Our changing Sun

M Lockwood, R Stamper, M N Wild, A Balogh and G Jones discuss how new research has been applied to historical data to improve our understanding of the Sun and its effect on Earth.

A continuous sequence of data on geomagnetic activity extends back to 1868 (covering sunspot cycles 11–22) and shows a consistent rise since the turn of the century. Near-Earth interplanetary space has been routinely monitored since 1964, giving data throughout the last three of these sunspot cycles (20–22). Recently, it has been shown that the largest of three major contributions to the rise over these last three cycles is an upward drift in the magnitude of the interplanetary magnetic field (IMF). In addition, the Ulysses spacecraft has made the first out-of-ecliptic observations and shown that the latitudinal gradients in the radial component of the IMF are small. By combining these results, we can deduce that the total “source” magnetic flux in the Sun’s atmosphere has risen by 41% since 1964. Using three extremely significant and theory-based correlations derived from data for solar cycles 21 and 22, we can estimate the coronal source flux using only the geomagnetic data. The method has been subjected to an independent test using IMF data for cycle 20 and the estimated mean value for the cycle shown to be accurate to within a few percent. This allows us to extrapolate the coronal field estimates back to 1868 with confidence: we find an increase by 130% since 1901. Furthermore, this coronal field (IMF) has been subjected to an independent test using IMF data for cycle 20 and the estimated mean value for the cycle shown to be accurate to within a few percent. This allows us to extrapolate the coronal field estimates back to 1868 with confidence: we find an increase by 130% since 1901.

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Spatial astronomy tells us much about the long-term evolution of our Sun while terrestrial evidence (for example, cosmic-ray products in ice cores) gives us indications of its fluctuations over the last millennium. However, such studies do not give us a sufficiently detailed understanding of solar change over the last century to allow us to detect and quantify any role that the Sun might have played in the observed rise in average surface temperatures on Earth. This paper describes recent research that has filled this gap by applying advances in our understanding of the effects and structure of the solar wind to historical data on the Earth’s magnetic field.
from the \( a \alpha \) data. This exploits two strong and extremely significant correlations between the IMF, the solar wind and the \( a \alpha \) index, which Lockwood \textit{et al.} derived using the data from the last three solar cycles (20–22). However, there are uncertainties concerning the calibration of the early interplanetary measurements (Gazis 1996), particularly for \( N_{\text{sw}} \) in solar cycle 20. Consequently, Lockwood and Stamper (1999) employed a different approach. They derived all correlations using data from cycles 21 and 22 only and then predictions for cycle 20 were compared with the IMF observations. Thus the cycle-20 IMF data provided an independent test of the method.

The method makes use of the theory of energy transfer into the Earth’s magnetosphere by Vasyliunas \textit{et al.} (1982). The power delivered to the magnetosphere, \( P_a \), is the multiplied product of three terms: (1) the energy flux density of the interplanetary medium surrounding the Earth (dominated by the kinetic energy of bulk solar-wind flow); (2) the area of the target presented by the geomagnetic field (roughly circular with radius \( l_o \)); (3) the fraction \( t \), of the incident energy that is extracted. The dayside magnetosphere is approximately hemispherical in shape, in which case \( l_o \) equals the stand-off distance of the nose of the magnetosphere which can, to first order, be computed from pressure balance between the Earth’s dipole field and the solar-wind dynamic pressure. We adopt the form of the dimensionless “transfer function” \( t \), as suggested by Vasyliunas \textit{et al.}, which includes an empirical \( \sin^4(\theta/2) \) dependence on the IMF clock angle \( \theta \) (the angle that the IMF makes with northward in the GSM frame of reference) (Scurry and Russell 1991) and thereby allows for the role of magnetic reconnection between the IMF and the geomagnetic field. The transfer function adopted also depends on the solar wind Alfvén Mach number, to the power 2\( a \), where \( a \alpha \) is called the “coupling exponent” and must be determined empirically. This yields (Stamper \textit{et al.} 1999):

\[
P_a = k m_a \alpha B_r^2 N_{\text{sw}}^2 \alpha \sin^4(\theta/2)
\]

(1)

where \( m_a \) is the mean ion mass of the solar wind, \( M_\alpha \) is the magnetic moment of the Earth and \( k \) is a constant. To compute \( a \alpha \) the aa index is assumed to be proportional to the extracted power \( P_a = (aa/5) \), an assumption that is verified by the scatter plot shown in figure 3a. The optimum \( a \alpha \) gives the peak correlation coefficient \( c \) between \( P_a \) and \( aa \) (see figure 2). The constant \( s = k l_o \) is then found from a linear regression fit (lower panel, figure 3a).

Stamper \textit{et al.} (1999) have analysed each of the terms in the best-fit coupling function given by equation (1). They showed that more than half of the change in \( a \alpha \) over the last three solar cycles was caused by an upward drift in \( B_{\alpha} \). There were also contributions from increases in \( N_{\text{sw}} \) and \( v_{\text{sw}} \) but the average IMF clock angle \( \theta \) had grown slightly less favourable for causing geomagnetic activity (because there was a slight tendency for the IMF vector to stay closer to the ecliptic plane).

In order to use equation (1) to evaluate \( B_{\alpha} \), we group the terms in the square brackets together into a parameter \( f \), the variation of which (on annual timescales) is dominated by that in \( v_{\text{sw}} \). The annual mean of \( v_{\text{sw}} \) rises in the declining phase of solar cycles (particularly even-numbered ones) (Oliver \textit{et al.} 1996; Hapgood 1993) because the Earth then repeatedly intersects the fast, low-density solar-wind streams that emanate from the low-latitude extension of coronal holes. These multiple intersections occur every 27 days and so also raise the recurrence index I shown in figure 1b. Hence both \( f \) and \( I \) increase together in the declining phase of sunspot cycles. However, \( I \) tends to remain high towards sunspot minimum, whereas \( v_{\text{sw}} \) and \( f \) are lower, because \( a \alpha \) values are low and relatively constant. Consequently, Lockwood \textit{et al.} (1999a) adopted a relationship for a predicted \( f \) of the form:

\[
f = s f + c l \quad (2)
\]

where the exponents \( s \) and \( l \) give the optimum correlation coefficient and the constants \( s \) and \( l \) are then found from a linear regression fit of \( f \) against \( f \) (figure 3b). Substituting for \( f \) in (1), using \( f \) given by (2), allowed Lockwood \textit{et al.} to compute \( B_{\alpha} \) from the \( a \alpha \) data series. They employed estimates of \( M_\alpha \) from the IGRF model fit to geomagnetic data and assumed the composition of the solar wind is constant with a mean ion mass of 1.15 a.m.u.

The heliospheric field

Parker spiral theory (e.g. Gazis 1996) predicts the heliospheric field in heliocentric polar coordinates \((\rho, \phi, \psi)\) will be:

\[
B_{\rho} = B_{\rho}^0 \left[ B_{\rho}^0 + B_{\psi}^0 \right]^{1/2}
\]

(3)

where \( B_{\rho} \) is the coronal source field at the solar source sphere, \( r = R_s \approx 2.5 R_E \) from the centre of the Sun, where the solar field becomes approximately radial \( (B_r/B_\psi) \) (Wang and Sheeley 1993); \( \rho \) is the equatorial angular solar rotation velocity, \( \psi \) is the heliographic latitude and \( R_s \) is the solar radius.

Figure 4 demonstrates that Parker spiral theory is very successful in predicting annual means of the heliospheric field orientation around Earth (Stamper \textit{et al.} 1999) because phenomena causing short-term perturbations, such as corotating interaction regions (CIRs) and transient coronal mass ejections (CMEs),
are averaged out. Figure 4a shows the annual means of the modulus of the out-of-ecliptic IMF component \(<|B_r|>\) (in orange), which is well-correlated with \(B_{\alpha\alpha}\), and the mean \(<|B_\phi|>\) (in red), which remains close to zero as is predicted by the theory. Figure 4c shows the “garden hose angle” \(\gamma\) of the IMF in the ecliptic plane (equal to \(\tan^{-1}(B_\phi/B_r)\)) and that predicted by equation (3) (blue line) remain close to 45° and, as a result, the radial heliospheric field component \(|B_r|\) is roughly proportional to \(B_{\alpha\alpha}\), i.e. \(|B_r|=|B_{\alpha\alpha}|\tan\gamma\) (see figure 3c).

Figure 4b shows the annual means of the radial component of the observed IMF. It reveals an upward drift superposed on the solar cycle variation. The validity of equation (3) on these annual time scales, revealed by figure 4, tells us that these variations in \(|B_r|\) reflect variations in the coronal source field, \(|B_r|\). The green line is a linear regression fit and reveals that the increase is by a factor of 1.3 over these three full solar cycles. With better allowance for magnetogram saturation effects, Wang and Sheeley (1995) modelled the coronal field from measurements in the underlying photosphere, using the discovery by the Ulysses spacecraft that there are sheet currents, but no significant volume currents, in the heliosphere (Balogh et al. 1995). Although they did not comment on it, their results do also show this upward drift.

The knowledge gained by the Ulysses spacecraft is vital. It has given us our first view of the heliosphere from out of the ecliptic plane. From its initial journey from the ecliptic to above the Sun’s southern pole, Balogh et al. (1995) found that the latitudinal gradients in \(|B_r|\) are small. This result was confirmed by the fast pole-to-pole solar pass by the spacecraft between 13 September 1994 and 31 July 1995, as demonstrated here in figure 5. During this pass, the \((r/R_s, \psi)\) co-ordinates of Ulysses vary from \((2.29,-80.2°)\) to \((2.02,+80°)\), crossing the heliographic equator (\(\psi=0°\)) on 4 March and reaching perihelion at \((1.34,+6°)\) on 12 March (where \(R_s=1\) AU). The data have been averaged into 26 day periods (roughly mean solar rotation periods) to remove longitudinal solar structure, CIRs and CMEs. The orange line shows the radial field, normalized to the Earth’s orbit using the \(r^2\) variation predicted by equation (3), \(|B_r/(r/R_s)|^2\). The data show the inward field \((B_r<0)\) in the southern heliographic hemisphere and the outward in the northern \((B_r>0)\). The average \(B_r\), close to the heliographic equator is near zero because the current sheet was crossed several times. The blue line shows the modulus of the normalized radial field, \(|B_r/(r/R_s)|^2\), which shows very little latitudinal structure. The green line shows the average value for the pass, \(<|B_r/(r/R_s)|^2>\) which agrees with the value seen when the spacecraft was closest to the ecliptic plane to within an uncertainty of 2.7%. This close agreement means that
Solar change

The long-term variation of the coronal source flux

Equations (1), (2) and (4) give a method for computing $F_s$ from the aa index, once the various exponents and coefficients have been derived from the data for cycles 21 and 22. Table 1 shows that the three correlations shown in figure 3 are all strong (correlation coefficients approaching unity) and extremely significant (almost zero probability of obtaining the result by chance). The least strong of the three correlations is that between the IMF magnitude and its value predicted from interplanetary measurements $a_{aa}$; (b) the observed interplanetary parameter $f$ and the value predicted from $aa$ and $f_p$; and (c) the observed modulus of the radial component of the IMF, $|B|$ and its value predicted from the IMF magnitude, $B_p - s_p B_{sw}$. The red line in (c) is a linear regression fit to $|B|$ for the solar cycles 21 and 22 and shows that the rise over cycles 20–22 (see figure 4b) is not just due to the low IMF values in cycle 20.

Table 1: Regression fits used to extrapolate $F_s$

<table>
<thead>
<tr>
<th>fitted parameters</th>
<th>correlation coefficient $c$</th>
<th>significance level (%)</th>
<th>$s_p$</th>
<th>slope $\lambda$</th>
<th>intercept $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$aa$ and $a_{aa}$</td>
<td>0.966</td>
<td>100 – $3.442 \times 10^{-11}$</td>
<td>$s_p = 4.7022 \times 10^{-18}$</td>
<td>$\alpha = 0.3085$</td>
<td>$\lambda$ = 1.2114</td>
</tr>
<tr>
<td>$f$ and $f_p$</td>
<td>0.934</td>
<td>100 – $3.925 \times 10^{-4}$</td>
<td>$s_p = 5.71 \times 10^{5}$</td>
<td>$\alpha = 0.2271$</td>
<td>$\lambda$ = 2.61 \times 10^{17}$</td>
</tr>
<tr>
<td>$&lt;</td>
<td>B</td>
<td>&gt;$ and $B_p$</td>
<td>0.926</td>
<td>100 – $4.382 \times 10^{-4}$</td>
<td>$s_p = 0.5806$</td>
</tr>
</tbody>
</table>

units:

$aa$ and $a_{aa}$ (in nT) $= s_p <M_0$ in Tm$^{-2}$ | $m_0^{0.25}$ | $M_{sw}$ in m$^{-3}$ | $m_{sw}^{0.25}$ | $<v_{sw}$ in km s$^{-1}$ | $v_{sw}^{(0.75-0.25)}$ | $<B_{sw}$ in nT$^{2}$ | $B_{sw}^{(0.75-0.25)}$ | $<\sin^4(u/22)$ | $f = <N_{sw}$ in m$^{-3}$ | $m_{sw}^{0.25}$ | $<v_{sw}$ in km s$^{-1}$ | $v_{sw}^{(0.75-0.25)}$ | $<\sin^4(u/22)$ | $f_p = s_p <aa$ in nT$^{2}$ | $a_{aa}$ in nT$^{2}$ | $B_{sw}$ in nT$^{2}$ >

The change revealed by figures 6 and 7 is significant. A wide variety of operational systems are influenced by $F_s$ through the power extracted by the magnetosphere from the solar wind. They include: communications, broadcast and radar systems; power distribution networks; spacecraft; oil pipelines; oil exploration rigs and radio and magnetic navigation and guidance systems. For example, the rise in $F_s$ may mean that near-Earth space would have been a less hostile environment for satellites back in 1900 than it is now (Lockwood et al. 1999b) and future changes in $F_s$ will be relevant to the design and safe operation of satellites. The upper atmosphere is known to be heated by the deposition of extracted solar wind energy and this heating will have risen with $F_s$. However, the most intriguing, and controversial, possibilities are that the changes in $F_s$ will be associated with changes in the Earth’s lower atmosphere, oceans and climate.
The concept that significant climate change is caused by changes in the solar output is certainly not new (e.g. Blanford 1891); indeed, as early as 1801 Herschel argued that this effect was the cause of an apparent anticorrelation between sunspot numbers and wheat prices (Herschel 1801). Monitoring over the last 15 years has shown that the total solar irradiance $I$ does indeed vary over the sunspot cycle (Willson 1997). There are two main contributions: firstly, sunspots being cooler, darker regions of the photosphere give a slight decrease in solar luminosity; however, this is outweighed by the positive contribution of brightenings like faculae which are associated with sunspots (Lean et al. 1995). These phenomena are both magnetic in origin, although they are near $r=R_s$ and in the region of closed solar flux, whereas $F_s$ is mainly open flux near $r=2.5 R_s$. However, if the change in $F_s$ reflects a fundamental variation in the solar dynamo, we would expect a relationship between $I$ and $F_s$. The observed solar cycle variation is small, $I$ varying between 1367.0 W m$^{-2}$ and 1368.3 W m$^{-2}$, a variation of just 0.1%. The various total solar output monitors are not well calibrated, but Lockwood and Stamper (1999) have shown that the annual means of $I$ from each are very well correlated with the annual means of $F_s$.

This point is demonstrated in figure 8. Using inter-calibration factors for the various instruments (e.g. Willson 1997), Lockwood and Stamper find a strong correlation (correlation coefficient $c=0.852$) and highly significant (100–6.15×10−10%) relationship between $I$ and $F_s$. If we assume that this is valid at all times, we can then use the best-fit regression $[I$ in W m$^{-2}]=1364.9+5.5[F_s$ in Wb]×10−14 (where the slope s=0.507±0.070) to extrapolate back to 1868. Given than the heat capacity of the oceans will smooth out most of the effects of variations in $I$ on the timescales of the solar cycle and shorter (Wigley and Raper 1990), we here look at 11-year running means, $I_{11}$; these smoothed variations being the most relevant to global temperature change. We find that the average total solar irradiance $I_{11}$ increased by $\Delta I_{11}=1.65±0.23$ W m$^{-2}$ in the interval 1901–1995, up to 1367.6 W m$^{-2}$. This is slightly lower than, but remarkably close to, the $\Delta I_{11} = 2.106$ W m$^{-2}$ estimated by Lean et al. (1995) using a solar cycle variation added to a long-term drift obtained by comparing the Sun’s Maunder minimum to the luminosity of non-cyclic, sun-like stars.

The agreement between the forms of the two extrapolations is remarkably close, considering we have used an entirely independent set of measurements, namely the $aa$ geomagnetic index. Furthermore, Lean and co-workers have recently refined their estimate and this has reduced their long-term drift factor by 25%, making their reconstruction of the variation of $I$ almost identical to that shown here (J Lean, private communication 1999). The mean rise in $I$ over the last three solar cycles is at a rate of $0.25±0.4$ W m$^{-2}$ per decade. We can compare this range with the estimates made from inter-calibrated measurements during the mini-ma at the start of cycles 22 and 23 by Willson (1995). He reported 0.50 and 0.37 W m$^{-2}$ per decade for ACRIM1/2 and ERBS observations, respectively. Thus our estimates of the recent rise in $I$ are comparable with (but somewhat smaller than) those by Willson. The reconstruction of solar brightness found here is also similar in its overall drift to that by Hoyt and Schatten (1993) and others, based on the length of the solar cycle. However, there are also some significant differences.

The 0.12±0.02% rise in $I$ since 1900 that is reported here is significant, being larger than the amplitude of the solar cycle variation, and because it is over a much longer timescale, its effects will not be smoothed out by factors such as the heat capacity of the oceans (Wigley and Raper 1990). It gives a change in the radiative forcing at the top of the atmosphere of $\Delta Q = \Delta I (1−a)/4=0.29±0.04$ W m$^{-2}$, where $a$, the Earth’s albedo, is here taken to be 0.3 (see discussion of the concept of $Q$ by Hansen et al. 1997). The effect of any change in $I$ on global mean surface temperatures will be complex because it will be made up of contributions that are much stronger at some wavelengths (for example, UV) than at others and because a variety of other effects (for example, changes in anthropogenic greenhouse gases, tropospheric sulphate aerosols and volcanic dust in the stratosphere, ozone absorption of UV etc) will also be active and will interact with each other in complex feedback loops (Rind and Overpeck 1993; Hansen et al. 1997). This estimate of $AQ$ due to solar change is similar to the estimate by the IPCC (Intergovernmental Panel on Climate Change). By way of comparison, the IPCC’s $\Delta Q$ estimates for the same interval due to CO$_2$, other greenhouse gasses, and aerosols are roughly 1.5 W m$^{-2}$, 1.1 W m$^{-2}$, and −1.3 W m$^{-2}$, respectively (e.g. Wigley et al. 1997).

In order to evaluate the effect of the solar brightness change, we need to know how sensitive the Earth’s climate system is to changes in the radiative power, $Q$. Figure 9 shows the
results for 11-year running means with various estimates of the “climate sensitivity”, $dT/dQ$, where $T$ is the global mean of the surface temperature. The orange line, bounded by uncertainty limits in green, is the inferred contribution of the increase in solar luminosity, on its own, $\Delta T_o$ using the mean regression slope $s$ of 0.507 ± 0.070 with a climate sensitivity estimate of $dT_o/dQ$ of 0.85 ± 0.15 °C/W m$^2$ (Rind and Overpeck 1993; Lean et al. 1995), giving $\Delta T_o = -0.16 + 0.147s/0.026$ x (l in W m$^{-2}$−1363).

This represents a consensus view of the Earth’s climate sensitivity, being the average of values from several large numerical models of the coupled atmosphere–ocean circulation system, with an uncertainty set by the range of the estimates. From this we infer that the Sun’s brightness change, on its own, could have caused a temperature rise of 0.24 ± 0.04 °C since 1900. The yellow line employs one of the largest published estimates of the climate sensitivity, $dT_o/dQ = 1.7$ °C/W m$^2$, by Nesme-Ribes et al. (1993). This gives $\Delta T_o = -0.70 + 0.293x(\text{[l in W m}^{-2}]−1363)$.

The inferred variations are very highly correlated with the observed global average of the surface temperature, $\Delta T_o$ (blue line) (Wigley et al. 1997), the correlation coefficient being 0.93 and at a lag of $\delta t$ = 2 years, which is consistent with the heat storage effect of the oceans (Wigley and Raper 1990). The red line is a best linear regression fit to $\Delta T_o$,

$\Delta T_o = -0.48 + 0.385x(\text{[l in W m}^{-2}]−1363)$ which corresponds to a climate sensitivity of $dT_o/dQ = 2.2$ °C/W m$^2$, which would be required to explain the observed temperature rise $\Delta T_o$ in terms of solar irradiance variations alone. This is a higher value than any of the published estimates from modelling studies and roughly twice the consensus value. Great care must be taken not to over-interpret this correlation. It undoubtedly argues for some variability effect on global warming, but adding an approximately exponential contribution (expected for man-made greenhouse gases and aerosols) does not decrease the correlation and can even make it higher (Laut and Gudermann 1998). Thus the high correlation does not support a purely solar effect. Multi-variable analysis that accounts for several mechanisms, including anthropogenic effects, does reveal improved correlations if some solar drift is included (Wigley et al. 1997; Tett et al. 1997; Benestad 1999). If we compare the inferred temperature rise $\Delta T_o$ (for the average prediction of the climate sensitivity) with that observed $\Delta T_s$, we find no significant difference for the period 1870–1910. On the other hand, the change in solar luminosity alone can account for only 52% of the rise in $\Delta T_o$ over the period 1910–1960, but just 31% of the rapid rise in $\Delta T_o$, over 1970–present. In the interval covered by figure 9, industrially-produced CO$_2$ in the atmosphere increased from about 280 to 355 ppmv. The implications are that the onset of a man-made contribution to global warming was disguised by the rise in solar brightness and that the anthropogenic effect may have a later, but steeper, onset than previously thought. Such an effect is consistent with the predictions for combined greenhouse and aerosol pollutants (Wigley et al. 1997; Hansen et al. 1997). Recently, Tett et al. (1999) have used a set of simulations made by a coupled atmosphere–ocean global circulation model to deduce a shift from solar forcing to anthropogenic effects as this century has progressed.

There is other evidence to support the view that solar changes have had a significant effect. For example, the decrease in global temperatures during about 1930–1965 was at a time when the concentration of greenhouse gases was increasing (Friis-Christensen and Lassen 1991) and anthropogenic climate forcing was increasing (Wigley et al. 1997). The decrease in solar luminosity helps explain this and consequently including solar forcing can improve the correlation found with observed temperature (Wigley et al. 1997). Furthermore, the present upward trend in global temperatures appears to have commenced considerably earlier than significant burning of fossil fuels (Bradley and Jones 1993) and there is some evidence that temperatures have been as high in past epochs as they are now (see Cliver et al. 1998).

From the above, we can conclude that for solar brightness change to explain all of global warming would require a climate sensitivity considerably higher than the values predicted (by a factor of about two on average). However, there is a second mechanism whereby $F_s$ would influence the global climate that has been proposed. This is more controversial and is based on the observation that total terrestrial cloud cover since 1984 is correlated with the flux of galactic cosmic rays reaching the Earth (Svensmark and Friis-Christensen 1997). Furthermore, this effect is strongest nearer the poles where cosmic rays have easier access to the atmosphere, the shielding by the Earth’s magnetic field being less efficient there. The
implication is that cosmic rays may be involved in the production of at least some clouds. The flux of galactic cosmic rays is well known to be anticorrelated with the sunspot numbers because the Earth is more shielded from cosmic rays at sunspot maximum by the heliosphere. More than one mechanism contributes to this shielding: the particles are scattered by irregularities in the heliosphere; they are converted and decelerated by the solar wind; and they suffer gradient and curvature drifts because of the large-scale structure of the heliospheric field. The relative importance of the various effects is not yet known (see review by Moraal 1993) although Cane et al. (1999) have shown that the cosmic-ray fluxes anticorrelate well with the coronal source flux. Stamper et al. (1999) have reported that the fluxes do show a significant long-term drift to lower values consistent, at least qualitatively, with the rise in heliospheric field which by equations (3) and (4) is power back into space, but also traps heat. The method reported here allows us to study the large-scale structure of the heliospheric field. The relative importance of the various effects is not yet known (see review by Moraal 1993) although Cane et al. (1999) have shown that the cosmic-ray fluxes anticorrelate well with the coronal source flux. Stamper et al. (1999) have reported that the fluxes do show a significant long-term drift to lower values consistent, at least qualitatively, with the rise in heliospheric field which by equations (3) and (4) is power back into space, but also traps heat. The method reported here allows us to study the large-scale structure of the heliospheric field. 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