Properties of Supergranulation During the Solar Minima of Cycles 22/23 and 23/24

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Abstract. The solar minimum at the transition from cycle 23 to 24 was notable for its low level of activity and its extended duration. Among the various fields of study, the evolution of the solar convection zone may provide insight into the causes and consequences of this recent minimum. This study continues previous investigations of the characteristics of solar supergranulation, a convection component strongly linked to the structure of the magnetic field, namely the time-evolution of the global mean of supergranule cell size, determined from spectral analysis of MDI Dopplergrams from the two previous solar minima. Analyses of the global mean of supergranule sizes show a quasi-oscillatory nature to the evolution of this particular supergranule characteristic. Performing similar analyses on realistic, synthetic Doppler images show similar time-dependent characteristics. We conclude that the observed fluctuations are not observational artifacts, and that an underlying trend exists within the evolution of the supergranulation network.

1. Introduction

Supergranulation is a large-scale component of solar convection. Supergranule cells are typically ∼35 Mm across and have a lifetime of between 1-2 days. Doppler observations have shown that they have strong divergent flows at the surface ($\sim$300 m s^{-1}), around a whole magnitude larger than their accompanying radial flows. The interaction between supergranulation and the solar magnetic field is well seen in Ca II K images of the chromospheric network. While this interaction takes place on local scales, it is of interest to determine the level of interaction between supergranulation and the global field.

Williams & Pesnell [1, 2] have analyzed data from the Michelson Doppler Imager (MDI) [3] taken from the solar minima that occurred in 1996 and 2008, relating to the transition between cycles 22/23 and 23/24, respectively. Physical characteristics were quantified by averaging values over the whole dataset for a given year. While the $1/e$ lifetimes, the time taken for the cross-correlation of a supergranule pattern to drop to $1/e$, are found to be the same for both years, supergranules are slightly larger and their flows weaker in 1996 than in 2008 [2].

The present paper extends this work by initiating a statistical comparison between the datasets to determine the noise characteristics of the average values by calculating some of the characteristics mentioned above for each individual image. This paper focuses on analyzing the fluctuation of the global average of the supergranule size throughout each year in question.

2. Analysis Methods, Results

Fifteen-minute cadence, de-rotated MDI Dopplergrams [4] are processed to remove dominant axi-symmetric flow signals [5], the resulting images comprising contributions from the surface manifestations of convective flows. Each image is remapped to heliographic coordinates and projected onto the spherical harmonics to extract the spectral coefficients in degree, ℓ, and order, m. The coefficients are summed over m to produce a power spectrum with respect to wavenumber, ℓ. The result is a series of spectra that have been averaged to determine a mean value for the supergranule size for a given year [2]. We now analyze them individually to calculate the noise characteristic of that mean value and to study any time-evolution of the global mean of the supergranule size.

Each power spectrum contains a dominant supergranulation feature, the peak of which, ℓ_{peak}, is calculated by fitting the data with a modified Lorentzian, and determining the wavenumber at which the fitting function peaks. This process is repeated for each image resulting in an array of values that is compiled into a time-series. Figure 1 shows these peak wavenumbers versus time in days. The mean peak wavenumber, $\langle \ell_{peak} \rangle$, and standard deviation, σ_{peak}, of the series are calculated; $\langle \ell_{peak} \rangle = 121.7$ and $\sigma_{peak} = 1.5$ for 1996, and $\langle \ell_{peak} \rangle = 124.8$ and $\sigma_{peak} = 2.0$ for 2008. From these peak wavenumbers, the global average for the supergranule sizes are found to be 35.9 Mm and 35.0 Mm for 1996 and 2008, respectively. Both ℓ_{peak} distributions deviate slightly from a Gaussian ($\chi^2 = 5.92$ for 1996 and $\chi^2 = 4.05$ for 2008). The right-hand panel of Figure 1 shows the distribution of values for 1996.

Figure 1 shows fluctuations within the 1996 time-series that have been investigated using Fourier analysis. Firstly, the time-series is smoothed to reduce the noise. Two sets of smoothed data are then produced using two different filters. One set is the result of smoothing with a 1-day (i.e. 96-point) wide boxcar. The other is produced using a 4th degree, zeroth order, 33-point wide Savitzky-Golay [6] smoothing filter. While the boxcar is a traditional, widely-used filter, Savitzky-Golay smoothing retains much of the variation that is lost when using a boxcar (Figure 1). To calculate the frequency distribution of the time-series, the smoothed data are processed to remove their respective means and low-frequency trends, the latter using a 5-day boxcar filter. The datasets (containing around 6000 data points) were padded out to $2^{13} = 8192$ points to removed aliasing prior to frequency distributions being produced by applying a Fast Fourier Transform (FFT) to the datasets.

Figure 2a shows the frequency distributions for both the boxcar and Savitzky-Golay smoothed 1996 data. Both distributions exhibit dominant peaks at around 0.258 cycles per day giving an oscillatory period of around 3.88 days. For 2008, the FFT produced two dominant peaks (Figure 2b), one at 0.211 cycles per day and another at 0.281 cycles per day. These peaks equate to periods of 4.74 and 3.56 days, respectively.

Data simulations, that produce realistic full-disk Dopplergrams from a synthetic spatial power spectrum modeled on spectra observed from MDI data [7], have been used to show that the fluctuations are inherent in the data and not artifacts of the observation process. 20 days of synthetic images are processed to construct a time series that produced frequency signals on the order of what is seen in the MDI data. Although no single dominant peak is seen, two peaks are seen in the same frequency region as those observed from the MDI data, at 0.281 and 0.328 cycles per day, relating to periods of 3.05 and 3.56 days.

3. Discussion and Conclusion

Frequency analysis of the time-series of supergranule sizes from MDI data, to study noise characteristics within the data, suggest that there exists quasi-oscillatory fluctuations of globally-averaged supergranule cell sizes with a period of around 4 days. Although similar signals are seen within the 2008 MDI data and the simulated data, there are no dominant single peaks. Indeed, both of the latter datasets exhibit strong double peaks. However, all the datasets analyzed show
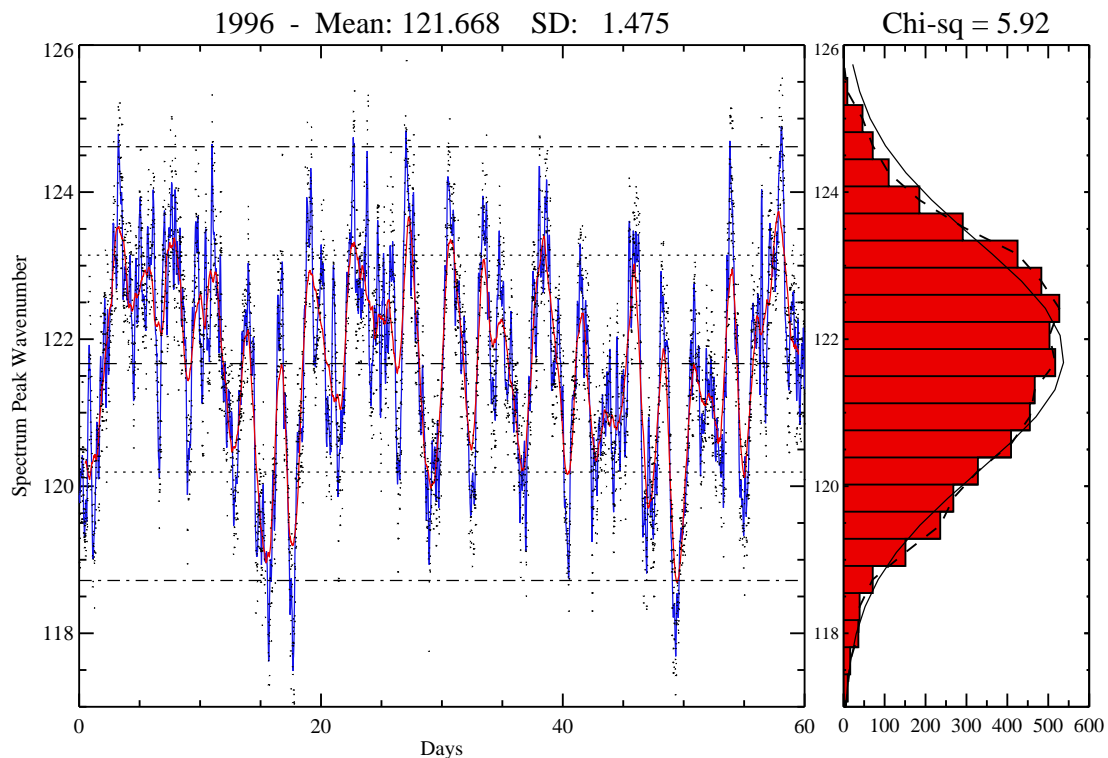
Figure 1.   Time-series showing the variation of the peak wavenumber of the fit to the supergranule spectral feature derived from each Doppler image within the 1996 dataset. Each dot represents the peak wavenumber for each spectrum. The red and blue lines are the results of smoothing with a boxcar and a Savitzky-Golay filter, respectively. The time-series values are collected into wavenumber bins producing a histogram that is fitted with a Normal distribution. The histogram shows a slight deviation from a Normal distribution of values.

signals that suggest size fluctuations of between 3-5 days.

We have also constructed Lomb-Scargle periodograms [8] from all the time-series to test the significance of the strong features. The results from these studies do not contradict those from the FFT analyses.

We conclude that correlations exist in time-series of the global average of supergranule sizes, indicating non-random process underlying the evolution of supergranulation. Coherence is observed as peaks within frequency distribution plots that give fluctuation periods on the order of around twice the turnover time of the supergranule pattern. We have also calculated the Hurst exponents [9] for each data-series to be $\sim$0.9, which suggests underlying trends.

Analyses of more datasets, e.g. the FWHM and velocity data [2], MDI data from the intervening years covering the solar cycle between 1996 and 2008, and a longer simulated time-series, should lead to a more rigid conclusion. The data simulations show, however, that the fluctuations are solar in origin and not instrumental effects. Using the observations of these fluctuations, time-dependent properties of these simulations can now be further constrained.

With the Helioseismic Magnetic Imager aboard the Solar Dynamics Observatory now delivering 4096×4096 resolution Dopplergrams every 45 seconds, it will be interesting to see whether these fluctuations appear in this new data.
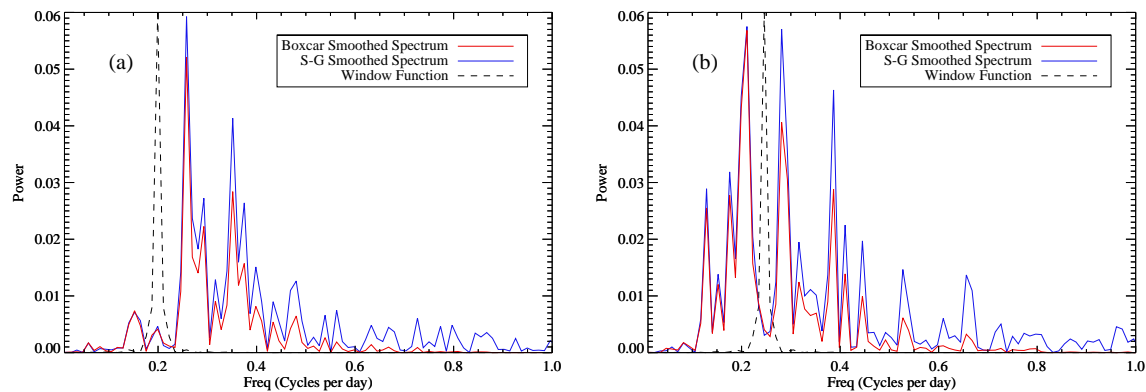
Figure 2. Frequency distributions derived from the (a) 1996 data and (b) 2008 data showing the results of FFTs applied to both of the filtered and reduced time-series, along with the window function.

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