The Astrophysical Journal, 549:L131–L134, 2001 March 1
© 2001. The American Astronomical Society. All rights reserved. Printed in U.S.A.

DIFFERENCES IN THE SUN’S RADIATIVE OUTPUT IN CYCLES 22 AND 23

Giuliana de Toma
Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, CO 80303; detoma@lasp.colorado.edu
Oran R. White
High Altitude Observatory, National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, CO 80307; orw@hao.ucar.edu
Gary A. Chapman, Stephen R. Walton, Dora G. Preminger, and Angela M. Cookson
San Fernando Observatory, CSUN, Department of Physics and Astronomy, Northridge, CA 91330;
gchapman@sfo.csun.edu, swalton@sfo.csun.edu, dora@sfo.csun.edu, acookson@sfo.csun.edu
and
Karen L. Harvey
Solar Physics Research Corporation, 4720 calle Descada, Tucson, AZ 85718; kharvey@sprc.com
Received 2000 August 31; accepted 2000 December 13; published 2001 February 23

ABSTRACT

Analysis of the current solar cycle 23 shows a greater increase in total solar irradiance (TSI) for the early phase of this cycle than expected from measurements of the total magnetic flux and traditional solar activity indices, which indicate that cycle 23 is weaker than cycle 22. In contrast, space observations of TSI from the *Solar and Heliospheric Observatory*/VIRGO and the *Upper Atmospheric Research Satellite*/ACRIMII show an increase in TSI of about 0.8–1.0 W m^{-2} from solar minimum in 1996 to the end of 1999. This is comparable to the TSI increase measured by *Nimbus 7*/ERB from 1986 to 1989 during the previous cycle. Thus, solar radiative output near the maximum of the 11 yr cycle has been relatively constant despite a factor of 2 smaller amplitude increase for cycle 23 in sunspot and facular areas determined from ground-based observations. As a result, empirical models of TSI based on sunspot deficit and facular/network excess in cycle 22 underestimate the TSI measurements in 1999. This suggests either a problem in the observations or a change in the sources of radiative variability on the Sun.

Subject headings: Sun: activity — Sun: magnetic fields

1. INTRODUCTION

In this Letter, we emphasize the difference between the current solar cycle 23 and the two previous cycles. Thus far, cycle 23 has been relatively weak magnetically, with photospheric magnetic flux lower than during the rising phase of cycle 22. Figure 1 and Table 1 illustrate the basic differences between cycles 22 and 23. The sunspot number, the coronal 10.7 cm radio flux, the chromospheric Mg II 280 nm core-to-wing index, and He I 1083 equivalent width are all systematically lower in cycle 23. Sunspot and facular areas in 1989 and 1999, 3 yr after solar minimum, are lower by a factor of 2 in the new cycle. As a consequence, there is a weaker effect of sunspots in total solar irradiance (TSI) data during cycle 23 (Fig. 2). Despite the apparent decrease in the effect of sunspot disk passages on the total irradiance, values of TSI in late 1999 are similar to those seen at the maximum of cycle 22. Empirical models of TSI, which well represented cycle 22 observations, fail to predict the observed rise in TSI in 1999 and underestimate the change in TSI by almost 50%. This indicates either a problem in the TSI observations or, if these observations are correct, a difference between solar cycles 22 and 23 in the physical processes that cause irradiance changes. The differences in sunspot and facular areas and TSI in cycles 22 and 23 lead us to consider relative contributions of photospheric surface structures in these two cycles.

In § 2, we review the current observations of solar activity and TSI for the past 20 years with special emphasis on the rising phase of cycles 22 and 23. In § 3, we present an empirical model of TSI based on accurate photometric measurements of the “bright” and “dark” structures on the Sun and compare the model results to TSI observations for the last two cycles. We then discuss the consequences of the difference in empirical modeling of the solar output and in our understanding the sources of radiative variability on the Sun.

2. REVIEW OF OBSERVATIONS

The time of minimal activity between cycles 22 and 23 occurred in the fall of 1996. The onset of cycle 23 in 1997–1999 has been slow and characterized by small, simple, and short-lived sunspots and by low flare activity. Highest values for magnetic flux during this period were reached in 1999 November. An increase in magnetic activity occurred in the spring and summer of 2000 and was associated with a larger number of coronal mass ejections and flares, often followed by geomagnetic storms. During this period, sunspot number fluctuated from relatively high values as on 2000 May 15 and July 19 (sunspot numbers 205 and 249) to low values as on 2000 May 6 and September 11 (sunspot numbers 50 and 26). Relatively low activity has characterized the fall of 2000. At present, the average values for sunspot number, magnetic flux, and UV irradiances remain systematically below the values observed during the maximum of the previous cycle.

In Figure 1, we show daily values for the composite TSI (Fröhlich & Lean 1997; C. Fröhlich 2000, private communication), the National Solar Observatory (NSO)/Kitt Peak magnetic flux data, the composite Mg II index (de Toma et al. 1997), and the radio flux at 10.7 cm from 1980 to the present. Measurements of sunspot and facular area from San Fernando Observatory (SFO) are also shown. The time series clearly show that cycle 23 is significantly weaker magnetically than the previous cycles and that chromospheric and coronal emission are lower as well. In Table 1 we report the yearly averages for activity indices and TSI during solar cycles 22 and 23. We give values at the time of minimum in 1986 and 1996 and at

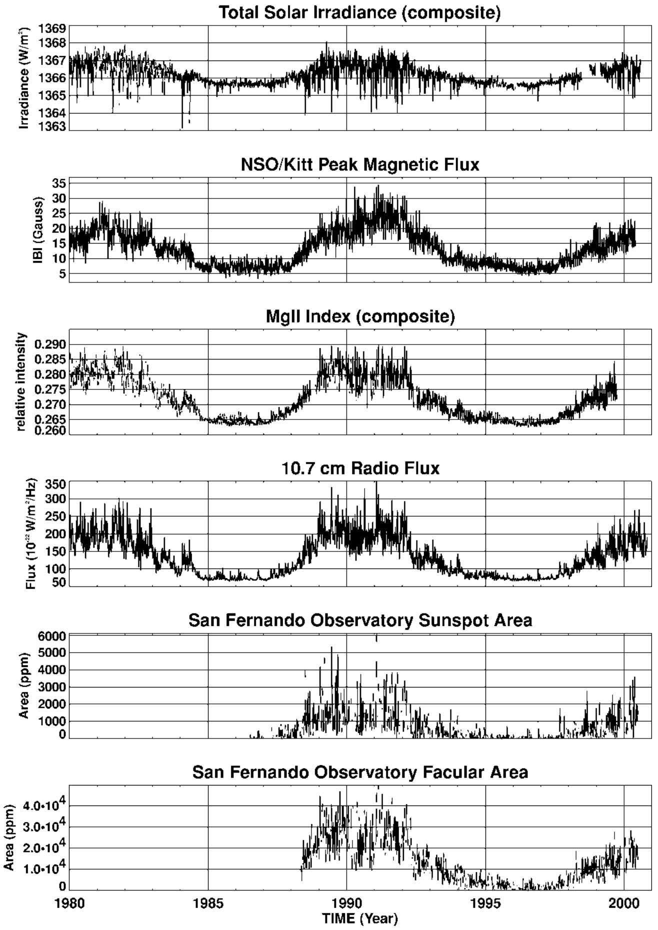

FIG. 1.—Time series of daily values for TSI (composite), photospheric magnetic flux, Mg II 280 nm index (composite), radio flux at 10.7 cm, and sunspot and facular area during the years 1980–2000. The period covers solar cycles 21, 22, and the rising phase of 23. The times of minimum activity between solar cycles 21–22 and 22–23 occurred in the fall of 1986 and 1996, respectively.

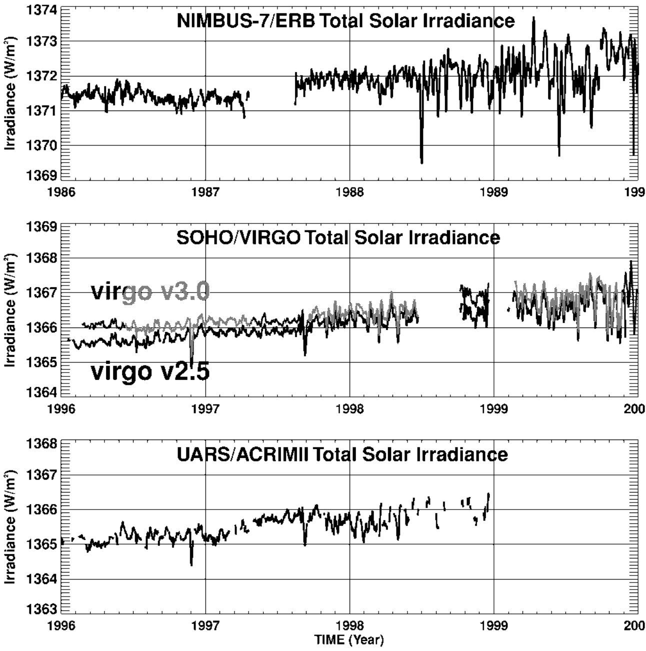

FIG. 2.—TSI observations from *Nimbus 7*/ERB, *SOHO*/VIRGO, and *UARS*/ACRIMII for the periods 1986–1990 and 1996–2000, corresponding to the ascending phase of cycles 22 and 23. The change in absolute scale between the three sets of observations is due to differences in the absolute calibrations of the radiometers. The relative increase, 3 yr after the time of minimum, is about the same for both cycles, but the sharp decreases associated with sunspot passages are fewer and smaller for cycle 23.

high activity. The ascending phase of solar cycles 22 and 23 is quite different. While in 1989, 3 yr after minimum, solar cycle 22 had already reached its maximum phase, solar cycle 23 had a much slower rise. In 1999, the mean value of the photospheric magnetic flux is almost 25% lower than in 1989. Sunspot and facular area are a factor of 2 or more lower than in cycle 22. Partial averages for the year 2000 are slightly higher, but still relatively low. A number of observations, including the distribution of coronal streamers, the topology of the unipolar magnetic fields in the polar regions, and the latitudinal distribution of sunspots, indicate that we are now near or at the maximum phase of solar cycle 23. Thus, data in 2000 confirm that cycle 23 is weaker than cycle 22.

2.1. *Total Solar Irradiance*

In Figure 2, we present TSI observations for the rising phase of cycles 22 and 23. There is a definite decrease in the number and strength of downward excursions caused by sunspot passages across the solar disk at the beginning of solar cycle 23. This is consistent with the photometric observations of sunspots, which indicate a scarcity of large groups of sunspots (Fig. 1), and is a consequence of the lower magnetic activity in this cycle. In contrast, the relative increase of TSI from minimum to maximum is about the same for both cycles (Table 1).

During the rising phase of cycle 23, space observations from the *Solar and Heliospheric Observatory* (*SOHO*)/VIRGO v2.5 and the *Upper Atmospheric Research Satellite* (*UARS*)/ACRIMII (Fig. 2) show an early increase for TSI at the end of 1996 and

TABLE 1

SOLAR ACTIVITY INDICES AND TOTAL SOLAR IRRADIANCE: YEARLY VALUES

Parameter	1986	1989	1990	1991	1996	1999	2000[a]
Magnetic flux (G)	7.20	18.90	21.06	23.81	6.74	15.06	17.08
He I 1083 nm index (mÅ)	46.14	76.58	74.96	76.70	42.73	68.77	74.23
Mg II 280 nm index	0.264	0.282	0.279	0.280	0.264	0.274	…
F10.7 radio flux ($\times 10^{-22}$ W m^{-2} Hz^{-1})	74.0	213.4	189.8	207.7	72.0	153.5	179.2
Sunspot number	13.4	157.6	142.6	145.6	8.6	93.3	122.1
Sunspot area (ppm)	73.7	1828.1	1333.8	1698.6	55.3	862.5	1456.8
Facular area (ppm)	…	28552.0	23369.2	27765.5	1444.5	12496.6	18317.7
TSI (*Nimbus 7*/ERB) (W m^{-2})	1371.41	1372.30	1372.64	1372.72	…	…	…
TSI (*SOHO*/VIRGO v2.5) (W m^{-2})	…	…	…	…	1365.63	1366.61	…
TSI (*SOHO*/VIRGO v3.0) (W m^{-2})	…	…	…	…	1366.04	1366.85	1366.92

[a] Averages for the year 2000 are based on the data available to us in 2000 October and are still preliminary.

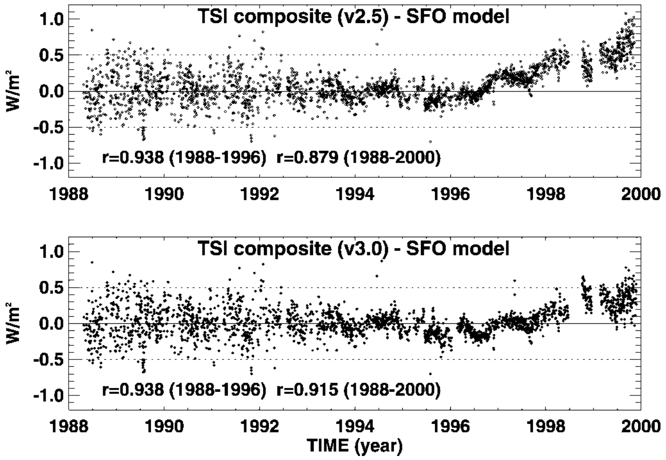

FIG. 3.—Residuals between TSI composite derived from satellite observations and modeled irradiance based on SFO photometric indices. The model is derived from a fit to observations for the period 1988–1996 and extrapolated forward in time. Modeled values are compared to both VIRGO v2.5 and v3.0. In both cases the observed increase is larger than the modeled increase.

continuing in 1997. In contrast, the magnetic flux remains low for most of 1997, and a significant increase occurs only in 1997 September (de Toma, White, & Harvey 2000). Indices of chromospheric and coronal activity show very little or no increase until the summer of 1997. In late 1999, *SOHO*/VIRGO v2.5 observations indicate an increase of about 1.0 W m^{-2} from the time of solar minimum. *UARS*/ACRIMII observations, available up to early 1999, seem to confirm such an increase. This is comparable to the increase in TSI observed from the *Nimbus 7*/Earth Radiation Budget (ERB) experiment at the maximum of cycle 22, as shown in Figure 2.

Empirical models of TSI based on solar photometric measurements that well represented solar cycle 22 observations could not reproduce the increase in TSI during 1996, which preceded by several months the increase in magnetic flux, nor the high values in 1999 (Fröhlich 1999). This "anomalous" behavior of TSI during the initial phase of cycle 23 has led to a significant revision of the VIRGO data. VIRGO data are the weighted averages of two pairs of independent radiometers, DIARAD and PMO6-V, on board the *SOHO* satellite (Anklin et al. 1999). Anomalies were found in both radiometers when the instruments were powered off (C. Fröhlich 2000, private communication). A new version of the VIRGO data, v3.0, was released in 2000 September and is shown in Figure 2; v3.0 is significantly different from v2.5 and *UARS*/ACRIMII and does not show the early increase in 1996. The relative increase from minimum to maximum is about 0.8 W m^{-2} instead of 1.0 W m^{-2}, as in the previous version.

3. EMPIRICAL MODELING OF TOTAL SOLAR IRRADIANCE

We computed several regression models of TSI composite time series for different epochs in the TSI variability record to illustrate quantitatively the change in cycle 23. We will discuss results from only two of the modeling approaches here. All of our cases show the same differences between cycles 22 and 23.

First, we followed the earlier work at SFO and used sunspot and facular photometric indices derived from the SFO full-disk solar images from 1988 to 2000 (Chapman et al. 1992; Chapman, Cookson, & Dobias 1996). In these indices, each solar structure is included with its measured contrast and area. We used the TIRR index derived from continuum images at 672.3 nm and the PSUM facular index derived from Ca II K images with a 1 nm spectral bandwidth (Walton & Preminger 1999; Preminger, Walton, & Chapman 2001). We fitted the TSI composite data from the beginning of the SFO Ca II K line data in 1988 to solar minimum in 1996. We extended this fitted function forward in time to 2000 and compared it with the *SOHO*/VIRGO measurements. Figure 3 shows the difference between observations and our model for v2.5 (*upper panel*) and v3.0 (*lower panel*). In the case of v2.5, the departure of the TSI measurements from the extrapolated model starts in 1997. The model shows an average increase of 0.5 W m^{-2} from 1996 to the end of 1999 compared to the increase of about 1 W m^{-2} in v2.5. If we regress the TSI data on the SFO indices for the entire epoch from 1988 to 1999, the correlation coefficient decreases from 0.94 to 0.88. There is better agreement between model and observations for *SOHO*/VIRGO v3.0, especially for the period 1996–1997. However, starting in 1998, the observations show a faster increase. The observed values in 1999 are larger than model estimates by about 50%. Thus, the same empirical model cannot be used for both cycle 22 and 23 TSI observations. We note that in 1998 there is a 3 month gap in the VIRGO observations caused by the temporary loss of the *SOHO* satellite. The differences we see (Fig. 3, *lower panel*) may be, at least in part, caused by the difficulty in calibrating the observations after the data gap.

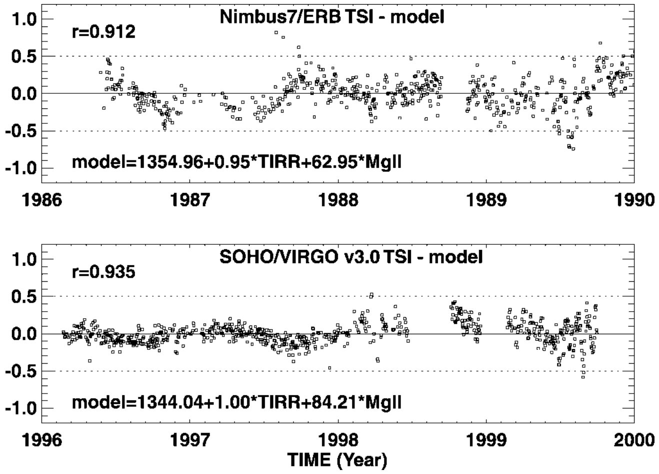

FIG. 4.—Empirical models of TSI based on the SFO index TIRR and the Mg II index. The model is run for *Nimbus 7*/ERB data from 1986 to 1990 and for *SOHO*/VIRGO v3.0 data from 1996 to the end of 1999. While a good fit to the observations can be achieved for both cases, the model equation is significantly different for cycles 22 and 23. To fit the observed rise in TSI during cycle 23, a higher coefficient for the facular term is needed.

In our second illustration, we included the ascending phase of cycle 22 from 1986 to 1990 in our regression analysis and compared the result to that obtained from 1996 to 2000 in cycle 23. In cycle 22, we regressed the *Nimbus 7*/ERB data on the SFO photometric TIRR and Mg II indices. In cycle 23, we used the *SOHO*/VIRGO v3.0 data and the same two indices to derive a regression transformation function. Use of the Mg II index for the facular and network contribution was necessary because the SFO Ca II K data did not extend back to 1986. Figure 4 shows the residual variation between the observations and the fitted functions for the two ascending phases. The correlation coefficients are $r = 0.91$ and $r = 0.94$ for 1986–1990 and 1996–1999, respectively. We give these empirical fitting functions in the two panels of Figure 4. We find a small change in the coefficient for the sunspot term, but the Mg II term representing faculae increases by about 33% to account for the current TSI increase in cycle 23. Thus, it appears that if we accept the spacecraft TSI at face value, sunspot and facular indices may not adequately represent variability in the TSI from cycle to cycle.

4. CONCLUSIONS

We have two options in accounting for the difference between the observed TSI and the estimates based on sunspot and facular properties: (1) the higher TSI suggests a change in nature of radiative sources on the Sun; and (2) the *SOHO*/VIRGO and *UARS*/ACRIMII observations are both too high in 1999.

Our study illustrates the difficulty in using simple proxies and regression techniques to deduce physical sources of solar radiative variability. We still have unknowns about variability of both the network and quiet Sun regions as the solar atmosphere evolves through the 11 yr Schwabe cycle. We also emphasize the difficulty of measuring TSI with an accuracy of 300 parts per million (ppm) or better, which is necessary to understand TSI variability over a solar cycle.

It is important to continue the investigation of this difference between the two cycles to clarify the role of magnetic activity in TSI variability. This is crucial not only for the understanding of the Sun itself but for the understanding of the solar influence on the Earth's atmosphere and climate. The similarity of the TSI behavior, despite the factor of 2 decrease in areas of sunspots and faculae, points to unanswered questions about radiative effects of these two surface structures.

This research was supported by NASA grants NAG5-4973, NAG5-7191, and NAG5-7838, by NSF grants ATM 97-07010 and ATM 99-12132, and partially by the High Altitude Observatory at NCAR. NCAR is sponsored by the National Science Foundation. The sunspot number and the 10.7 cm radio flux were made available by the NOAA/National Geophysical Data Center. The NSO/Kitt Peak data used here are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL.

REFERENCES

Anklin, M., Fröhlich, C., Finsterle, W., Crommelynck, D. A., & Dewitte, S. 1999, Meterologia, 35, 685
Chapman, G. A., Cookson, A. M., & Dobias, J. J. 1996, J. Geophys. Res., 101, 13541
Chapman, G. A., et al. 1992, J. Geophys. Res., 97, 8211
de Toma, G., White, O. R., & Harvey, K. L. 2000, ApJ, 529, 1101
de Toma, G., White, O. R., Knapp, B. G., Rottman, G. J., & Woods, T. N. 1997, J. Geophys. Res., 102, 2597
Fröhlich, C. 1999, Adv. Space Res., 24, 157
Fröhlich, C., & Lean, J. L. 1997, in IAU Symp. 185, New Eyes to See the Sun and the Stars, ed. F. L. Deubner, J. Christensen-Dalsgaard, & D. Kurtz (Dordrecht: Kluwer)
Preminger, D. G., Walton, S. R., & Chapman, G. A. 2001, Sol. Phys., submitted
Walton, S. R., & Preminger, D. G. 1999, ApJ, 514, 959