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Two solar cycles of nonincreasing magnetic flux

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[1] Since measurements began in the late nineteenth century, there has been a secular increase (with superposed ripples due to solar cycles) of the *aa* geomagnetic index [*Mayaud*, 1972]. Starting from this observation, *Lockwood et al.* [1999a, 1999b] conclude that the total open solar magnetic flux has increased by 41% from 1964 to 1995 and by 130% over all but the last 5 years of the twentieth century. However, solar data for more than two solar cycles - Carrington maps from Mount Wilson, and Wilcox Solar Observatories and newly reanalyzed data from the National Solar Observatory - show no secular trend in overall photospheric flux. More importantly, the magnetic flux open to interplanetary space (as calculated from photospheric measurements and assuming potential fields to a height of 2.5 $R_\odot$) fails to show evidence of a secular increase over the last two solar cycles. Like Lockwood et al., we do not explicitly take account of transient events. Thus both data and calculations imply that the Sun's average coronal magnetic flux has not increased over the last two solar cycles. Analysis of simulations with the potential field source surface model shows that the interplanetary magnetic flux is not simply related to the erupted photospheric solar magnetic flux. Both results are in agreement with the findings of *Wang et al.* [2000]. The topology, rather than the strength, of the emergent solar magnetic field may be a major determinant of the interplanetary magnetic field experienced at Earth. *INDEX TERMS:* 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 1650 Global Change: Solar variability; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; *KEYWORDS:* solar magnetic flux, aa index, solar cycle variations, coronal holes

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1. Introduction

[2] The *aa* index [*Mayaud*, 1972] is a well calibrated 3-hour geomagnetic activity index extending back to 1868. The puzzling, steady increase in the index over the last century has been noted by a number of authors [e.g., *Russell*, 1975; *Feynman and Crooker*, 1978; *Clilverd et al.*, 1998]. Recently, *Lockwood et al.* [1999a, 1999b] reported finding two strong correlations between the *aa* index, the magnitude of the interplanetary magnetic field (IMF), and the solar wind (e.g., density and velocity) using *Vasyliunas et al.*'s [1982] theory of energy transfer into the Earth's magnetosphere. Based on this discovery, they proposed that the increase in the *aa* index over the last century is almost entirely due to a gradual increase in the average strength of the IMF near Earth. Noting that the Ulysses spacecraft has found only small latitudinal gradients in the radial heliospheric component of the IMF [e.g., *Balogh et al.*, 1995], *Lockwood et al.* [1999a, 1999b] suggest that total open solar flux can be deduced reliably from point measurements (i.e., from spacecraft near Earth) of the mean radial field. This has led them to conclude that the amount of magnetic flux leaving the Sun has increased over the last century. In fact, they suggest that total open solar flux has increased by a factor of 1.4 since 1964 and by a factor 2.3 since 1901. This conclusion is based on indirect measures of the Sun's source field that depend critically on the notion that the global heliospheric field can be deduced from point measurements in the ecliptic and on a long-term correlation between the magnitude of the IMF and the *aa* index. While a direct test of this claim

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is not possible over the last century, it certainly is over the last two solar cycles.

[3] Routine full disk measurements of the Sun's photospheric field began at Mount Wilson Solar Observatory (MWO) in ~1966, resulting in a near-continuous set of daily magnetograms over approximately the last 3 solar cycles. Similar measurements began both at the National Solar Observatory on Kitt Peak (NSO) and Wilcox Solar Observatory (WSO) roughly a solar cycle later in the mid-1970s. There are thus 3 solar observatories with near continuous daily observations of the global photospheric field over approximately the last quarter century. In this paper, we test Lockwood et al.'s claim directly by using these global measurements of the sun's photospheric field and a potential field source surface model to calculate total open solar flux. Since there are known calibration issues and other problems (discussed in the next two sections of the paper) with the data from each solar observatory, we analyze here only the approximately two solar cycle time interval (i.e., ~1974 to ~2001) for which there are concurrent observations from all 3 observatories. We take this approach in order to have greater confidence in our conclusions. As we report below, our analysis of these data shows no indication of an upward trend in either the total (unsigned) solar photospheric or open flux over the last two solar cycles.

[4] In Section 2, we discuss the nature of the data available from each observatory and all corrections and modifications applied to them before they are analyzed. Specific problems with the data from the observatories are noted and discussed in this section as well as the next. In Section 3, the methods used to obtain the photospheric and the open field (source-surface) fluxes are explained and the results are presented. In Section 4, we discuss the results. In the final section, we summarize and present our conclusions.

2. Corrections to the Data

[5] Both WSO and MWO use the Fe I 525.0 nm line in the solar spectrum to measure the line-of-sight (LOS) photospheric field strength. However, *Ulrich* [1992] has demonstrated that the LOS magnetic field strength derived using this line must be modified by a correction factor due to observational saturation effects. This correction factor depends both on the spatial resolution of the instrument and the center-to-limb position of the observation, and it was determined by comparing photospheric field strengths derived from the Fe I 525.0 nm line to those derived from the Fe I 523.3 nm line, which does not readily saturate. The saturation is a manifestation of the concentration of most of the photospheric magnetic flux into spatially unresolved, kG strength flux tubes. The LOS field strength is inferred from the amount of circular polarization measured in two wavelength windows straddling the spectrum line, and an assumption that this signal is linearly proportional to the wavelength derivative of the quiet sun spectrum line profile. This assumption is adequate if the Zeeman splitting is small compared to the wavelength separation of the observation windows and if the spectrum line does not change in strength or shape (other than Zeeman splitting) in a magnetic flux element compared to the non-magnetic photosphere. Neither of these factors hold for the 525.0 nm line. The effects are strongest at disk center where the observed signal arises from most deeply in the photosphere. As one moves from center to limb, both effects become smaller as the observed level in the atmosphere increases. For data taken with large apertures such as with WSO and MWO, *Ulrich* [1992] determined that the empirical correction factor for the Fe I 525.0 nm line depends only on the center-to-limb angle. Since Carrington maps of the LOS photospheric field are essentially the time history of the field along the central meridian, the center-to-limb angle can be replaced with the heliographic latitude (λ). This approach is identical to that taken by *Wang and Sheeley* [1995] and results in the following empirical multiplication factor for the Fe I 525.0 nm line: $f = 4.5 - 2.5sin^2(\lambda)$. We applied this factor to the LOS magnetic field data from both MWO and WSO, as neither observatory accounts for saturation effects. NSO data does not require such a large correction because the LOS magnetic field strength is measured using the Fe I 868.8 nm line, which is much broader than the 525.0 nm, has a profile that changes only modestly in magnetic flux elements, and is formed higher in the atmosphere. The magnitude of a correction for the 868.8 nm line is not known but is expected to be similar to one for the 523.3 nm line (for which a correction is also unknown). Accordingly, the 868.8 nm measurements without a saturation correction should be closely comparable to the 525.0 nm measurements after the latter are corrected to the scale established by comparison with the 523.3 nm line.

[6] There are many other observational and instrumental factors that can affect the accuracy of the LOS field measurements. Anything that alters the amount of circular polarization in the wings of the spectrum lines used will degrade the measurements. For example, oblique reflection of the solar light by mirrors in front of the polarization analyzer can systematically reduce the strength of the measured LOS field. Scattering of light in the telescope and spectrograph is another degrading factor. All three telescopes and instruments whose data are used here can suffer from these effects. Since the observations are made by scanning the solar image over several tens of minutes, as the angle of reflection from feed mirrors changes it is possible that a systematic change of LOS field strength will affect the scanned solar image. It is also possible that a relatively larger amount of scattered light near the solar limb will systematically reduce the measured strength of the LOS fields there. These, and other factors, have not been explored in detail for any of the telescopes and instruments used to produce the data we use. Accordingly, we do not consider them further here except to note that it is unlikely for all three data sets to synchronously suffer the same degradations over a period of decades of numerous instrument upgrades and changes.

[7] Observational evidence [*Wang and Sheeley*, 1992] suggests that the solar magnetic field is nearly radial at the photosphere. Assuming that the magnetic field is truly radial in the region of the photosphere where the measurements are taken, the relationship between the radial field (B_r) and the LOS field (B_{los}) is $B_r = B_{los}/cos(\lambda - b)$ along the central meridian, where the solar b angle is the tilt of the Sun's rotation axis toward or away from Earth.

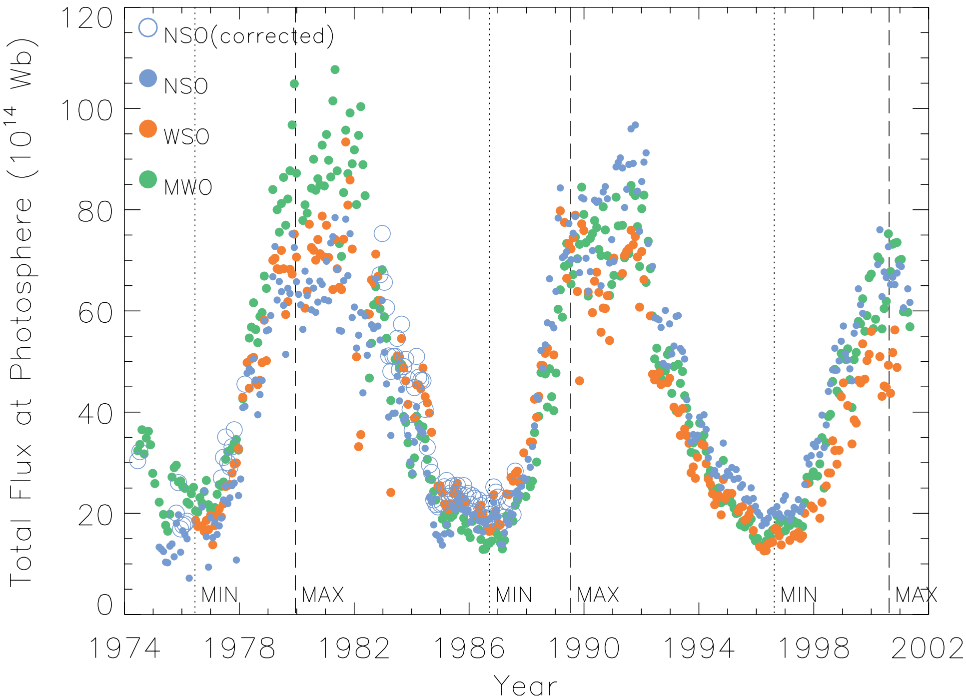

Figure 1. Total (unsigned) photospheric flux for each Carrington rotation since 1974 for National (NSO), Wilcox (WSO), Mount Wilson (MWO) Solar Observatories. The fluxes were derived from line-of-site photospheric field Carrington maps available from each observatory (see text for details). Results based upon previously available NSO data (solid blue dots) should be replaced prior to 1990 with those based upon corrected NSO data (open blue dots). Solar cycle sunspot maxima and minima are indicted on this and all subsequent figures by long-dash and short-dash vertical lines, respectively.

The LOS field can thus be converted to radial (i.e., flux) by simply dividing it by the factor $cos(\lambda - b)$. We converted the MWO LOS field in this way. NSO measurements were previously converted in a similar manner and missing or noisy polar measurements replaced by interpolation in a polar projection. However, the polar field measurements at WSO tend to have significantly greater uncertainly than those found at the other two observatories. This problem with the WSO polar fields is only further compounded when the LOS data are converted to radial, since the largest amplifications of the LOS field occur near the poles where the above cosine factor is small. When the b angle is large, the amplification is especially large for the pole tilted away from the Earth. Given the problems with the WSO polar fields, we find that the best approach for converting this observatory's photospheric field data to radial is to neglect the solar b angle and divide by $cos(\lambda)$.

[8] The Carrington maps available from the three solar observatories are all in sine latitude format but their photospheric field data all have different spatial resolutions, in increasing order, WSO, MWO, and NSO. Because of this, we interpolate all of the Carrington maps to a uniform $360° \times 180°$ grid with $5° \times 5°$ cell sizes. However, we expect, other factors being equal, that the higher intrinsic resolution observations will include more flux, which is of mixed polarity over a wide range of scales. Since the Carrington maps are not true synoptic maps (i.e., the data are not taken all at the same instant), they usually have a small monopole moment that requires removal. To ensure that $\nabla \cdot B = 0$, each map's monopole moment was calculated and then uniformly subtracted from it.

3. Analysis

[9] Once all of the necessary corrections and modifications were applied to the data from each observatory, we calculated the total (unsigned) photospheric flux for each Carrington rotation (CR). This is determined by taking the area-weighted sum of the magnitude of the flux in each of the $5° \times 5°$ cells on a map (i.e., $\Sigma \mid B \mid sin\theta \triangle \theta \triangle\phi$, where θ is the colatitude and ϕ is Carrington longitude). Maps with large data gaps were not used.

[10] Plotted in Figure 1 is the total (unsigned) photospheric flux (filled circles) calculated for each Carrington rotation from approximately the beginning of 1974 through 2001 for WSO, MWO, and NSO. The open blue circles seen in the figure are corrected NSO data and will be discussed in detail below. The vertical dashed lines are the dates of solar cycle maxima and minima according to SIDC - RWC Belgium World Data Center for the Sunspot Index (http://sidc.oma.be/index.php3). The photospheric fluxes from the three observatories agree reasonably well with one another over the entire ~28-year time period. However, the MWO fluxes around the ~1980 sunspot maximum have larger values than those from either WSO or NSO. Also, the uncorrected NSO flux values during the 1976 sunspot minimum are often unusually low as compared to the results from other two observatories. After 1992, when the quality of observations from all three

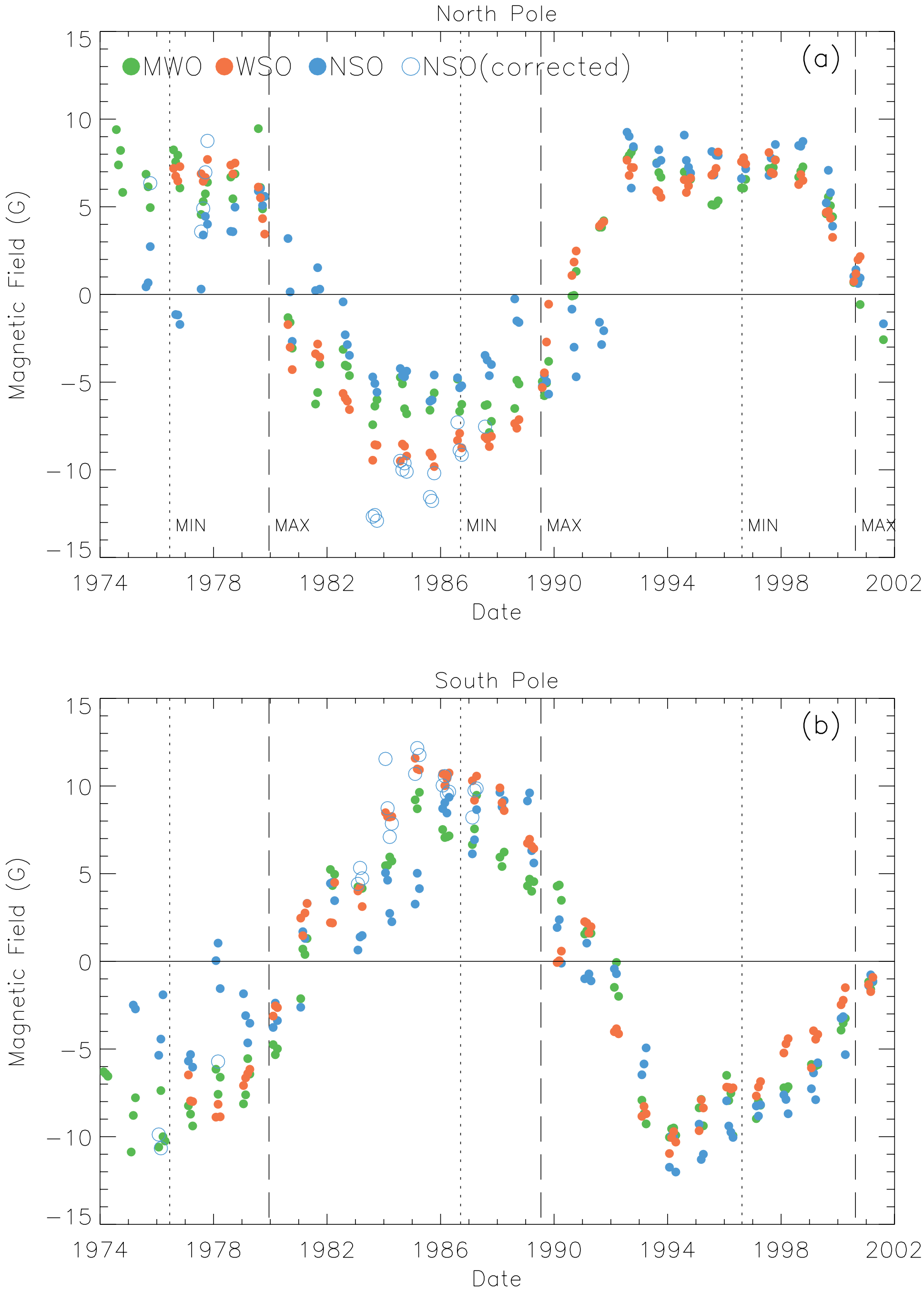

Figure 2. Average polar field strength of the Sun for each Carrington rotation since 1974 for times when the relevant hemisphere was pointed toward Earth (i.e., when $b > +5°$ for northern and $<-5°$ for southern hemisphere). The measurements of line-of-sight fields have been adjusted to yield radial field values. (a) Northern hemisphere values. (b) Southern hemisphere values.

observatories is good, the expected dependence of total flux on spatial resolution is clearly visible.

[11] Total photospheric flux is only a coarse measure of a potential change in the coronal field. The distribution of that flux is an important consideration as well. In particular, the polar field strength and extent has a strong influence on the total open flux. The reason for this is that although the poles occupy only a small fraction of the total area on the photosphere, for significant fractions of the solar cycle, the magnetic flux open to interplanetary space emerges primarily from coronal holes located over the poles. Thus, the time-dependent behavior of the polar field distributions from each observatory must be carefully investigated.

[12] Figure 2 shows the average polar field strength in the Sun's northern (Figure 2a) and southern (Figure 2b) hemispheres for each observatory since 1974. Since the polar fields are difficult to measure reliably, we calculate the average polar field strength in a given solar hemisphere only when its pole is inclined toward Earth by more than 5° (i.e., when the solar b angle is greater than $+5°$ for the northern

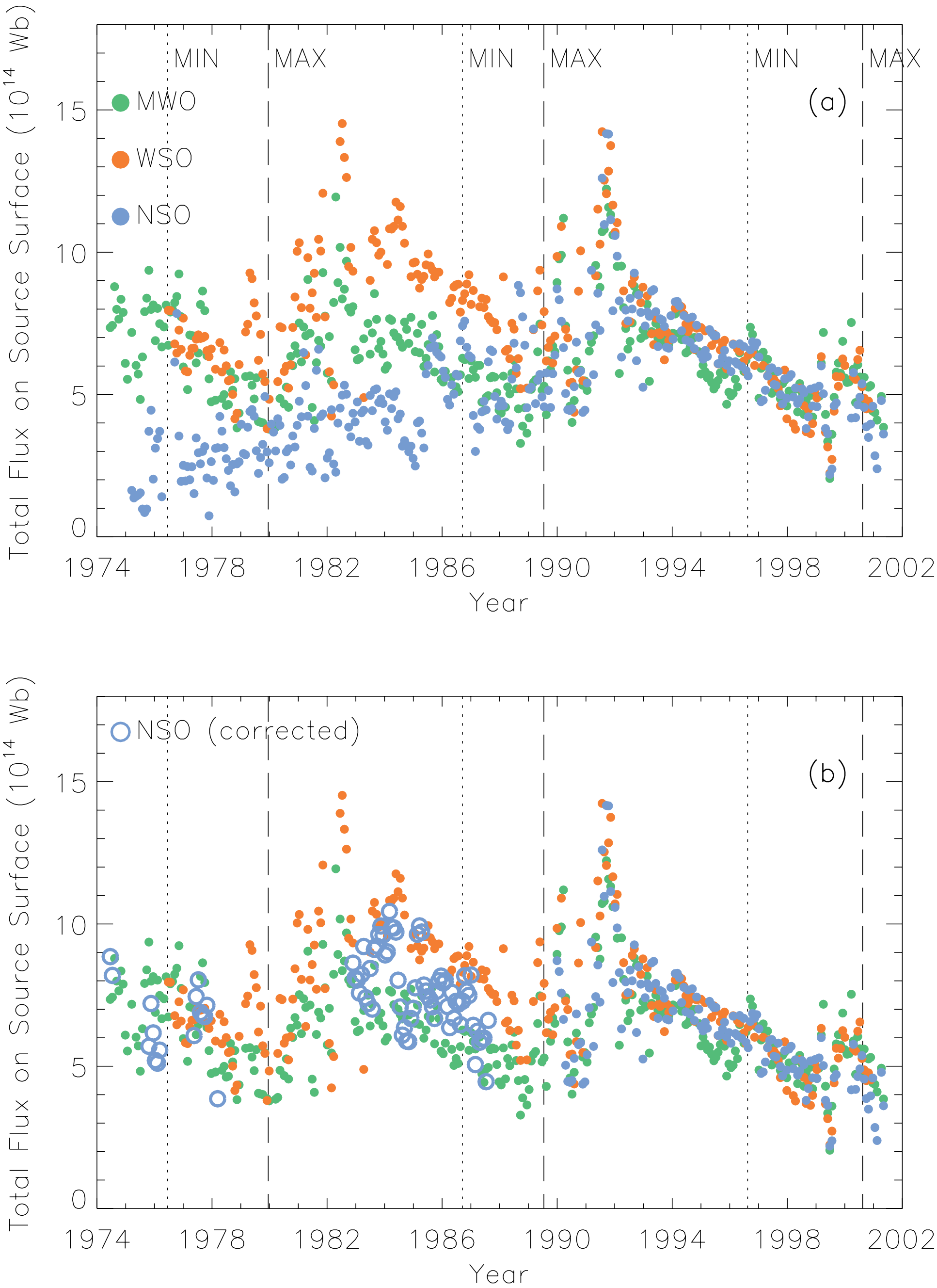

Figure 3. Total open (unsigned) flux at the source surface for each Carrington rotation since 1974. The fluxes were calculated using a potential field source surface model (see text for details). (a) Original results (solid dots) for each observatory. (b) Same as (a) except now the original NSO fluxes before 1990 have been replaced by a set of corrected ones (open blue dots).

hemisphere and less than $-5°$ for the southern hemisphere). Figure 2 is therefore a plot of the most reliable polar field measurements. As seen in the figure, the average polar field strengths (solid dots) from each observatory agree reasonably well after 1992. However, NSO's northern polar field values show significant disagreement with the other two observatories before ~1992, and its southern values differ significantly before ~1985. Large differences are seen between the average polar field values of MWO and WSO for approximately a 4-year interval centered roughly about the 1986 solar minimum. However, they are generally less than those observed between NSO and WSO. The brief systematic difference between the MWO and WSO polar fields is not present in the total photospheric flux and its origin is not clear. The discrepancies seen between NSO's polar fields and the other two observatories are both substantial and persistent prior to 1992.

[13] This discrepancy motivated an examination of the NSO observations prior to 1992. The NSO magnetograph was replaced in 1992 and subsequent observations are believed to be free of significant systematic problems. The examination showed that observations with the original

magnetograph frequently suffered from systematic biases in the zero point of the measurements. Three different zero point biases in many, but not all, daily observations were uncovered: an overall shift, an east-west variation and a variation from center to limb. The latter is by far of most concern here. To first order, the biases have no effect on the total unsigned flux. The radial bias significantly affects the weak polar field measurements by increasing the apparent strength of the polar fields having the same polarity as the bias and decreasing the strength of the opposite polarity.

[14] A correction procedure was developed to measure and then subtract the bias from each daily observation for selected periods between 1974 and 1992 (specifically: CR1615-16, CR1621-22, CR1633-38, CR1654-60, CR1665, and CR1728-91). The LOS measurements of each corrected observation were divided by the cosine of the heliocentric angle to convert to flux. These observations were then mapped to a sine latitude - Carrington longitude grid and finally averaged with strong weighting of the central meridian to produce Carrington maps. The new NSO polar fields (open blue circles in Figure 2) agree significantly better with the values from the two other observatories than do those from the uncorrected maps. The disk-integrated photospheric field fluxes obtained with the improved NSO Carrington maps (i.e., open blue dots in Figure 1) do not differ substantially from those calculated from the uncorrected maps. The corrected values are somewhat larger because the conversion from LOS to flux was done before mapping to Carrington form in the newly corrected data set.

[15] A potential field source surface (PFSS) model [e.g., *Schatten et al.*, 1969; *Altschuler and Newkirk*, 1969; *Wang and Sheeley*, 1992] was used to estimate total (unsigned) open solar flux for each Carrington rotation. The total open flux is determined using the same technique as described above for the photospheric field except that the field values at the source surface, positioned at 2.5 $R_\odot$ from the Sun's center [*Hoeksema et al.*, 1983], are used instead. Figure 3a is a plot of the total (unsigned) source surface flux for the same ~28-year time interval shown in Figure 1. As can be seen in the figure, the open fluxes determined for each observatory agree well with each other from ~1990 onward, and there is reasonable agreement between WSO and MWO before that time. Although MWO and WSO fluxes are clearly offset from one another during the 1980s, they follow similar trends.

[16] The most notable feature in the plot is that NSO's open fluxes deviate substantially from the other two observatories before ~1990, with the differences being most pronounced before 1985. Moving backward in time from ~1990 to 1974, the NSO fluxes show a steep, essentially linear, decline in magnitude. However, as seen in Figure 3b, the open fluxes obtained from the new NSO Carrington maps (open blue circles in the Figures) are in good agreement with those from the other observatories. Clearly, the uncorrected open fluxes from NSO are unreliable before 1990.

4. Discussion

[17] As seen in Figure 1, for the three maxima and three minima considered here, total (unsigned) photospheric flux varies by a factor of about 10 over the solar cycle, with minimum flux occurring near sunspot minimum and maximum flux peaking roughly a year or two after sunspot maximum. These results are consistent with those of *Wang et al.* [2000]. The fluxes have their largest values and greatest scatter over a 3–4 year period that begins just before sunspot maximum. Right after the 1980 sunspot maximum, the fluxes are larger, on average, than those just after the 1989 sunspot maximum with the exception of the (uncorrected) NSO values. Properly corrected NSO maps from the early 1980s are not yet available. However, comparison of the corrected (open blue dots) with uncorrected (filled blue dots) NSO fluxes (c.f., Figure 1) suggest that the corrected values for this time will be larger than the uncorrected ones. During sunspot minimum, the fluxes from the three observatories are in good agreement. Excluding the uncorrected NSO results, the fluxes during the 1976 sunspot minimum range from $15-25 \times 10^{14}$ Wb. A similar result is found for the 1986 minimum, if the MWO values are excluded. Photospheric fluxes range from about $12-20 \times 10^{14}$ Wb during the 1996 sunspot minimum, which is somewhat lower than that found for the previous two minima.

[18] To look for secular trends in the Sun's photospheric flux, we calculate least squares fits to the results shown in Figure 1. To avoid introducing artificial trends, we consider only an integral number of cycles, i.e., one fit is made to the values between the 1976 and 1996 cycle minimums (~21 years) and another between the 1980 and 2000 cycle maximums (~20 years). Between the minima the MWO and WSO slopes are -1.13×10^{14} Wb/year and -0.70×10^{14} Wb/year, respectively, with correlation coefficients of −0.25 and −0.20. These correlations have high statistical significance [*Taylor*, 1982] as the probability of either of them occurring by chance is less than 1%. Between the two sunspot maxima, slopes of -1.32×10^{14} Wb/year for MWO and -1.42×10^{14} Wb/year for WSO are obtained, with correlation coefficients of −0.31 and −0.41 and both having high statistical significance. A least squares fit is made to the original set of NSO fluxes (solid dots) and another to a combined set consisting of the reliable NSO flux values from 1990–2001 and the corrected (open circles) NSO values before then (i.e., the combination is the most reliable set of NSO photospheric fluxes). Neither one of these two fits are statistically significant, as both have probabilities of chance occurrence greater than 5%. The most likely explanation for the discrepancy between the results obtained for the combined NSO set and those for MWO and WSO is the lack of corrected NSO Carrington maps around the time of the 1980 sunspot maximum. In summary, the data from MWO and WSO imply declines in total photospheric flux at maximum and minimum since ~1976, while the NSO data suggest no change at all at minimum.

[19] As seen in Figure 3, total (unsigned) open flux, as calculated by the potential field source surface model, varies by roughly a factor of 2–3 over a solar cycle. Thus the variation of the Sun's open flux over a solar cycle is much less than that of photospheric flux. *Wang et al.* [2000] drew attention to this point by considering the joint behavior of the photospheric flux and coronal hole area over the solar cycle. In Figure 4a, the fractional area of the photosphere with open flux is plotted. The fractional area reaches a peak of ~25% approximately 2–3 years before solar minimum, while near solar maximum it has a minimum value of 5–10%. However, photospheric flux (see Figure 1) is at its minimum value near sunspot minimum but at its maximum value about

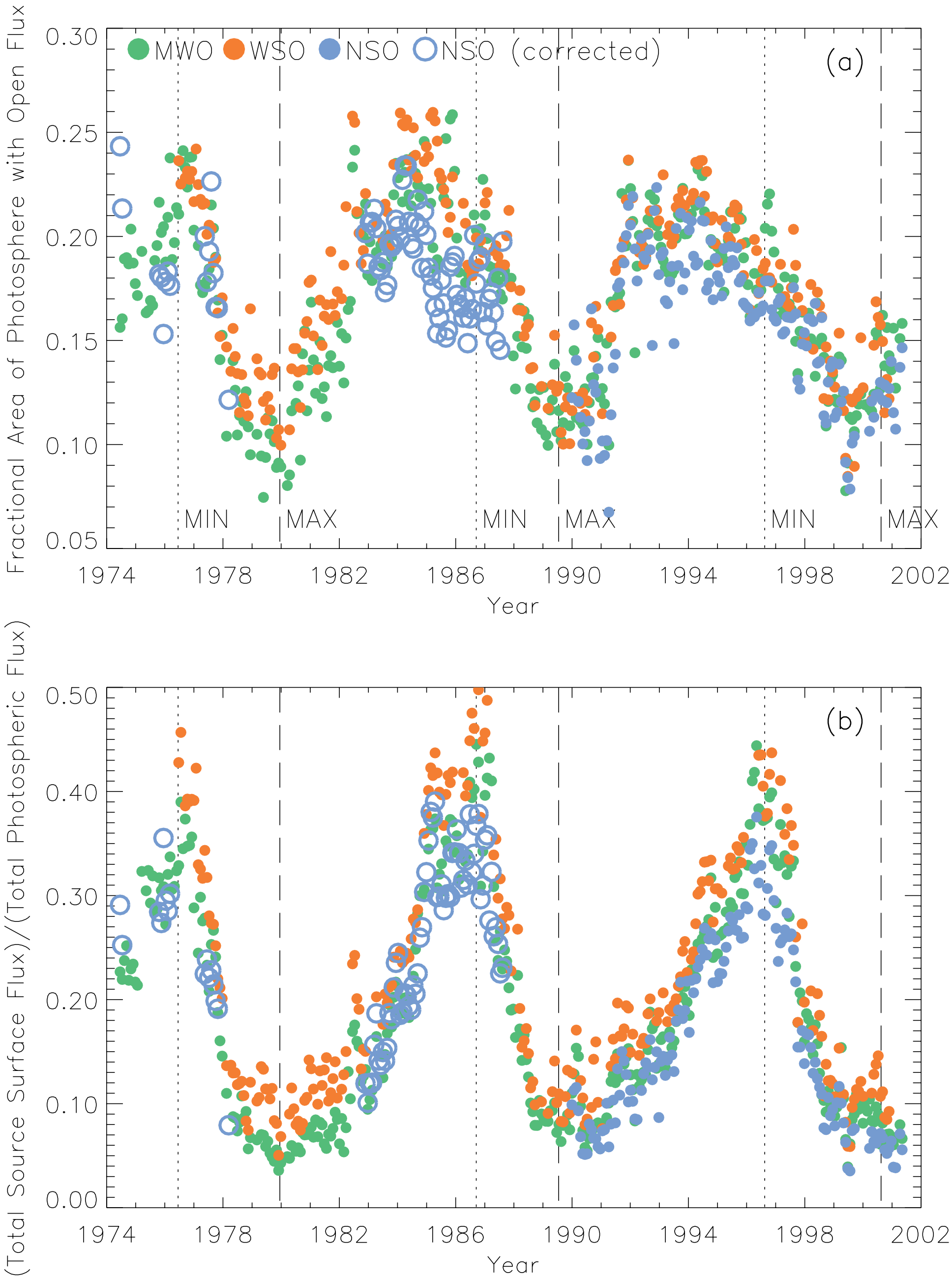

Figure 4. (a) Fractional area of the photosphere with open flux for each Carrington rotation since 1974. (b) Ratio of total source surface flux to total photospheric flux for each Carrington rotation since 1974.

2 years after sunspot maximum. Thus, the maximum and minimum phases of fractional area and photospheric flux are sufficiently offset from one another as to significantly reduce the degree of variation of total open flux over the solar cycle.

[20] Figure 4b shows the ratio of source surface flux to photospheric flux as a function of time. The ratio indicates the fraction of total photospheric flux open to interplanetary space. As can be seen in the figure, the ratio varies by a factor of 10 over the solar cycle: from as little as ~5% near solar maximum to as much as ~50% around solar minimum. The results from each observatory show good agreement and are in line with the findings of *Wang et al.* [2000]. Unlike photospheric flux, open flux, and fractional area, the time-dependent behavior of the fraction of open photospheric flux follows the sunspot cycle very closely, but with its maximum and minimum occurring opposite to that of the sunspot cycle. As seen in Figure 4b, it slowly rises over 6–7 years from a minimum at sunspot maximum to a maximum at sunspot minimum and then rapidly falls back to a minimum 3–4 years later.

[21] As with the photospheric flux, we look for secular trends in the Sun's open flux by computing least squares fits to the results shown in Figure 3. For each observatory, we again make two fits: one to values between the 1976 and 1996 sunspot minimums and the other to values between the 1980 and 2000 sunspot maximums. Between the sunspot minima, the MWO and WSO slopes are both positive and small with values of $+0.025 \times 10^{14}$ Wb/year and $+0.022 \times$

10^{14} Wb/year, respectively. The corresponding correlation coefficients are +0.088 and +0.062 and are not statistically significant. Between the sunspot maxima, slopes of -0.056×10^{14} Wb/year for MWO and -0.20×10^{14} Wb/year for WSO are obtained, with correlation coefficient of -0.20 and -0.53. Both of these have high statistical significance with each having a probability of chance occurrence many orders of magnitude less than 1%. Since the NSO fluxes in Figure 3a are unreliable before 1990, least squares fits are not made to them. Both fits to the NSO fluxes in Figure 3b yield negative slopes. The slope between the sunspot minima is -0.04×10^{14} Wb/year and the slope between the sunspot maxima is -0.18×10^{14} Wb/year. The correlation coefficients are -0.11 and -0.53, respectively. The first correlation coefficient is not statistically significant, while the second has high statistical significance. Thus the data from all three observatories show no linear trend in total open solar flux from 1976 to 1996, while they all show statistically significant downward trends from 1980 to 2000.

5. Summary

[22] We have used global photospheric field measurements to directly determine the total (unsigned) photospheric and open solar fluxes from ~1974 to ~2001, the period for which there are concurrent observations from Mount Wilson, Wilcox, and National Solar Observatories.

[23] While uncertainties exist with the data from each observatory, the results agree surprisingly well. They clearly indicate that no major secular increase in total photospheric flux has occurred on the Sun since 1976. Data from WSO and MWO solar observatories suggest that total photospheric flux has decreased since 1976, while NSO data suggest no change at all. The lack of corrected NSO synoptic maps around the 1980 sunspot maximum is the most likely explanation for the discrepancy in the results from the observatories.

[24] The data from all three solar observatories show no statistically significant secular change in open solar flux from 1976 to 1996, although there is a hint of a decrease in open solar flux from 1980 to 2000. Thus the Lockwood et al. claim that open solar flux has increased by 41% from 1964 to 1995 would require that the entire increase must have occurred over the twelve-year period between 1964 to 1976, which does not seem credible. It is possible, but in our judgment very unlikely, that all three observatories suffered from systematic observational problems in just such a way to cancel out a secular increase in the amount of open magnetic flux. In passing, we note that the revised model of *Solanki et al.* [2002] shows an approximate doubling of total solar flux in the first half of the twentieth century. However, their Figure 3 shows little or no trend in open flux in the second half of the twentieth century, in agreement with our results presented in this paper, and inconsistent with the Lockwood et al. claim of a 41 percent increase from 1964 to 1995.

[25] A problem with pre-1992 NSO polar field measurements highlights the cautionary point that minor changes to the observations that result in only small changes to the total measured photospheric flux can, nonetheless, produce significant changes in the modeled total open flux. Thus, it is possible that the photospheric field distribution has evolved in such a way that the cycle of both total (unsigned) photospheric and open flux has remained relatively steady but that the global distribution (i.e., topology) of the open flux has changed. As shown, we find no long-term trend in total open solar flux from 1974 to 1996. However, it is also a fact that the Sun's polar fields during this same time interval often have unequal strengths as can clearly be seen in Figure 2 and as reported by others [e.g., *Smith et al.*, 2000]. We suggest that the topology, rather than the strength, of the erupted solar magnetic field may be the prime determinant of the interplanetary magnetic field experienced at Earth. We plan to pursue this issue in a future paper.

[26] **Acknowledgments.** We wish to thank National, Mount Wilson, and Wilcox Solar Observatories for allowing us access to their photospheric field data. We also wish to express our thanks to Janet Luhmann for encouraging us to write this paper. This work was supported by grants from the Office of Naval Research (N00014-01-F-0026) and the National Science Foundation (University of California, Berkeley agreement SA2384JB).

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