

The effect of increasing solar activity on the Sun's total and open magnetic flux during multiple cycles: Implications for solar forcing of climate

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[1] We investigate the relationship between solar irradiance and cosmogenic isotope variations by simulating with a flux transport model the effect of solar activity on the Sun's total and open magnetic flux. As the total amount of magnetic flux deposited in successive cycles increases, the polar fields build up, producing a secular increase in the open flux that controls the interplanetary magnetic field which modulates the cosmic ray flux that produces cosmogenic isotopes. Non-axisymmetric fields at lower latitudes decay on time scales of less than a year; as a result the total magnetic flux at the solar surface, which controls the Sun's irradiance, lacks an upward trend during cycle minima. This suggests that secular increases in cosmogenic and geomagnetic proxies of solar activity may not necessarily imply equivalent secular trends in solar irradiance. Questions therefore arise about the interpretation of Sun-climate relationships, which typically assume that the proxies imply radiative forcing. *INDEX TERMS*: 7537 Solar Physics, Astrophysics, and Astronomy: Solar and stellar variability; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance; 1650 Global Change: Solar variability. *Citation*: Lean, J. L., Y.-M. Wang, and N. R. Sheeley Jr., The effect of increasing solar activity on the Sun's total and open magnetic flux during multiple cycles: Implications for solar forcing of climate, *Geophys. Res. Lett.*, 29(24), 2224, doi:10.1029/2002GL015880, 2002.

1. Introduction

[2] Solar activity causes the Sun's electromagnetic radiation to vary. Solar activity also modulates the heliospheric magnetic field which affects the flux of galactic cosmic rays and magnetic activity at the Earth. Cosmic rays produce ^{14}C and ^{10}Be isotopes which are deposited in tree-rings and ice-cores, respectively, and used to infer the impact of solar variability on Earth's past climate [Crowley, 2000].

[3] Relationships among solar activity, solar irradiance and cosmogenic proxies are not well known on long time scales. Solar activity exhibits 11-year cycles that at times increase monotonically in amplitude, as the sunspot numbers in Figure 1a show between 1922 and 1965. At the same time, 11-year solar-related cycles in ^{10}Be and the *aa* index shown in Figure 1b are superimposed on a secular increase of the levels at cycle minima [Beer et al., 1988]. Solar irradiance also undergoes 11-year cycles which are reconstructed in Figure 1c from sunspot data [Foukal and Lean,

1990]. In the alternative reconstructions in Figure 1d, the 11-year irradiance cycles are superimposed on a secular component [Lean, 2000; Lockwood and Stamper, 1999].

[4] Solar irradiance and cosmogenic isotope variations depend on the Sun's magnetic flux in different ways. Surface magnetic fields produce features that alter radiative output [Frölich and Lean, 2002]. These features - dark sunspots and bright faculae - account for the bulk of the Sun's total magnetic flux. As a result, annual values of total irradiance and total magnetic flux are well correlated. A relatively small fraction of the Sun's magnetic flux (whose footpoint regions are observed as coronal holes) extends into the heliosphere. These "open" magnetic fields, which have negligible effect on solar irradiance, are the source of the interplanetary magnetic field (IMF) [Wang et al., 2000]. IMF variations modulate the terrestrial flux of cosmic rays that produce cosmogenic isotopes [Cane et al., 1999], as well as affecting geomagnetic activity [Ahluwalia, 2000].

[5] To investigate how solar irradiance and cosmogenic isotope variations are related, we examine the time dependence of the total and open magnetic flux as the Sun's field evolves during multiple cycles. We simulate rising solar activity cycles by systematically increasing the flux of bipolar magnetic regions (BMRs) that are the sources of the magnetic field, and we evolve the surface field using a transport model tested against total magnetic flux and IMF variations during cycle 21 [Wang et al., 2002a]. The total flux is obtained by adding the absolute values of all surface magnetic fields and the open flux is estimated from those fields that extend beyond 2.5 solar radii.

2. Photospheric Flux Transport and Coronal Field Extrapolation Models

[6] Magnetic flux erupts on the Sun mostly at latitudes below 40° in the form of BMRs with separated positive and negative poles. Differential rotation, diffusion associated with supergranular convection, and meridional flow redistribute this flux over the surface, producing a net poleward migration that reverses the existing polar field.

[7] For the magnetic flux sources we use a database of 3047 BMRs compiled from visual estimates of the strengths, locations, axial tilts and polarities of newly emerged regions in ground-based magnetograms from 1976 to 1986. In accordance with the discussion of Wang et al., [2002a] the originally estimated strengths of the BMRs are increased by a factor of 3. As in Wang et al., [2002a] we specify the synodic rotation rate as $\omega(L) = 13.38 - 2.30\sin^2 L - 1.62\sin^4 L$ deg day $^{-1}$, the supergranular diffusion rate as $\kappa = 500$ km 2 s $^{-1}$ and the poleward meridional flow velocity

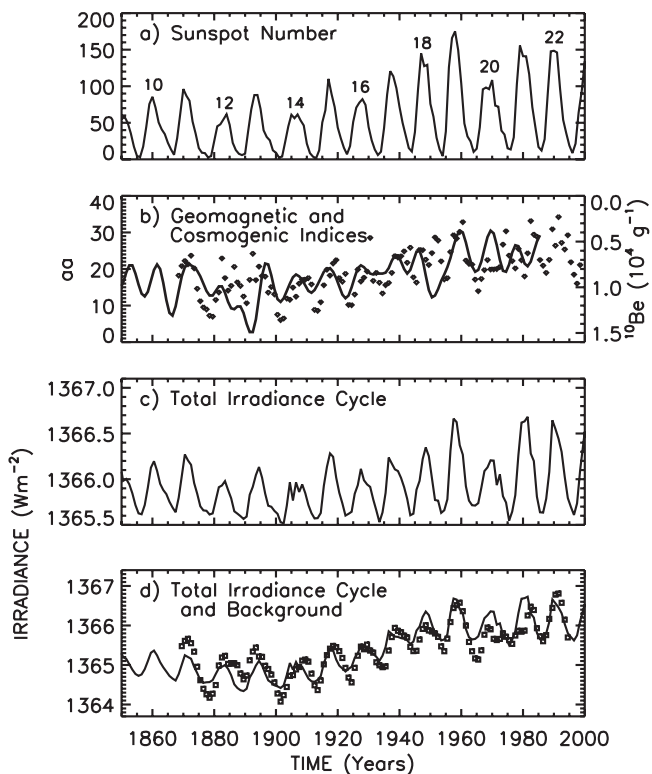


Figure 1. Shown in (a) are variations in the sunspot number compared in (b) with variations in terrestrial proxies of solar activity. The solid line is ^{10}Be [Beer *et al.*, 1988] and the symbols are the aa index. In (c) is reconstruction of total solar irradiance arising from 11-year activity cycles, whereas in (d) the irradiance reconstructions assume an additional varying background component. The solid line is from Lean [2000] and the symbols are from Lockwood and Stamper [1999]. The sunspot numbers and aa indices were obtained from NOAA’s National Geophysical Data Center.

as $v(L) = 25\cos^2 L \sin^{0.025} L \text{ m s}^{-1}$, where L denotes heliographic latitude. The photospheric field is extrapolated to a spherical “source surface” at 2.5 solar radii, below which the corona is taken to be current-free [Schatten *et al.*, 1969]. The open flux is that portion of the field that extends radially beyond the source surface. The flux transport and potential field extrapolation models successfully reproduce the observed evolution of the large scale solar magnetic field and radial IMF during solar cycle 21.

3. Simulated Total and Open Flux

[8] To investigate how magnetic flux evolves when solar activity increases, we adjust the strengths of the BMRs in cycle 21 by the factor $0.2 + (C_n - 1) \times 0.1$ for ten 11-year cycles, $C_n = 1, 10$. The initial field is taken to be of the form $\pm 2.4 \text{ G} \sin^8 L$. No sources are deposited for 1.5 years between successive cycles. The BMR polarities are reversed in alternating cycles, in accordance with Hale’s law, but other characteristics, including their emergence locations and axial tilts, are unchanged. Figure 2a shows 27.3-day Carrington averages of the prescribed fluxes.

[9] Each BMR is deposited at the appropriate time onto a 128×64 photospheric grid and transported using the specified rotation, diffusion and meridional flow parameters. Flux is removed when opposite-polarity regions converge and cancel each other. The net surface field distribution is calculated for every solar rotation. Figure 2b shows the longitudinally averaged field as a function of latitude and time over the 110-year simulation interval. The newly emerged BMRs are represented by the enhanced magnetic fields (active regions) at low to mid heliographic latitudes, which display the well-known butterfly pattern during each cycle. Although all of the sources are deposited below $\sim 40^\circ$ heliographic latitude, magnetic flux is nevertheless present at higher latitudes as a consequence of poleward transport by meridional flow and diffusion. This transport and the resulting reversal of the polar fields during each cycle are clearly evident in Figure 2b. As the strength of each activity cycle grows, so too do the polar field strengths, even though the transport parameters are constant. Figure 2c shows the flux above 60° latitude for the north and south polar fields.

[10] As shown in Figure 3, the total and open magnetic flux evolve differently during the 110-year simulation. The total flux tracks the BMR sources (Figure 2a) (correlation of 0.91). In contrast, the open flux bears much less resemblance to the BMR sources (correlation 0.28) or the total flux (correlation 0.43), showing a pronounced secular trend with only a slight 11-year cycle superimposed. The increase in open flux at cycle minima from ~ 0.5 to 3 nT over ten activity cycles is comparable to the amplitude of the tenth cycle (~ 2 to 4 nT). The very small increase in total magnetic flux during cycle minimum, equivalent to only 10% of the amplitude of the tenth cycle, reflects the contribution of open flux to the total and is not a result of scaling the BMRs since there are no sources for ~ 1.3 years during each minimum.

[11] As Wang *et al.* [2000] have demonstrated for the contemporary Sun, open flux reflects the Sun’s low-order multipole components, and approximately follows the evolution of the total dipole strength shown in Figure 3c. The axisymmetric (axial) dipole component can be seen in Figure 3d to dominate during cycle minima (indicated by the dotted lines). The non-axisymmetric (equatorial) dipole component, also shown in Figure 3d, dominates during cycle maxima (when the axisymmetric component is near zero) and produces the highly structured intra-cycle variations which are superimposed on the secular inter-cycle trend.

[12] The buildup of the Sun’s axial dipole during a given cycle is due to two effects: (1) The axial dipoles of the individual BMRs point in the same direction and reinforce each other; (2) The axial dipole component (both of an individual BMR and of the Sun as a whole), unlike the equatorial dipole component, is not subject to rotational shearing and therefore decays slowly due to the effects of supergranular diffusion and meridional flow (time scale $\sim 15 \text{ yr}$ for $\kappa \sim 500 \text{ km}^2 \text{ s}^{-1}$, much longer when a strong poleward flow is present). Because of these two effects, the Sun’s axial dipole grows cumulatively in our simulations as more and more sources are deposited (after sunspot maximum; before sunspot maximum, it decreases progressively to zero). The buildup of the polar fields and open flux from

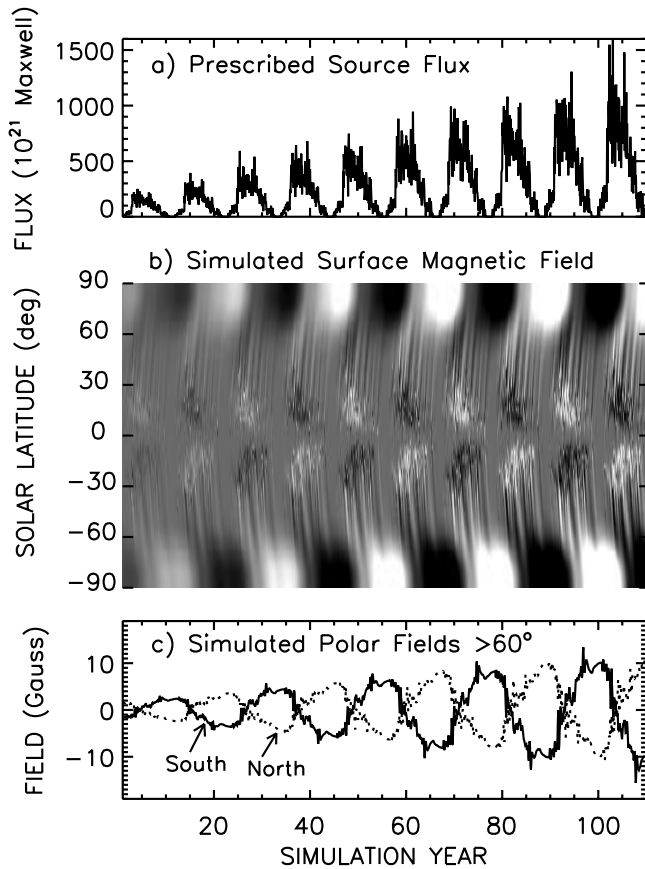


Figure 2. Shown in (a) is the total flux of sources deposited at the Sun’s surface every 27.3 days synthesized for 110 years from actual sources measured in solar cycle 21. Shown in (b) is the meridional distribution of the large scale magnetic field simulated in response to the transport of the sources and in (c) are variations in the polar fields at heliospheric latitudes above 60° .

one cycle to the next occurs because the number of BMRs (and thus their net axial dipole strength) increases from one cycle to the next.

[13] The total magnetic flux does not show this accumulation from one activity minimum to the next because it is dominated by high-order multipoles (in the form of relatively small scale flux concentrations), which undergo diffusive decay on time scales less than a year. At solar minimum, a relatively weak eruption rate accompanied by this rapid decay causes the ambient flux level to be relatively small. By adopting longer transport times and adding small ephemeral regions *Solanki et al.* [2002] concluded from arbitrary parameterizations of flux emergence and decay rates that there is a parallel accumulation of open and total flux during multiple solar cycles. Our simulation does not show such an accumulation of total flux during cycle minima. In order for the total flux to have a secular trend, the flux emergence rate at sunspot minimum must undergo a large increase from one cycle to the next and be dominated by ephemeral regions that do not appear in the sunspot record. Although we cannot rule out this possibility on a time scale of 110 years, *Foukal and Milano* [2002], in their study of Ca K solar images since 1910, did not detect

long-term changes in the network, where ephemeral regions mainly reside.

4. Implications for Solar Forcing of Climate

[14] Our simulation suggests that secular changes in terrestrial proxies of solar activity (such as the ^{14}C and ^{10}Be cosmogenic isotopes and the *aa* geomagnetic index) can occur in the absence of long-term (i.e., secular) solar irradiance changes. Increasing solar cycle amplitudes produce a secular increase in open flux and IMF, and can therefore explain variations like the cosmogenic isotope decrease from 1922 to 1965. Total magnetic flux, however, does not have an equivalent secular trend during minima. Since the primary sources of the total flux are features that modulate solar irradiance, this suggests that total solar irradiance may also lack significant secular trends. The total solar irradiance reconstruction in Figure 1c likewise lacks significant secular trends, so may therefore be more plausible than the reconstructions in Figure 1d which include an assumed varying background component. *Foukal* [2002] reaches a similar conclusion from an independent study of total irradiance brightness sources deduced from Mt Wilson Ca spectroheliograms.

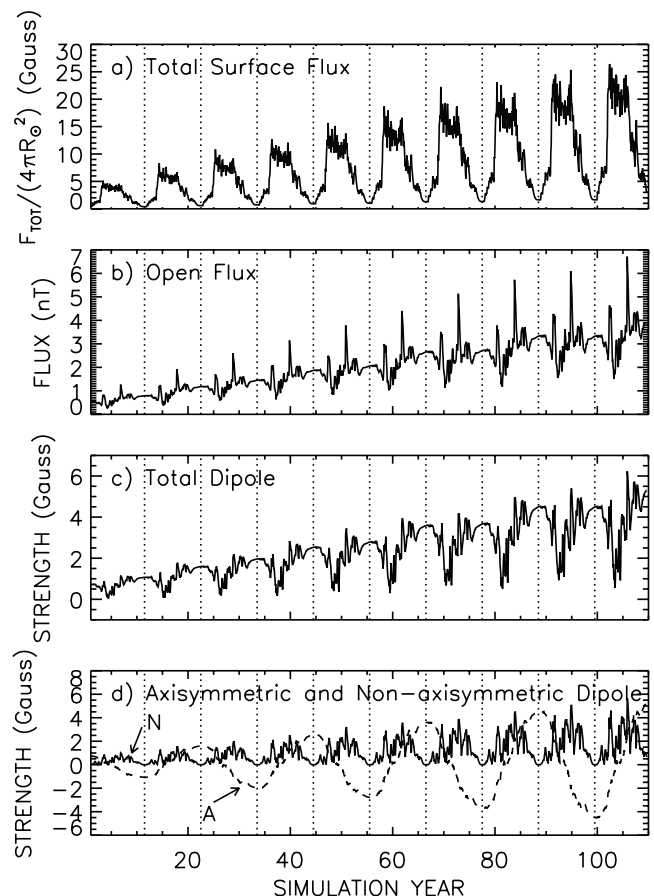


Figure 3. Compared in (a) and (b) are the total and open flux corresponding to the magnetic field evolution shown in Figure 2b, simulated in response to the sources. The Sun’s total dipole strength is shown in (c) and in (d) are its axisymmetric and non-axisymmetric components.

[15] Solar radiative forcing of climate is reduced by a factor of 5 when the background component is omitted from historical reconstructions of total solar irradiance, i.e., when the forcing is specified by the irradiance time series in Figure 1c instead of that in Figure 1d. This suggests that general circulation model (GCM) simulations of twentieth century warming may overestimate the role of solar irradiance variability.

[16] There is, however, growing empirical evidence for the Sun's role in climate change on multiple time scales including the 11-year cycle [Douglass and Clader, 2002]. Climate response to solar variability may involve amplification of climate modes which the GCMs do not typically include. Possible responses may involve the excitation of the El Niño Southern Oscillation and the Northern Atlantic Oscillation. "Noise" arising from unforced climate fluctuations may enable weak solar forcing to produce an unexpectedly large response [Rahmstorf and Alley, 2002]. In this way, long-term climate change may appear to track the amplitude of the solar activity cycles because the stochastic response increases with the cycle amplitude, not because there is an actual secular irradiance change.

5. Summary

[17] The result that the Sun's total and open magnetic flux variations are not the same suggests that cosmogenic isotope variations may not necessarily signify concurrent changes in solar irradiance. By monotonically increasing the amplitude of the Sun's activity cycle we have simulated a secular trend in open magnetic flux. This open flux is the source of the interplanetary magnetic field that affects the ^{14}C and ^{10}Be cosmogenic isotopes and the *aa* geomagnetic index, which are often used as proxies of solar activity in studies of Sun-climate relationships. At the same time, the total magnetic flux at solar minimum showed little increase. Since the primary sources of the total magnetic flux are the features that modulate solar irradiance, this suggests that the corresponding increase in total solar irradiance would also be small. It is therefore possible that during the Maunder Minimum, solar irradiance was not significantly lower than during contemporary cycle minima, even though levels of ^{10}Be were higher.

[18] Our simulations clarify how transport of magnetic field causes the total and open magnetic flux to evolve differently during multiple activity cycles. The total flux varies primarily in concert with the combined strengths of all sources and is dominated by high-order multipoles. Even when solar activity increases from one cycle to the next, there is little accumulation of total flux during cycle minima because the higher-order multipoles decay on time scales of less than a year. In contrast, the open flux is dominated by low-order multipoles which decay much more slowly. The polar fields and the axisymmetric component of the open flux are formed cumulatively from the sources of a given

cycle, and build up from one cycle to the next when the source rate is increased.

[19] Somehow the Sun prevents indefinite polar field accumulation, since in reality a weak cycle (e.g., cycle 20 in Figure 1a) often follows an epoch of monotonically increasing cycle amplitudes (e.g., cycles 16 to 19); if the transport parameters are kept fixed, such fluctuations could prevent the reversal of the polar fields. Further simulations that consider more realistic solar activity scenarios and allow meridional flow to vary from one cycle to the next are in progress [Wang *et al.*, 2002b]. A better understanding of how the Sun's total and open magnetic flux vary on time scales of centuries may better define the relationship of solar irradiance and historical proxies of solar activity, which is needed to physically interpret empirical Sun-climate associations.

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