 301, 1994.

Eddy, J. A., The Maunder Minimum, Science, 192, 1189–1196, 1976.

Eddy, J. A., The historical record of solar activity, in The Ancient Sun: Fossil Record in the Earth, Moon and Meteorites, edited by R. O. Pepin, J. A. Eddy, and R. B. Merrill, pp. 119–134, Pergamon Press, New York, 1980.

Foukal, P., Sunspots and changes in the global output of the Sun, in Physics of Sunspots, edited by L. Crum and J. Thomas, pp. 391–404, Sacramento Peak Observatory, Sunspot NN, 1981.

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

Garduño, R. and J. Adem, Interactive log wave spectrum for the thermodynamic model, Atmósfera, 1, 157–172, 1988.

Garduño, R. and J. Adem, Parameterizations of cloudiness as a function of temperature for use in a thermodynamic model, World Res. Rev., 5, 246–253, 1993.

Hickey, J. R., B. M. Alton, H. L. Kyle, and D. V. Hoyt, Total solar irradiance measurements by ERB/Nimbus-7. A review of nine years, Space Sci. Rev., 48, 321–342, 1988.

Howard, R., Observations of solar magnetic fields, Astrophys. J., 130, 193–201, 1959.

Hoyt, D. V., H. L. Kyle, J. R. Hickey, and R. H. Maschhoff, The Nimbus 7 solar total irradiance: A new algorithm for its derivation, J. Geophys. Res., 97, 51–63, 1992.

Krause, F. and K. H. Radler, Mean-Field Magnetohydrodynamics and Dynamo Theory, 271 pp., Pergamon Press, Oxford, 1980.

Kuperus, M., J. A. lonson, and D. S. Spicer, On the theory of coronal heating mechanisms, Ann. Rev. Astron. Astrophys., 19, 7–40, 1981.

Kyle, H. L., D. V. Hoyt, and J. R. Hickey, A review of the Nimbus-7 ERB solar dataset, Solar Phys., 152, 9–12, 1994.

Lean, J., A. Skumanich, and O. R. White, Estimating the Sun’s radiative output during the Maunder Minimum, Geophys. Res. Lett., 19, 1591–1594, 1992.

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

Legrand, J. P., M. Le Goff, and C. Mazaudier, On the climatic changes and the sunspot activity during the XVIIth century, Ann. Geophys., 8, 637–644, 1990.

Leighton, R. B., Observations of solar magnetic fields in plage regions, Astrophys. J., 130, 366–380, 1959.

Mendoza, B., Estimations of Maunder Minimum solar irradiance and Ca II H and K fluxes using rotation rates and diameters, Astrophys. J., 1997 (in press).

Nesme-Ribes, E. and A. Mangeney, On a plausible physical mechanism connecting the Maunder Minimum to the Little Ice Age, Radiocarbon, 34, 263–270, 1992.

Nesme-Ribes, E., E. N. Ferreira, R. Sadoumy, H. Le Trent, and Z. X. Li, Solar dynamics and its impact on solar irradiance and terrestrial climate, J. Geophys. Res., 98, 18923–18935, 1993.

Posey, J. and P. F. Clapp, Global distribution of normal surface albedo, Geofis. Int., 4, 38–48, 1964.

Reid, G., Solar total irradiance variations and the global sea surface temperature record, J. Geophys. Res., 96, 2835–2844, 1991.

Ribes, J. C. and E. Nesme-Ribes, The solar sunspot cycle in the Maunder Minimum AD 1645 to AD 1715, Astron. Astrophys., 276, 549–563, 1993.

Schlesinger, M. E. and N. Ramankutty, Implications for global warming of intercycle solar irradiance variations, Nature, 360, 330–333, 1992.

Schrijver, C. J., J. Cote, C. Swaan, and S. H. Saar, Relation between the photospheric magnetic field and the emission from the outer atmospheres of cool stars I. The solar Ca II K line core emission, Astrophys. J., 337, 964–976, 1989.

Skumanich, A., Time scales for Ca II emission decay, rotational braking, and lithium depletion, Astrophys. J., 171, 565–567, 1972.

Thomson, P. D., Numerical Weather Analysis and Prediction, 170 pp., McMillan, New York, 1961.

White, O. R., A. Skumanich, J. L. Lean, W. C. Livingston, and S. Keil, The Sun in a non-cycling state, Publications of the Astronomical Society of the Pacific, 104, 1139–1143, 1992.

Willson, R. C. and H. S. Hudson, The Sun’s luminosity over a complete solar cycle, Nature, 351, 42–44, 1991.

Wilson, O. C., Chromospheric variations in main sequence stars, Astrophys. J., 226, 379–396, 1978.