Centennial changes in the solar wind speed and in the open solar flux


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Centennial changes in the solar wind speed and in the open solar flux

A. P. Rouillard,1,2 M. Lockwood,1,2 and I. Finch1

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[1] We use combinations of geomagnetic indices, based on both variation range and hourly means, to derive the solar wind flow speed, the interplanetary magnetic field strength at 1 AU and the total open solar flux between 1895 and the present. We analyze the effects of the regression procedure and geomagnetic indices used by adopting four analysis methods. These give a mean interplanetary magnetic field strength increase of 45.1 ± 4.5% between 1903 and 1956, associated with a 14.4 ± 0.7% rise in the solar wind speed. We use averaging timescales of 1 and 2 days to allow for the difference between the magnetic fluxes threading the coronal source surface and the heliocentric sphere at 1 AU. The largest uncertainties originate from the choice of regression procedure; the average of all eight estimates of the rise in open solar flux is 73.0 ± 5.0%, but the best procedure, giving the narrowest and most symmetric distribution of fit residuals, yields 87.3 ± 3.9%.


1. Introduction

[2] Lockwood et al. [1999] used the aa geomagnetic index to find that the mean open solar magnetic flux increased during the 20th century, whereas Feynman and Crooker [1978] used the same data to infer a rise in the mean solar wind speed at Earth. Four recent developments allow us to investigate these changes further and reconcile these results: (1) the aa index has been corrected to allow for intercalibration errors [Lockwood et al., 2007]; (2) Svalgaard and Cliver [2005] have developed a new geomagnetic index, termed IDV; (3) Lockwood et al. [2007] have developed another new geomagnetic index termed the median index, m; (4) Finch and Lockwood [2007] have carried out an extensive study (in particular, looking at the effect of data gaps) of the solar wind–geomagnetic field coupling functions used in these extrapolations.

[3] The IDV index is based on the variation of hourly mean geomagnetic data on successive nights and extends back to 1872 (almost the same as the corrected aa index, aaC, which extends back to 1868). The m index extends back to 1895 and, like IDV, is based on hourly mean data. Unlike IDV, however, m does not discard data when the stations are on the dayside; rather, it treats data from a given station and at a given UT as an independent data series. The hourly means of the horizontal field perturbation for a given station-UT combination are then scaled by linear regression with aaC and m is the monthly median of the 288 data series obtained. Figure 1a shows the variations of the annual means of aaC, m, and IDV. Note that the scaling of the data for each station-UT in terms of aaC means that the m index and aaC are comparable in magnitude, whereas IDV but does show some significant

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1Rutherford Appleton Laboratory, Chilton, UK.
2Also at Solar-Terrestrial Physics Group, Department of Physics and Astronomy, University of Southampton, Southampton, UK.
Figure 1. (a) Annual means of geomagnetic indices: the corrected $aa$ index, $aa_{C}$ (blue); the median index, $m$ (in red); and IDV (in black). (b) Annual means of the sunspot number, $R$. In both panels the even-numbered solar cycles are shaded grey, the odd cycles orange: cycle numbers are given along the top of Figure 1b.

Figure 2. Analysis of the long-term change in the corrected $aa$ index, $aa_{C}$: (a) The annual means and standard deviations of daily averages of $aa_{C}$, $\langle aa_{C} \rangle$ and $\sigma_{aa_{C}}$, respectively; (b) the ratio $\sigma_{aa_{C}}/\langle aa_{C} \rangle$; and (c) Sargent’s recurrence index derived from $aa_{C}$, $I_{aa_{C}}$. 
of spacecraft observations of the interplanetary medium. The level of all geomagnetic indices dropped at this time (before recovering again) and the recurrence index and relative storminess settled down to the behavior and level seen throughout the space age.

2. Dependence of Geomagnetic Indices on Interplanetary Coupling Functions

Svalgaard and Cliver [2005] note that IDV depends on the magnitude $B$ of the Interplanetary Magnetic Field (IMF) but is almost independent of the solar wind flow speed $V$, in contrast to the $aa_C$ index that varies with both $V$ and $B$. The $m$ index shows the same dependence on $B$ as $aa_C$ and IDV and shows a weak dependence on $V$. This is demonstrated by Figure 3. A variety of combinations of interplanetary parameters, termed “coupling functions,” have been proposed as predictors of geomagnetic activity (see review by Finch and Lockwood [2007]). Figure 3a shows the correlation between the corrected aa index, $aa_C$, and various proposed coupling parameters as a function of averaging timescale, $T$, using the analysis procedure of Finch and Lockwood [2007]. All interplanetary data used in this paper are hourly averages from the OMNI-2 data set. These have subsequently been averaged again over the timescale $T$ which is varied between 3 hours and 1 year. In Figure 3a, only geomagnetic data with coincident interplanetary observations (allowing for the predicted satellite-to-Earth propagation lag) are used and 50% coverage is required for each averaging period. The data are for 1974–2006. (dark blue) $P_\alpha = m_4^{(r+2)/3} M_E^{2/3} N^{(2/3-\alpha)} V^{(7/3-\alpha)} B^{2\alpha} \sin^4(\theta/2)$, where $m_4$ is the mean solar wind ion mass, $N$ is the solar wind number density, $M_E$ is the Earth’s magnetic moment, $\theta$ is the IMF clock angle in the [Z-Y]$_{GSM}$ frame; (light blue) $V^2 B_z$; (green) $V^2 B_z$, where $B_0 = |B_z|_{GSM} \geq 0$ and $B_0 = 0$ if $|B_z|_{GSM} < 0$; (black) $B$; and (red) $V^{0.3} B$ [see Finch and Lockwood [2007] for further details]. (b), (c), and (d) The corresponding correlations for annual means (of all available data from 1 January 1974) for $aa_C$, IDV, and $m$, (for which the best fit exponent $\alpha$ in $P_\alpha$ is 0.3, 0.99, and 0.65, respectively).

Figure 3. (a) The correlation coefficients between various interplanetary coupling functions and the corrected aa index, $aa_C$, as a function of averaging timescale, $T$. Only coincident (lagged) data are used in Figure 3a and 50% coverage is required for each averaging period. The data are for 1974–2006. (dark blue) $P_\alpha = m_4^{(r+2)/3} M_E^{2/3} N^{(2/3-\alpha)} V^{(7/3-\alpha)} B^{2\alpha} \sin^4(\theta/2)$, where $m_4$ is the mean solar wind ion mass, $N$ is the solar wind number density, $M_E$ is the Earth’s magnetic moment, $\theta$ is the IMF clock angle in the [Z-Y]$_{GSM}$ frame; (light blue) $V^2 B_z$; (green) $V^2 B_z$, where $B_0 = |B_z|_{GSM} \geq 0$ and $B_0 = 0$ if $|B_z|_{GSM} < 0$; (black) $B$; and (red) $V^{0.3} B$ [see Finch and Lockwood [2007] for further details]. (b), (c), and (d) The corresponding correlations for annual means (of all available data from 1 January 1974) for $aa_C$, IDV, and $m$, (for which the best fit exponent $\alpha$ in $P_\alpha$ is 0.3, 0.99, and 0.65, respectively).

\[ P_\alpha = m_4^{(r+2)/3} M_E^{2/3} N^{(2/3-\alpha)} V^{(7/3-\alpha)} B^{2\alpha} \sin^4(\theta/2), \]
with Figure 3b shows that the data gaps in the interplanetary data tend to lower good correlations but raise poor ones. It can be seen that, whereas B correlates with \(a_C\) significantly more poorly than does \(B'V^2\) (using the Meng et al. [1992] modified Fisher-Z test), the difference between the two correlations is significant at the 99.99% level), B is more highly correlated with IDV than \(B'V^2\) (this difference being significant at the 98.85% level). We can readily understand this dependence by noting that \(a_C\) is based on the range of variation of the horizontal field at the ground in 3 hourly intervals and this range can arise either from substorm cycles (driven by IMF \(B_z\) in the GSM frame and lasting typically 1–2 hours) and/or from more rapid variations associated with solar wind buffeting, the latter being greater when the mean \(V\) is high [Bowe et al., 1990]. On the other hand, IDV is based on hourly means of geomagnetic activity, in which the high-frequency buffeting effect is averaged out. Because the correlation time of \(V\) is long (\(\approx 30\) hours) [Lockwood, 2002], high \(V\) causes very little difference between hourly means on successive nights, and hence IDV does not respond to high \(V\) [Lockwood, 2002] showed that the autocorrelation of \(V\) at 24 hours lag was as large as 0.65).

[7] The \(m\) index correlates best with \(V^{0.5}\). We would expect a lower dependence on \(V\) than for \(a_C\), because \(m\), like IDV, employs hourly mean data in which the buffeting effect is averaged out; however, data for a given station-UT are multiples of 24 hours apart, on which timescales \(V\) can vary more significantly. The difference between correlations with \(B'V^2\) and \(B'V^{0.5}\) for \(a_C\) is significant at the 99.99% level and for \(m\) this figure is 95.55%. A summary of the significance of the differences between correlations is given in Table 1.

### 3. Determination of IMF Strength and Solar Wind Velocity From Geomagnetic Data

[8] From the above, IDV and \(a_C\) can be used to determine the variations of \(B\) and \(B'V^2\), respectively, and the variations in both \(B\) and \(V\) can therefore be derived. Cliver and Svalgaard [2006] proposed this technique and applied it to infer a century-scale rise in \(V\), as found by Feynman and Crooker [1978]. Similarly, \(a_C\) and \(m\) can be used to determine the variations of \(B'V^{1/2}\) and \(B'V^2\), respectively, and estimates of \(B\) and \(V\) that are independent of IDV can be obtained. Figure 4 shows the scatterplots of annual means of IDV against \(B\) (Figure 4a); \(a_C\) against \(V^{1/2}\) (Figure 4c); and \(m\) against \(V^{0.5}\) (Figure 4e). The best correlations found in Figures 3b, 3c, and 3d, respectively. Lockwood et al. [2006] have shown that the assumptions of Ordinary Least Squares (OLS) regression are seriously violated for case a, and in general there are outliers in the annual means of IDV that must be investigated. Specifically, the data are not “homoscedastic” (i.e., the variance increases with the fit parameter), the distribution of residuals is not Gaussian, the residuals show systematic drift with the fit parameter, and the regression line is strongly influenced by outliers. These problems are much less severe for either \(m\) or \(a_C\). Hence in addition to OLS, we here also use least squares regression based on Bayesian statistics (BLS). The latter enables us to allow for the fact that a geomagnetic activity index is necessarily an indirect measure of any interplanetary parameter. The mathematical derivation is lengthy but the key result is that least squares minimization is applied to the residuals in the geomagnetic activity index, rather than in the interplanetary parameter, even when predicting the latter (M. Lockwood et al., How large was the rise in open solar flux during the 20th century?: Application of Bayesian Statistics, submitted to Annales Geophysicae, 2007). OLS and BLS regression fits for the three data sets are shown in Figure 4 as solid and dashed lines, respectively. The BLS fits are closer to satisfying the assumptions of least squares regression than the OLS fits [Lockwood et al., 2006] as seen from the fit residual distributions plotted in Figures 4b, 4d, and 4e using the same line-type scheme. The errors in the slopes are shown as grey bands on the scatterplots. It can be readily seen that IDV and (to a lesser extent) \(m\) have divergent OLS and BLS estimates due to the outliers, whereas regressing \(a_C\) against \(B'V^2\) is a very good LS analysis. The best-fit linear regression lines for OLS and BLS can be used to derive the variations of \(B\), \(B'V^2\) and \(B'V^{0.5}\) from these, both \(B\) and \(V\) are derived in two ways: by combining the fits for (1) IDV and \(a_C\) and (2) \(m\) and \(a_C\), the two sets of parameters whose dependences differ significantly as shown in Table 1.

### Table 1. Significance of the Differences Between the Best Correlation Coefficients, \(r(a_C, B'V^2)\), \(r(IDV, B)\), and \(r(m, B'V^{1/2})\), and Correlations of \(a_C\), IDV, and \(m\) With the Other Two Simple Interplanetary Coupling Functions From the Set of Three (\(B'V^2\), \(B\), and \(B'V^{1/2}\))

<table>
<thead>
<tr>
<th></th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r(a_C, B'V^2))</td>
<td>–</td>
<td>98.85%</td>
<td>95.55%</td>
</tr>
<tr>
<td>(r(IDV, B))</td>
<td>99.99%</td>
<td>–</td>
<td>50.38%</td>
</tr>
<tr>
<td>(r(m, B'V^{1/2}))</td>
<td>99.99%</td>
<td>77.22%</td>
<td>–</td>
</tr>
</tbody>
</table>

*The geomagnetic index termed “x” is always \(a_C\) for column 1, IDV for column 2, and \(m\) for column 3. (So, for instance, the significance of the difference between \(r(m, B'V^{1/2})\) and \(r(m, B'V^2)\) is 95.55%). All correlations are for annual mean data. These significances of the differences between two correlations are derived using the modified Fisher-Z (asymptotic) test introduced by Meng et al. [1992], which accounts for the persistence in the data and for the fact that the correlation coefficients are obtained from correlated predictors.*
increased $V$ in the declining phases of sunspot cycles caused by repetitive intersections by the Earth of long-lived coronal hole-extensions that cross the ecliptic (also giving the peaks in $I_{aac}$ seen in Figure 2). The residuals show similar distributions in all cases, but the BLS fits give the most symmetric (and slightly narrower) distributions. A summary of the 11-year running means of $V$ and $B$ for 1903 and 1956 are given in Table 2, as well as the corresponding percentage changes between these 2 years [see Lockwood et al., 2006].

### 4. Determination of the Open Solar Flux

[10] The Parker theory of the spiral configuration of the average orientation of the solar wind field has been exceptionally successful in reproducing the average IMF direction both in the ecliptic plane [Balogh et al., 1995; Lockwood et al., 2004] and at higher heliographic latitudes [Forsyth et al., 1996]. The theory predicts that the magnitude of the radial field $|B_r| = B(1 + (r \omega \cos \psi / V^2)^{-1/2}$, where $r$ is the heliocentric distance, $\psi$ is the heliographic latitude, $B$ is the IMF magnitude, $V$ is the solar wind speed, and $\omega$ is the angular velocity of the Sun. Using the Ulysses result that the radial component of the IMF is independent of $\psi$, $|B_r| = |F|_{\theta=\text{IAU}}/(2\pi r^2)$, where $|F|_{\theta=\text{IAU}}$ is the (signed)
total flux threading the sphere at \( r = 1 \) AU [see Lockwood, 2004, and references therein]. Hence
\[
[F]_{r=1AU} = 2\pi^2B\left\{1 + (r_s\cos\psi/F_s)^2\right\}^{-1/2}
\]

A measure of the total open solar magnetic flux is the total signed flux derived from potential field source surface (PFSS) extrapolations of solar magnetograms into the solar corona [Wang and Sheeley, 2002]. These extrapolations assume that the open magnetic field threads a spherical source surface (of radius 2.5 solar radii) such that it is everywhere orthogonal to that surface, that the corona is current-free, and that the field detected in magnetograms is orthogonal to the photospheric surface. Lockwood et al. [2006] showed that the PFSS estimates of the total signed flux agree best with estimates from measurements at 1 AU when the absolute value of the radial field \( B_r \) is taken for means of IMF observations for a timescale \( T \) between 1 and 2 days:
\[
F_S = (4\pi^2|B_r|)/2.
\]

Figure 7a shows a scatterplot of annual means of \( F_S \) for \( T = 1 \) day as a function of \([F]_{r=1AU}\) from hourly means of IMF and solar wind observations for 1967–2005, using equations (3) and (2), respectively. The plot is linear with a correlation coefficient of 0.92 and an OLS regression of \( F_S = 0.65(\pm 0.03)[F]_{r=1AU} - 0.69(\pm 0.26) \) (for fluxes in \( 10^{13} \) Wb). Using \( T = 2 \) days in equation (2) to derive \( F_S \), this regression becomes \( F_S = 0.64(\pm 0.03)[F]_{r=1AU} - 0.89(\pm 0.25) \). The fit residuals do not show any drift in time (not shown here) and their distribution is approximately Gaussian, as shown by Figure 7b. The difference between \( F_S \) and \([F]_{r=1AU}\) arises from (1) disconnected flux \( F_d \) that threads the heliocentric sphere at \( r = 1 \) AU but not the source surface; (2) distortions from Parker spiral that give multiple crossings of field lines of the sphere at \( r = 1 \) AU (flux \( F_m \)); (3) newly emerged open flux \( F_o \) that has yet to reach \( r = 1 \) AU. In general, \([F]_{r=1AU} - F_S = \Delta F = (F_d - F_n + F_m)\). Table 2 gives results for averaging timescales of both 1 day and 2 days as ways of estimating and removing the flux \( \Delta F \) [Lockwood et al., 2007]. Note that the factors in \( \Delta F \) also contribute to the difference between the long-term changes in \( B \) and \( F_S \) (the latter being related to \( |B_r|_T \) by equation (3)). This is because opposite-polarity \( B_r \) is within the averaging interval \( T \) cancels, but \( B \) is always positive and hence there is no corresponding effect on \( B \). Hence as pointed out by Lockwood et al. [2007], although \( B \) and \( F_S \) are close to being linearly related, they are not proportional. In addition, the use of the regression given in Figure 7a allows for the fact that the ratio \( B_r/B \) increases toward unity as the Parker spiral unwinds with increasing \( V \), as predicted by Parker spiral theory.

Figure 6. (left) Variations in \( V \) derived using the OLS (top) and BLS (bottom) regression fits shown in Figure 4. (right) The distribution of the residuals relative to measured annual means. Colors and symbols are as for Figure 5.

Figure 7a allows for the fact that the ratio \( B_r/B \) increases toward unity as the Parker spiral unwinds with increasing \( V \), as predicted by Parker spiral theory.

5. Discussion and Conclusions

Table 2 shows that the average open solar flux increase derived from the four procedures is 69.9 ± 6.8%
Table 2. The 11-Year Running Mean Values of $V$, km s$^{-1}$, $B$, nT, and $F_S$, $10^{14}$Wb, for Years 1903 and 1956 Estimated Here From Both Ordinary Least Squares (OLS) and Bayesian Least Squares (BLS) Regressions and Also Using the Recurrence Corrected Method (RCM) of Lockwood et al. [1999]*

<table>
<thead>
<tr>
<th></th>
<th>Method</th>
<th>$T$, days</th>
<th>1903 Value</th>
<th>1956 Value</th>
<th>Change, $\lambda$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>OLS</td>
<td>V (IDV, aa$_c$)</td>
<td>-</td>
<td>391</td>
<td>454</td>
</tr>
<tr>
<td>B</td>
<td>OLS</td>
<td>V (m, aa$_c$)</td>
<td>-</td>
<td>401</td>
<td>460</td>
</tr>
<tr>
<td>C</td>
<td>BLS</td>
<td>V (IDV, aa$_c$)</td>
<td>-</td>
<td>395</td>
<td>451</td>
</tr>
<tr>
<td>D</td>
<td>BLS</td>
<td>V (m, aa$_c$)</td>
<td>-</td>
<td>406</td>
<td>457</td>
</tr>
<tr>
<td>Mean V from A-D</td>
<td>-</td>
<td>-</td>
<td>401</td>
<td>460</td>
<td>14.4 ± 0.7</td>
</tr>
<tr>
<td>A</td>
<td>OLS</td>
<td>B (IDV, aa$_c$)</td>
<td>-</td>
<td>5.4</td>
<td>7.4</td>
</tr>
<tr>
<td>B</td>
<td>OLS</td>
<td>B (m, aa$_c$)</td>
<td>-</td>
<td>5.2</td>
<td>7.2</td>
</tr>
<tr>
<td>C</td>
<td>BLS</td>
<td>B (IDV, aa$_c$)</td>
<td>-</td>
<td>5.0</td>
<td>7.6</td>
</tr>
<tr>
<td>D</td>
<td>BLS</td>
<td>B (m, aa$_c$)</td>
<td>-</td>
<td>4.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Mean B from A-D</td>
<td>-</td>
<td>-</td>
<td>5.2</td>
<td>7.2</td>
<td>45.4 ± 4.5</td>
</tr>
<tr>
<td>A1</td>
<td>OLS</td>
<td>$F_S$ (IDV, aa$_c$)</td>
<td>1</td>
<td>2.8</td>
<td>4.4</td>
</tr>
<tr>
<td>B1</td>
<td>OLS</td>
<td>$F_S$ (m, aa$_c$)</td>
<td>1</td>
<td>2.7</td>
<td>4.3</td>
</tr>
<tr>
<td>C1</td>
<td>BLS</td>
<td>$F_S$ (IDV, aa$_c$)</td>
<td>1</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>D1</td>
<td>BLS</td>
<td>$F_S$ (m, aa$_c$)</td>
<td>1</td>
<td>2.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Mean $F_S$ from A1-D1</td>
<td>-</td>
<td>-</td>
<td>2.6</td>
<td>4.5</td>
<td>69.9 ± 6.8</td>
</tr>
<tr>
<td>E1</td>
<td>RCM</td>
<td>$F_S$ (aa$_c$)</td>
<td>1</td>
<td>2.1 ± 0.2</td>
<td>4.3 ± 0.2</td>
</tr>
<tr>
<td>A2</td>
<td>OLS</td>
<td>$F_S$ (IDV, aa$_c$)</td>
<td>2</td>
<td>2.5</td>
<td>4.1</td>
</tr>
<tr>
<td>B2</td>
<td>OLS</td>
<td>$F_S$ (m, aa$_c$)</td>
<td>2</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>C2</td>
<td>BLS</td>
<td>$F_S$ (IDV, aa$_c$)</td>
<td>2</td>
<td>2.3</td>
<td>4.2</td>
</tr>
<tr>
<td>D2</td>
<td>BLS</td>
<td>$F_S$ (m, aa$_c$)</td>
<td>2</td>
<td>2.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Mean $F_S$ from A2-D2</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
<td>4.1</td>
<td>76.5 ± 7.6</td>
</tr>
<tr>
<td>Mean $F_S$ from A1-D1 &amp; A2-D2</td>
<td>1-2</td>
<td>-</td>
<td>2.2</td>
<td>4.0</td>
<td>73.0 ± 5.0</td>
</tr>
<tr>
<td>Mean $F_S$ from D1&amp;D2</td>
<td>1-2</td>
<td>-</td>
<td>2.2</td>
<td>4.0</td>
<td>87.3 ± 3.9</td>
</tr>
<tr>
<td>E2</td>
<td>RCM</td>
<td>$F_S$ (aa$_c$)</td>
<td>2</td>
<td>1.9 ± 0.2</td>
<td>4.0 ± 0.2</td>
</tr>
</tbody>
</table>

*The corresponding percentage increases $\lambda$ between 1903 and 1956 are also shown. Means for all methods are given and for the optimum method (BLS applied to $m$ and aa$_c$, shown in the rows labeled D1 and D2 for the timescale $T$ of 1 and 2 days, respectively). All rows labeled A give the results of OLS regression analysis using IDV and aa$_c$; rows labeled B give the results of OLS regression analysis using $m$ and aa$_c$; rows labeled C and D are the corresponding results for BLS analysis. For the open solar flux $F_S$, the results also depend on the averaging timescale $T$ employed and, for example, A1 and A2 are the results for OLS regression analysis using IDV and aa$_c$ with $T$ of 1 and 2 days, respectively. Results using the RCM of Lockwood et al. [1999] are given in rows E1 and E2 (for $T$ of 1 and 2 days, respectively).

Figure 7. (a) Scatterplot and regression fit for annual means of the (signed) open solar flux $F_S$ as a function of the (signed) flux threading $r = 1$AU, $[F_{\text{r=1AU}}]$ from hourly means of IMF and solar wind observations for 1967–2004, using equations (3) and (2), respectively. In this example, a timescale $T = 1$ day is used. The correlation coefficient is 0.92 (significant at the 99.9% level). The dotted lines show the effect of the estimated maximum errors in the slope on the best-fit line. (b) The distribution of best-fit residuals (thick line). The residuals are close to Gaussian, validating the use of the estimated error in the slope and intercept.
between 1903 and 1956 for $T = 1$ day, rising to $76.5 \pm 7.6\%$ for $T = 2$ days. Using the BLS regression with $m$ and $aa_c$, which gives the best fit to the IMF observations, these rises become 83.3% and 91.5% and, given this is the range of uncertainty in the optimum $T$, we here find $87.3 \pm 3.9\%$ to be the best estimate. Svalgaard and Cliver [2005] discuss the change in $B$ and not the total open flux, and their estimate of “~25%” is directly comparable to the corresponding average of $45.4 \pm 4.5\%$ for the change in $B$ that we derive here. An increase in open solar flux, as inferred by Lockwood et al. [1999], is here confirmed by all methods. The relationship between the derived increases in the open solar flux and the mean solar wind speed at Earth can be understood from the empirical law derived by Wang and Sheeley [1990]. This law relates the large/low expansion of open magnetic flux tubes between the photosphere and the coronal source surface to slow/fast solar wind speeds in the heliosphere [Wang and Sheeley, 1997]. On annual timescales, the accumulation of open field lines in coronal holes should force lower expansion rates of magnetic flux tubes. This in turn should increase the probability of the Earth intersecting the fast solar wind, thereby raising the average measured solar wind speed.

The above estimates of the percentage change in open solar flux can be directly compared to the $105 \pm 10\%$ and $116 \pm 11\%$ rises obtained by applying the RCM method of Lockwood et al. [1999] to the corrected aa, $aa_c$, for $T$ of 1 and 2 days, respectively. The differences arise out of the long-term drift in $V$ revealed by Figure 6. The method of Lockwood et al. [1999] assumed that the relationship of $B$ and $B_T$ over the past 150 years had been as it was during the past four solar cycles, i.e., it did not allow for the effect of a long-term change in $V$ on the Parker spiral “garden hose” angle. By using a regression of the type shown in Figure 7, we generalize this assumption to allow for changes in $V$ by assuming that Parker spiral theory has remained valid for annual means over the 150 years. The above numbers show that the 14% rise in $V$ has reduced the estimated change in open solar flux by of order 15%.

Finally, we stress that the magnitude of the rise in open solar flux derived here has been predicted by several numerical models. Solanki et al. [2002] used a simple continuity model to reproduce the rise and fuller numerical modelling of the emergence and evolution of solar flux by Lean et al. [2002], Wang and Sheeley [2002], Wang et al. [2005], and Schrijver et al. [2002] has also reproduced the change. These models show that the open solar flux variation is what one should expect because of the enhanced flux emergence in active regions, associated with increased peak sunspot numbers, over the same period [Foster and Lockwood, 2001] (see Figure 1b) and the mean lifetime of the open flux. The best estimate of the magnitude of the rise (derived here to be $87.3 \pm 3.9\%$) is very similar indeed to that produced by the numerical simulations: Wang et al. [2005] obtained a cycle-averaged increase of ~83% over the first half of the 20th century and the various simulations presented by Schrijver et al. [2002] give rises between 70% and 90%. Analysis of cosmogenic isotope abundances reveals decreases in the production of both $^{14}$C and $^{10}$Be that are highly anticorrelated with the rise in open solar flux. Lockwood [2003] showed that variations of the $^{40}$Be isotope (from the Dye-3 Greenland ice core) and of the $^{14}$C production rate (derived from observed abundances in tree rings using a two-reservoir model) both show a strong and significant anticorrelation with the open solar flux deduced from $aa$. Further evidence for the century-scale drift in open flux has been found from the $^{44}$Ti cosmogenic isotope found in meteorites [Taricco et al., 2006]. The relationship between the decreases in $^{10}$Be and the increase in open flux has been investigated quantitatively by McCracken et al. [2004] and Caballero-Lopez et al. [2004]. We note that the Caballero-Lopez et al.’s most-likely estimate of a 40% change in $B$ agrees very well with the 45% change in $B$ derived here (consistent with the 87% open flux variation) but will be a slight underestimate as it does not allow for the effect of the associated rise in $V$.

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I. D. Finch, Space Science Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK. (i.d.finch@rl.ac.uk)

M. Lockwood and A. Rouillard, Solar-Terrestrial Physics Group, Department of Physics and Astronomy, University of Southampton, University Road, Southampton SO17 1BJ, UK. (m.lockwood@rl.ac.uk; AlexisRouillard@yahoo.co.uk)