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Solar mean magnetic field variability: A wavelet approach to Wilcox Solar Observatory and SOHO/Michelson Doppler Imager observations

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[1] Solar mean magnetic field (SMMF) measurements from the Wilcox Solar Observatory and with the SOHO/MDI instrument are described and analyzed. Even though two completely different methods of observation are used, the two data sets obtained show a strong similarity. Using continuous wavelet transforms, SMMF variability is found at a number of temporal scales. Detected SMMF signals with a 1–2 year period are considered to be linked to variations in the internal rotation of the Sun. Intermediate SMMF oscillations with a period of 80–200 days are probably connected to the evolution of large active regions. We also find evidence for 90 min variations with coronal mass ejections as a suggested origin. *INDEX TERMS:* 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 7537 Solar Physics, Astrophysics, and Astronomy: Solar and stellar variability; 7594 Solar Physics, Astrophysics, and Astronomy: Instruments and techniques; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; *KEYWORDS:* Solar magnetic field, wavelet analysis, internal rotation, active regions, coronal mass ejections

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1. Introduction

[2] Solar activity and space weather are fundamental characteristics rooted in the evolution of solar magnetic fields. Large-scale manifestations of solar magnetism can be described by a mean magnetic field. The solar mean magnetic field (SMMF) is the average field as observed over the entire visible disk [*García et al.*, 1999]. SMMF measurements were first produced at the Crimean Astrophysical Observatory in 1968 [*Kotov and Severny*, 1983]. These measurements continued until 1976. At the Mount Wilson Observatory regular SMMF measurements were made between 1970 and 1982 [*Kotov et al.*, 1998]. The National Solar Observatory at Kitt Peak have made daily SMMF data available since 1977. In this study we describe and analyze daily SMMF measurements from the Wilcox Solar Observatory (WSO) [*Scherrer et al.*, 1977] and 1 min resolution measurements using the Michelson Doppler Imager (MDI) on board SOHO [*Scherrer et al.*, 1995]. By using a wavelet technique we search for temporal variations in the two SMMF data sets. The found variations are then linked to solar phenomena.

[3] We start by describing the observational methods at WSO (section 2) and with SOHO/MDI (section 3). A short comparison of the two recorded SMMF data sets is then given in section 4, followed by a short introduction to wavelets in section 5. Recurrent and nonrecurrent variations in the SMMF on different temporal scales are analyzed and interpreted in section 6. A conclusion is given in section 7 together with a short discussion on solar activity predictions and a summary on future solar missions focused on solar magnetism.

2. Observations at WSO

[4] Large-scale solar magnetic fields have been measured at WSO since 1975 [*Scherrer et al.*, 1977] in an effort to better understand changes in the Sun and how these changes affect the Earth. The WSO observations uses a 33 cm coelostat, a Littrow spectrograph, and a Babcock type magnetograph [*Babcock*, 1953]. The magnetic signal is taken as the difference between the Zeeman splitting in the Fe I line at 5250 Å and the zero offset signal in the magnetically insensitive Fe I line at 5124 Å.

[5] A SMMF value is obtained by integrating the magnetic signal over the entire solar disk reaching an average statistical observational uncertainty of about 0.04 G. A full observation takes about twenty minutes to complete and is repeated several times each day. The final daily SMMF value is given as a weighted average of the individual

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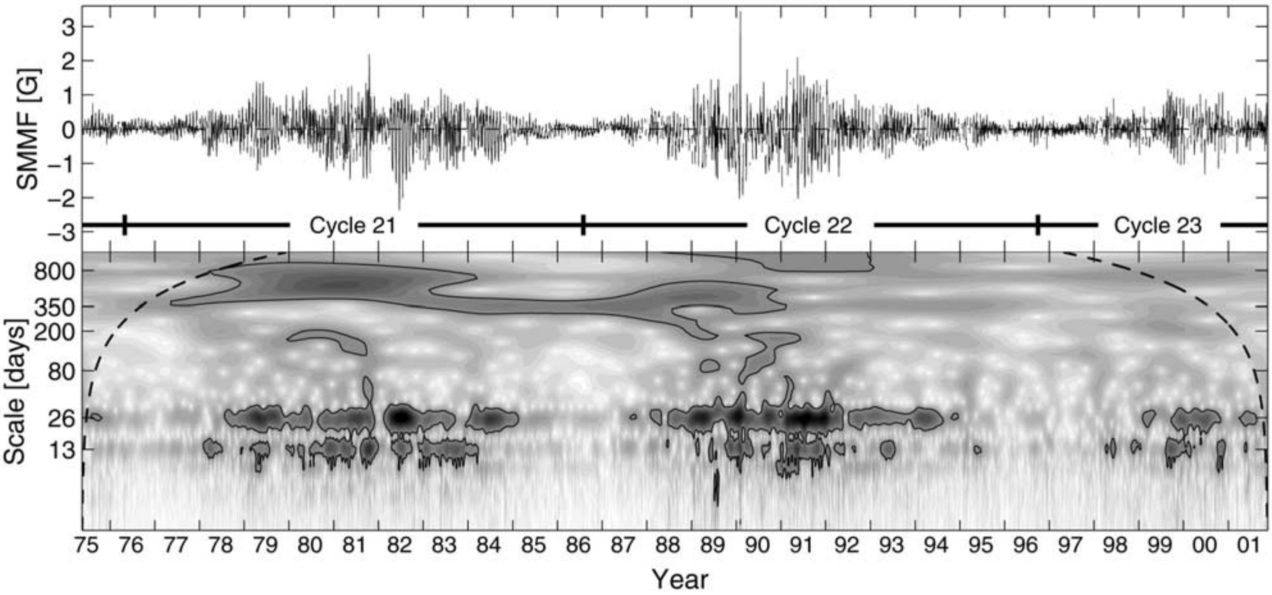

Figure 1. A wavelet analysis of mean magnetic field observations at WSO. Daily SMMF values, measured in Gauss, between 16 May 1975 and 18 November 2001 are presented in the top panel. The sequence contain 7932 data points and 1752 (18%) data gaps. The 21st cycle is from May 1976 to July 1986, the 22nd cycle from August 1986 to September 1996, and the 23rd cycle started in October 1996. Good coherence is shown between the large-scale features in the SMMF data and the solar cycle variation. The calculated wavelet power spectrum in the bottom panel shows a number of distinguishing SMMF variations. These are described in the text. The dashed lines indicate the zone of influence as described in section 5. The solid lines show the 95% confidence level.

observations. The complete data set, which at the moment spans more than 26 years, of daily SMMF observations at WSO is plotted in the top panel of Figure 1.

3. Observations With SOHO/MDI

[6] Solar magnetic fields have been measured with the MDI instrument [*Scherrer et al.*, 1995] on board SOHO since December 1995. These measurements will hopefully continue for several more years. Compared to WSO, the observational conditions for SOHO are by far improved due to the absence of an intervening atmosphere together with an orbit in continuous sunlight. The observational method is also quite different to the one at WSO: The MDI consists of a refracting telescope feeding sunlight through a cascade of filters onto a CCD camera [*Scherrer et al.*, 1995]. Two tunable Michelson interferometers define a 94 mÅ bandpass that can be tuned across the Ni I solar absorption line at 6768 Å. The magnetic flux is measured as the difference between the Doppler shift in right and left circularly polarized light separately.

[7] SOHO/MDI has made continuous recordings of solar magnetograms since May 1996 with a spatial resolution of 4″. With 15 magnetograms per day the temporal resolution is most often 96 minutes but during certain periods the resolution reach down to 1 min. We have chosen a subset of the, at present, full 5.5 year data sequence. The subset covers the period March 1999 to August 2000 and has predominantly a temporal resolution of 1 min, is long enough to enable detailed wavelet analysis for a wide temporal spectrum, and at the same time with as few data gaps as possible. The selected 1.5 year SMMF sequence is plotted in Figure 2.

4. Comparing WSO With SOHO/MDI SMMF

[8] By making daily averages of the SOHO/MDI measurements one can make simple but qualitative comparisons of the two SMMF sets. Even though the measuring techniques are quite different, the two recorded SMMF sets show a satisfactory correlation (see top panel of Figure 3 and also *Liu et al.* [2001]).

5. Wavelets

[9] The SMMF data are analyzed using wavelets. Wavelet analysis can be compared to a mathematical microscope with variable position and magnification. The microscope can be used when searching for localized variations of power within a time series of N observations

$$x_n, \quad n = 0, 1, \ldots, N-1 \tag{1}$$

with sample interval δt. The wavelet transform can then be defined as the convolution of x_n with an analyzing wavelet $\psi(\tau)$, where τ is a nondimensional time parameter. A frequently used wavelet when searching for oscillating signals is the Morlet wavelet [*Grossman and Morlet*, 1984]. This wavelet represents a sinusoidal oscillation contained within a Gaussian envelope:

$$\psi(\tau) = \pi^{-1/4} e^{i\omega_0\tau} e^{-\tau^2/2}, \tag{2}$$

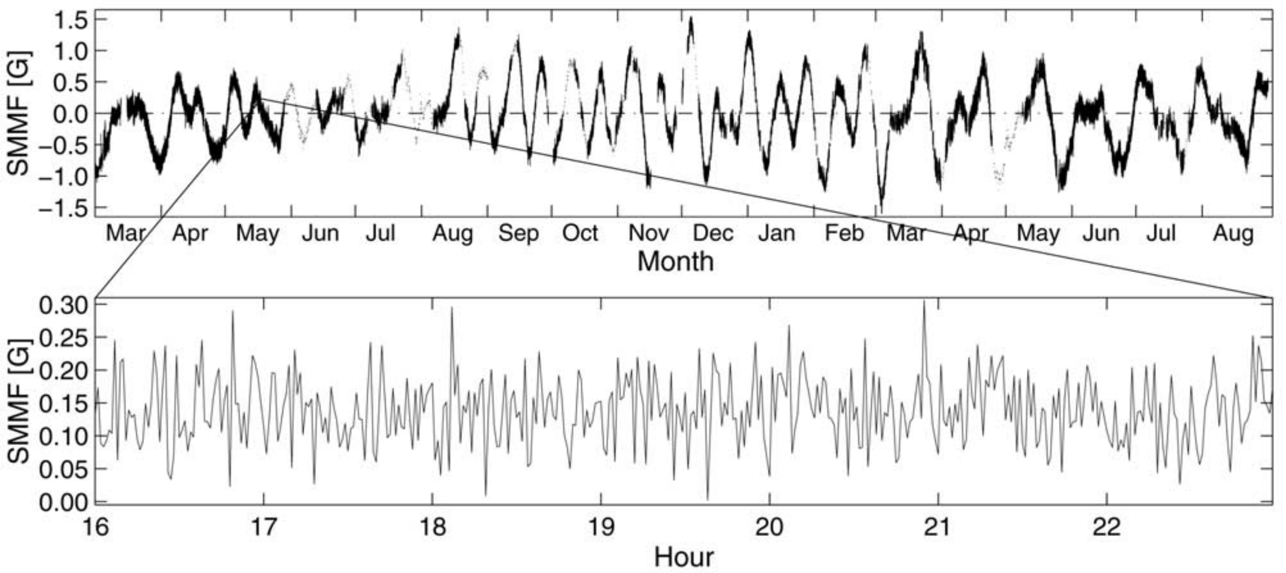

Figure 2. SOHO/MDI mean magnetic field observations. The top panel gives the SMMF data sequence, measured in Gauss, selected for this study. With a temporal resolution of 1 min covering 18 months (March 1999 to August 2000) the MDI SMMF sequence contains 459,146 data points and 332,854 (42%) data gaps. An extracted seven hour SMMF period during 16 May 1999 is given in the lower panel, indicating quite significant SMMF fluctuations down to scales of minutes.

where ω_0 is a nondimensional frequency often set equal to 6. The wavelet transform of the time series x_n can now be written as

$$W_n(s) = \sum_{k=0}^{N-1} \hat{x}_k \hat{\psi}^*(s\omega_k) e^{i\omega_k n\delta t}, \tag{3}$$

where $\hat{x}_k$ is the discrete Fourier transform of x_n and $\hat{\psi}^*(s\omega_k)$ is a scaled and translated version of $\psi(\tau)$ where the angular frequency is defined as

$$\omega_k = \begin{cases} \frac{2\pi k}{N\delta t} & , \; k \le \frac{N}{2} \\ -\frac{2\pi k}{N\delta t} & , \; k > \frac{N}{2} \end{cases}. \tag{4}$$

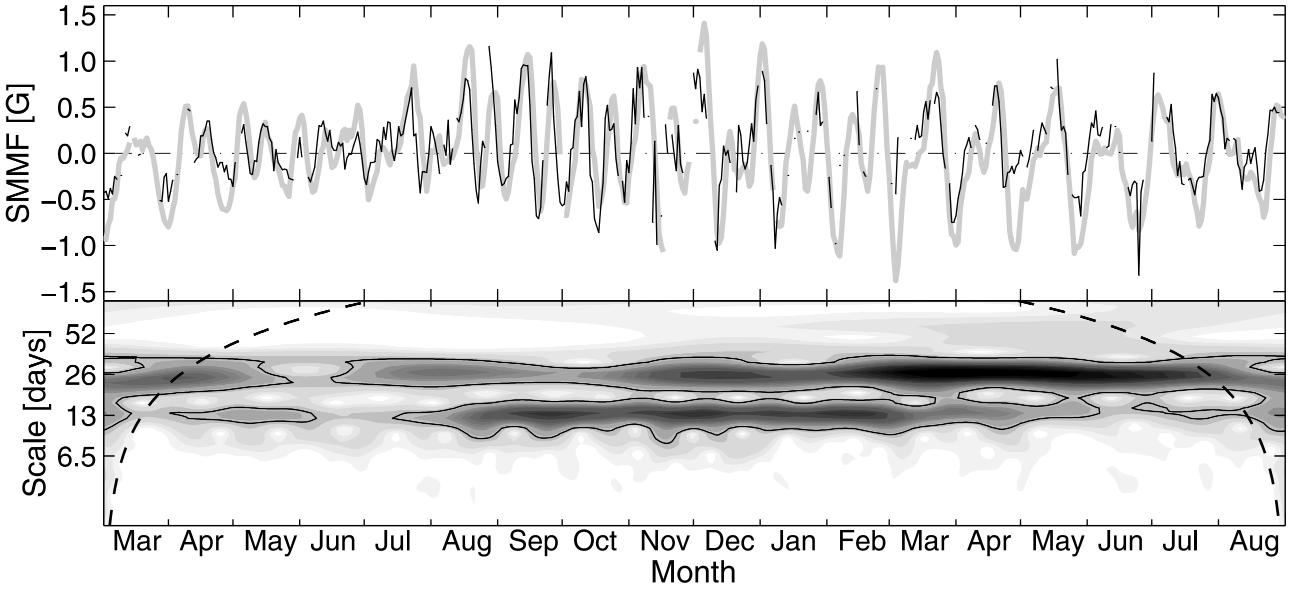

Figure 3. The top panel compares the WSO SMMF with the MDI SMMF. Both data sets are given as daily averages from March 1999 to August 2000 and measured in Gauss. The SOHO/MDI data (thick line) contain 8 (1.5%) data gaps; the WSO data (thin line) contain 115 (21%) data gaps. The linear correlation between the two sets is 0.82. A wavelet power spectra for the MDI data set is presented in the bottom panel. The 13/26 day oscillations due to the solar rotation are clearly seen. The dashed lines indicate the zone of influence. The solid lines show the 95% confidence level.

Table 1. A Summary of SMMF Variations and Their Origin

Period	Origin
11 years	solar cycle
1–2 years	internal rotation variations
80–200 days	evolution of active regions
13/26 days	solar rotation
90 min	coronal mass ejections?

[10] By varying the wavelet scale *s* and the localized time index *n* one can construct a picture showing the amplitude of any features as a function of both scale and time. The wavelet transform $W_n(s)$ is in general complex and the result is then best represented by a wavelet power spectrum defined as $|W_n(s)|^2$. To make it easier to compare different wavelet power spectra, one can normalize the result by dividing the power spectrum with the variance σ^2 giving a measure of the power relative to white noise. We will furthermore construct 95% confidence contour lines, as described by *Torrence and Compo* [1998], to separate the true signal in the power spectrum from the background noise. Due to a finite time series, the edges of the wavelet power spectrum are biased. This bias is proportional to the scale *s* and will be represented by a region-of-influence in the power spectrum where edge effects become important.

[11] A number of wavelet studies on solar magnetic data have been performed in the past. *Komm* [1995] studied solar magnetograms to define an entropy measure related to the intermittency of magnetic elements. *Lawrence et al.* [1995] examined the temporal scaling properties of solar magnetic activity using the daily sunspot number and found evidence of a turbulent structuring of the magnetic fields as they rise through the convective zone. The wavelet studies by *Mordvinov and Plyusnina* [2000] are of particular interest since they also studied temporal changes in the SMMF.

6. SMMF Variability

[12] SMMF variability takes place on a wide range of temporal scales. In this section we will present these variabilities using a wavelet approach, investigating large-scale oscillations as well as intermediate scale oscillations. All presented variabilities, with their associated origin, are summarized in Table 1.

6.1. Large-Scale SMMF Variations

[13] The strength of the global magnetic flux varies with the solar cycle. This 11-year variation is also clearly discernible in the SMMF, plotted in the top panel of Figure 1. More than two complete solar cycles are covered shown by the distinct variation in SMMF amplitude. Since most magnetic structures are bipolar the SMMF value is small: ±0.2 G during solar minimum, at solar maximum peaks reach above ±1 G.

[14] A wavelet power spectrum calculated using the full WSO SMMF data set is presented in the lower panel of Figure 1 (cf. results by *Mordvinov and Plyusnina* [2000]). The top of the wavelet power spectrum show SMMF variations with periods between 1 and 2 years. The solar magnetic field originates in a thin layer called the tachocline just below the convective zone in the solar interior. *Howe et al.* [2000] detected rotational variations with a period of about 1.3 years near this tachocline. Since magnetic fields are produced by relative motions between neighboring plasma layers, it seems justified to relate the detected 1–2 year SMMF variations to the variations found near the base

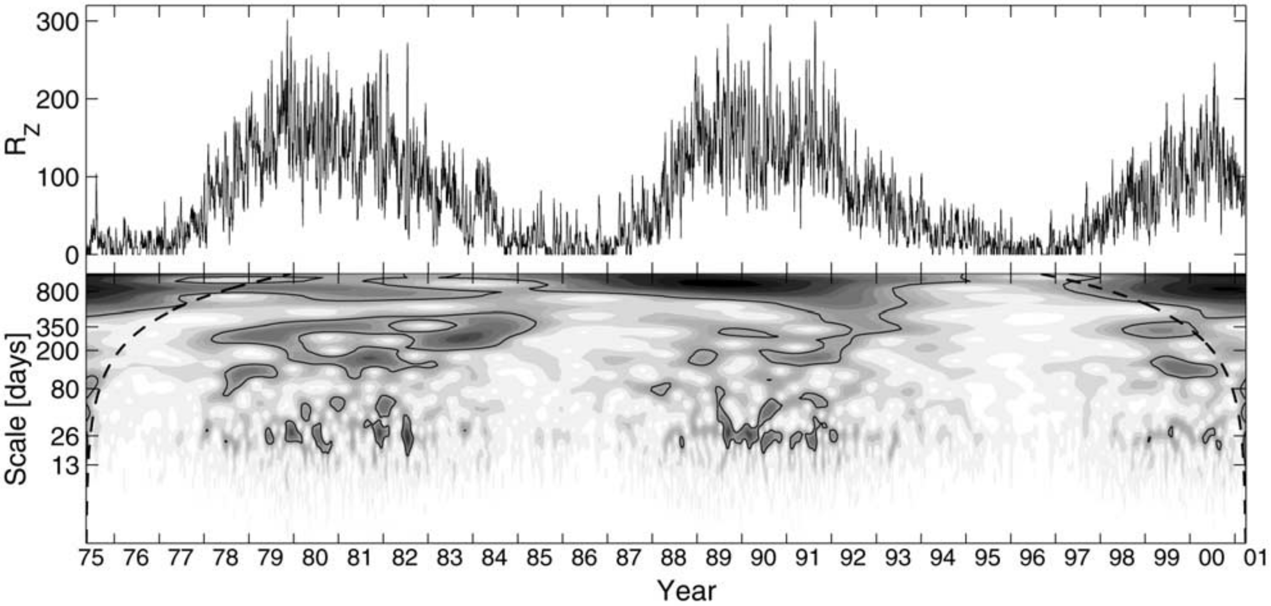

Figure 4. A wavelet analysis of Wolf sunspot numbers. Daily values of R_Z between 16 May 1975 and 31 March 2001 are plotted in the top panel. A number of distinguishing oscillations are evident in the wavelet power spectrum in the bottom panel. The peaks occurring at scales between 80 and 200 days are probably due to the evolution of large active regions. Considering their position in the wavelet power spectra, the peaks are assumed to have the same origin as the 80–200 day peaks in Figure 1. The dashed lines indicate the zone of influence. The solid lines show the 95% confidence level.

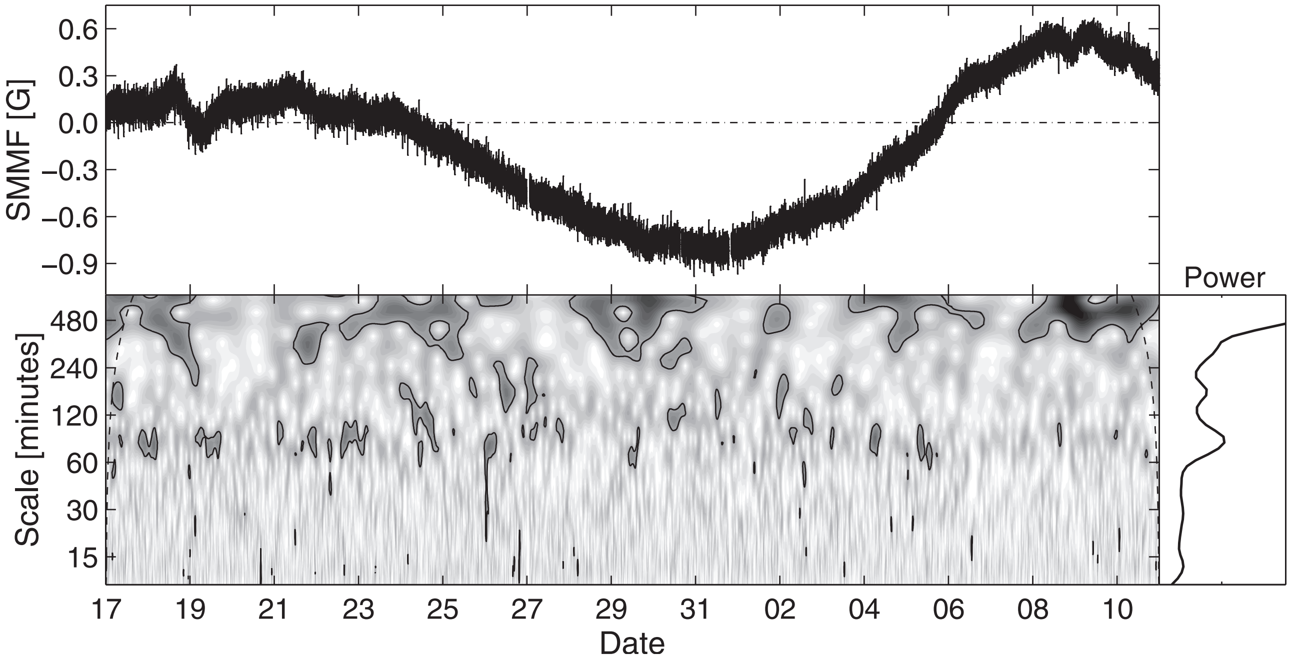

Figure 5. A wavelet analysis of SOHO/MDI SMMF observations. One minute resolution MDI measurements from March 17 to April 10 1999 are shown in the top panel. The data sequence contain 34,852 data points and 1148 (3.2%) data gaps and is given in Gauss. The calculated power spectra in the lower panel cover possible SMMF oscillations with periods from 10 to 500 min. The most distinguishing peaks are found at a period of about 90 min indicated by the power density plot in the lower right panel. The dashed lines indicate the zone of influence. The solid lines show the 95% confidence level.

of the convective zone. For a more detailed discussion on these SMMF variations, see H. Lundstedt and F. Boberg (manuscript in preparation, 2002).

[15] The SMMF oscillations seen in Figure 1 with periods ranging from 80 to 200 days could be explained by the evolution of large solar active regions. Figure 4 gives daily Wolf sunspot numbers for the period May 1975 to March 2001. The peaks between 80 and 200 days in the lower panel of Figure 4 are probably due to the lifetime of solar active regions and solar active region complexes. It is also possible that the 80 to 200 day SMMF variations have the same origin as the 152–154 day periodicity in the occurrence of solar flares [*Rieger et al.*, 1984; *Bogart and Bai*, 1985].

[16] The peaks at scales of about 13 and 26 days are due to solar rotation. These oscillations are of course also discernible in the SOHO/MDI SMMF data, shown in the lower panel of Figure 3. For a detailed analysis on these SMMF oscillations we refer to *Mordvinov and Plyusnina* [2000].

6.2. Intermediate SMMF Variations

[17] Figure 5 gives 26 days of 1 min resolution SMMF with adherent power spectra for scales between 10 and 500 minutes. The existence of intermediate time SMMF variations has been demonstrated in a number of studies. *Severny* [1971] studied magnetic maps of quiet solar regions and saw slow oscillations on time scales of 2–3 hours. Figure 5 shows evidence for magnetic oscillations in this time region with additional peaks at scales of 6–8 hours.

[18] *Demidov* [1995] found evidence for field variations with periods of 80 min. Variations with about this period are also evident in our wavelet spectra (see Figure 5). Solar magnetic fields are the main source to all solar activity. The detected 90 min oscillations could be due to the largest manifestations of solar activity: CMEs [*Gosling*, 1997; *St. Cyr et al.*, 2000]. Erupting CMEs has been proven to influence the solar magnetic field topology [*Low*, 1997; *Zhao et al.*, 1997; *Luhmann et al.*, 1998; *Boberg and Lundstedt*, 2000]. Solar flare activity associated with CMEs has also shown to be accompanied by magnetic flux changes [*Kosovichev and Zharkova*, 2001]. The erupted CME propagates through interplanetary space and may have a considerable impact on Earth causing large geomagnetic storms [*Tsurutani and Gonzalez*, 1997] and energetic proton events [*Reames*, 1997]. These facts, together with a desire to increase the knowledge about solar activity, motivate a study on variations in the global solar magnetic field (best represented by the SMMF) during periods with CMEs.

[19] Figure 6 is an attempt to relate the 90 min oscillations presented in Figure 5 to CME activity. The power spectrum given in the top panel is a sum of 28 individual wavelet power spectra, where each spectrum is obtained from a 512 min long SMMF period centered at a reported CME (at minute 256 as indicated by the arrow). Only 4 of these 28 CME events were found to be accompanied by solar flares. The bottom panel of Figure 6 is the sum of 23 power spectra during quiet periods with no CME activity. A comparison of the two power spectra in Figure 6 suggests that the 90 min oscillation might be the result of CME activity. A reasonable explanation to the magnetic oscillations could be that the photospheric magnetic field is influenced by the expanding legs of the CME configuration. The peak in the power spectrum in the top panel of Figure 6

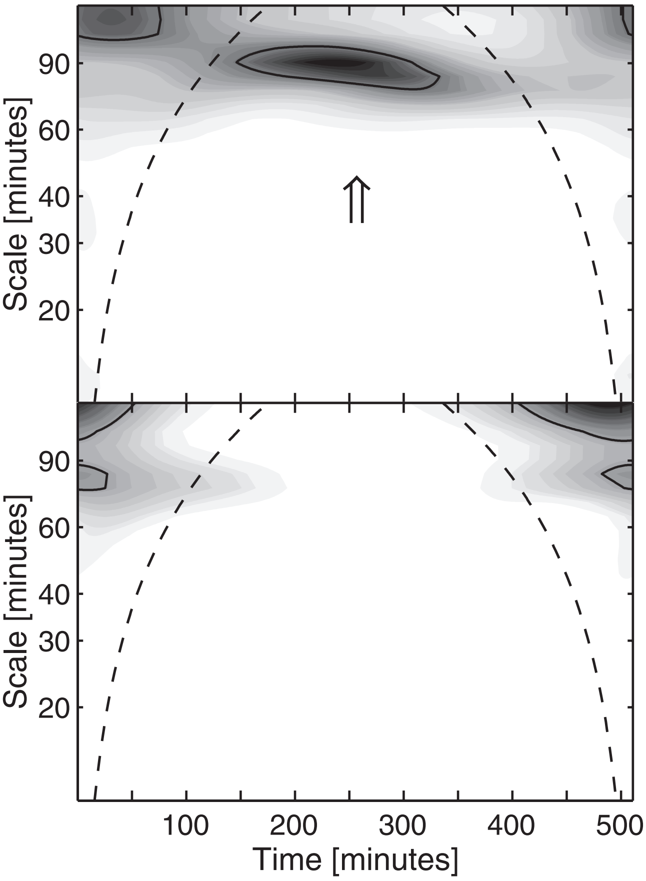

Figure 6. SMMF oscillations linked to CME activity. A sum of 28 wavelet power spectra, obtained from SMMF sequences, during CME activity is presented in the top panel. The arrow indicate CME onsets (positioned at minute 256) according to SOHO/LASCO observations. The bottom panel gives the sum of 23 wavelet power spectra during periods with no reports of CME activity. The dashed lines indicate the zone of influence. The solid lines show the 95% confidence level.

seems to be located somewhat prior to the CME appearance time. This is probably due to the difficulty in determining the onset time of the individual CMEs.

7. Conclusion

[20] Applying a wavelet analysis on daily and 1 min resolution SMMF data we detect SMMF variations on a wide range of temporal scales. These variations are then related to different solar phenomena (see Table 1). The next step is to model the nonlinear coupling between these oscillations of solar activity using neural networks. Many have tried to predict the solar activity using neural networks and sunspot numbers [*Lundstedt*, 2001] or using information about the polar solar magnetic field strength [*Schatten and Pesnell*, 1993; *Hathaway et al.*, 1999]. Our approach is somewhat different. We chose to use the solar mean magnetic field as the indicator of global solar activity, a more physics based indicator compared to the sunspot number. We then chose to use nonlinear prediction methods (neural networks complemented by wavelet techniques) since the variability of solar activity has been described as a nonlinear chaotic dynamic system [*Mundt et al.*, 1991]. By using a neural network model described by *Zhang and Benveniste* [1992], where the network's activation functions are wavelet transformation functions, the modeling of the found oscillations and predicting solar activity would be possible (H. Lundstedt and F. Boberg, manuscript in preparation, 2002).

[21] There are two major future space missions that will produce solar magnetic field observations useful for solar activity modeling: the Solar Dynamics Observatory (SDO) and the Solar Orbiter (SO). The aim of SDO, with a launch date set to 2007, is to better understand the magnetic topologies, dynamics, and evolution in CME processes. The magnetograph planned for SO, with a launch date set to 2009, will enable a study of the evolution of fine-scale structure of the Sun's magnetism. There are also a few ground-based missions planned for the near future dealing with solar magnetism. An upgrade is in progress for the Global Oscillation Network Group (GONG) that will provide continuous magnetograms with a resolution of 5″. A campaign for investigating the 90 min SMMF oscillations presented in section 6.2 started at WSO in June 2001.

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