MID-TERM QUASI-PERIODICITIES IN GEOMAGNETIC ACTIVITY DURING THE LAST 15 SOLAR CYCLES: CONNECTION TO SOLAR DYNAMO STRENGTH

To the memory of Karolen I. Paularena (1957-2001)

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Abstract. Several recent studies have reported quasi-periodicities with a period between 1 and 2 years (to be called here 'mid-term quasi-periodicities') in various heliospheric parameters, like solar wind speed, interplanetary magnetic field, cosmic rays, and geomagnetic activity. Here we study their long-term occurrence in geomagnetic activity using an extended aa index which covers the last 15 solar cycles. We confirm their intermittent occurrence and the alternation of their dominant period between a slightly shorter period of about 1.2 – 1.4 years and a slightly longer period of about 1.5 – 1.7 years. We find that the mid-term quasi-periodicities were strong during two intervals of high solar activity: in the mid-19th century and since 1930. Instead, contrary to earlier studies, we find that they were consistently weak during low solar activity from 1860s to 1920s. This implies a long-term connection between the amplitude of mid-term quasi-periodicities and the solar dynamo strength. Since the rotation speed at the bottom of the solar convection layer (tachocline) has recently been found to vary at a mid-term periodicity, this suggests that the stronger the solar dynamo is, the more variable the rotation rate of the tachocline is. We also note that the disappearance of mid-term periodicities may be used as a precursor for long intervals of very weak solar activity, like great minima.

1. Introduction

Richardson *et al.* (1994) found a strong periodicity in solar wind (SW) speed after 1987 which showed large variations at a period of about 1.3 years. This observation activated the recent interest in 'mid-term quasi-periodicities' (MTQP). They also compared the SW speeds at 1 AU and in the outer heliosphere to show that very similar fluctuations are observed at both heliocentric distances. Gazis, Richardson, and Paularena (1995) extended this analysis, and verified that the 1.3-year periodicity was dominating the low-latitude heliosphere after 1987 from the inner (Venus orbit at 0.72 AU) to the outer heliosphere (almost 60 AU). Later, Gazis (1996) showed that the SW speed enhancements responsible for the 1.3-year variation do not arise from the merging of structures during SW evolution, and suggested that they are of solar origin.

Even earlier, several authors had detected related spectral peaks in geomagnetic activity (e.g., Fraser-Smith, 1972; Delouis and Mayaud, 1975) and auroral

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activity (Silverman and Shapiro, 1983) at varying levels of significance at different times. Paularena, Szabo, and Richardson (1995) showed that the 1.3-year periodicity occurs concurrently in SW speed and geomagnetic activity after 1987. Szabo, Lepping, and King (1995) discovered the 1.3-year variation in the IMF north-south component. A strong, slightly longer periodicity of about 1.7 years was found in cosmic rays during solar cycle 21 (Valdés-Galicia, Pérez-Enríquez, and Otaola, 1996). Moreover, the 1.3-year periodicity was recently observed in the variation of the solar rotation speed around the tachocline at the bottom of the solar convection layer (Howe *et al.*, 2000). This observation gives additional importance for mid-term periodicities by suggesting that they are related to the variation of the solar dynamo and the emergence of magnetic flux.

We have recently studied the occurrence of MTQP in SW speed since 1964 and in geomagnetic activity since 1932 (Mursula and Zieger, 2000; to be called P1). We found there that the spectral structure in the mid-term period range is very similar in these two variables over the whole common time interval of nearly 40 years of direct SW measurements. In the present paper we discuss the MTQP occurrence in geomagnetic activity over nearly 160 years using the extended aa index. The close similarity between SW speed and global geomagnetic activity in the mid-term period range established in P1 allows us to use the extended aa index as a proxy of SW speed in this period range for a considerably longer time interval than available by direct SW measurements.

2. Data and Method

In this work we use the extended *aa* index which was obtained by combining the *aa* index (Mayaud, 1973) and the the *Ak*(Hel) index (Nevanlinna and Ketola, 1993), derived from early magnetic observations made at Helsinki since 1844. It has been shown earlier (Nevanlinna and Kataja, 1993) that the *aa* index and the *Ak*(Hel) index have an excellent correlation for the overlapping time interval 1868 –1880. The extended *aa* index (Mursula and Zieger, 2001) allows us to study the occurrence of MTQP during two additional solar cycles (9 and 10) before the time covered by the *aa* index. We use here 27-day averages of the extended *aa* index.

In P1 we used a band pass convolution filter (boxcar tapered with Hanning window) repeatedly for several frequency bands in order to produce the dynamic spectrum of SW speed and geomagnetic activity in the mid-term period range. However, here we use, for comparison, the wavelet transformation method with a complex Morlet wavelet as the mother wavelet function. The complex Morlet wavelet consists of cosine and sine oscillations with a Gaussian window as its real and imaginary parts, respectively. We have selected the value of the classical Morlet wavelet of $\omega_0 = 5.34$ (Lagoutte *et al.*, 1992) for the mother wavelet angular frequency and $\sigma = 4$ for the width of the Gaussian window (Holter, 1995). Using these parameter values the frequency resolution corresponding to the half-width

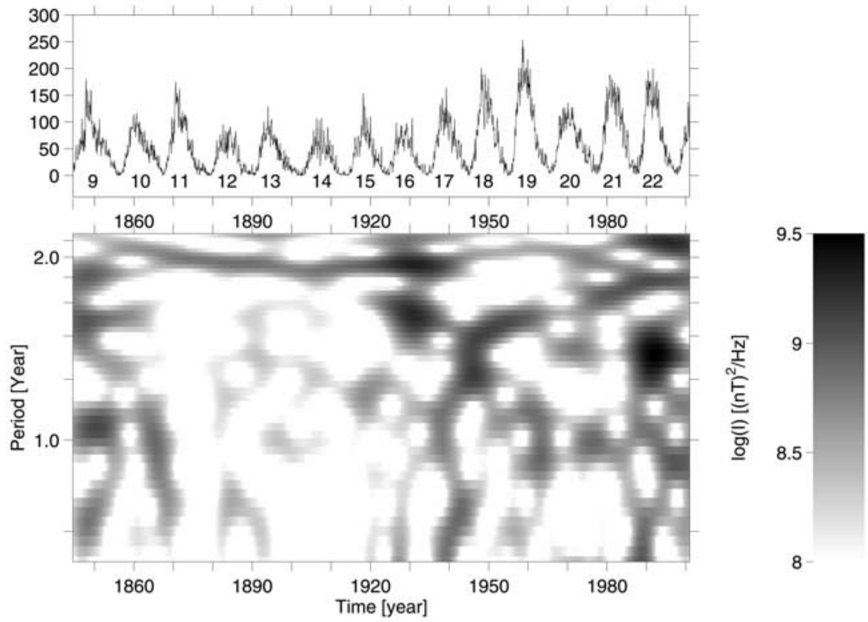

Figure 1. Top: monthly sunspot numbers with cycles indicated. *Bottom*: wavelet power spectrum of the extended *aa* index for periods between 0.75–2.3 years. Power is given in black and white scale with highest (lowest) amplitudes in *black* (*white*).

power (3 dB amplitude) decrease is $\pm 3.9\%$. The time resolution is determined by the effective wavelet transformation length which increases with the period T as $5.7T$. By plotting the wavelet power over a certain time and frequency interval we can obtain the wavelet dynamic spectrum (actually the wavelet scalogram) for the signal.

3. Long-Term MTQP Occurrence

Figure 1 depicts the wavelet dynamic spectrum for the extended aa index in the period range of 0.75–2.3 years. The wavelet method yields a very similar dynamic spectrum as the convolution filter method of P1 over the common time interval. This underlines the reliability of the two methods and the significance of the common spectral structures in the two spectra. As noted in P1 and seen in Figure 1, the mid-term period range consists of separate enhancements (quasi-periodicities) with greatly different amplitudes and with the dominant period varying between 1.2 and 1.8 years. The strongest mid-term enhancement in Figure 1 takes place during cycle 22 and has a period of about 1.3 years. (In P1 we showed that this enhancement was also the strongest in SW speed). This is the periodicity first reported by Richardson *et al.* (1994). During cycle 21 the strongest enhancement in the mid-term period range had a period of about 1.6–1.7 years. This enhancement was earlier found in the mid-latitude coronal hole area (Macintosh, Thompson, and Willock, 1992), and later in cosmic rays (Valdes-Galicia, Perez-Enriquez, and Otaola, 1996). During cycle 20 the dominant enhancement had a period of 1.3 years but a much lower amplitude than during cycle 22. Three other strong mid-term enhancements occurred during the last century, the first one around 1930 with the dominant period of about 1.6 years, the second in 1940s at 1.2–1.3 years and the third in 1950s at 1.5 years.

Accordingly, there has been a nearly continuous series of MTQP enhancements of considerable power since late 1920s, i.e., slightly before the start of the interval of recent high-amplitude solar cycles. On the other hand, as seen in Figure 1, there was hardly any power in the mid-term period range of 1.2–1.8 years during the low-amplitude cycles around the turn of the 19th and 20th centuries. However, interestingly, mid-term periodicities were quite strong in the middle of the 19th century in 1840s and 1850s when solar activity was almost as high as recently.

Outside of the mid-term period range, the dominant spectral feature during the low-activity times was a quasi-two-year periodicity. As this was not observed in the 35-years of SW speed observations studied in P1, it may not be of solar origin and therefore has not been included here in the MTQP range. This periodicity may be related to the well known quasi-biannual oscillation of atmospheric winds. However, if it was of solar origin, it would imply a very different solar behavior during the weak solar activity cycles. Also, one can see in Figure 1 the intermittent appearance of power at the period of one year. We have shown (Zieger and Mursula, 1998; Mursula and Zieger, 2001; Mursula, Hiltula, and Zieger, 2002) that this is related to a persistent north-south asymmetry in the distribution of the solar wind speed.

4. Discussion

As discussed above, the MTQP power during the last 70 years consists of separate enhancements whose dominant period has slightly changed from one enhancement to another. In fact, an interesting alternation of the dominant period can be found (Mursula and Zieger, 2000) according to which every second enhancement has a slightly shorter dominant period of about 1.2–1.3 years while the intervening enhancements have a slightly longer period of about 1.5–1.7 years. This pattern is valid for 6 subsequent strong enhancements from 1930 to 2000. (Even the weak enhancement at around 1920 follows this pattern.) Note that this allows an obvious prediction of a new mid-term enhancement with the longer period within a few years. The alternation of the dominant period can also be seen in Figure 2 where we have plotted the amplitudes of the two frequency bands. One can see in Figure 2 that the two curves are in a rough overall anti-correlation since 1930s. Note that a similar two-period structure and an approximate anti-correlation between the two

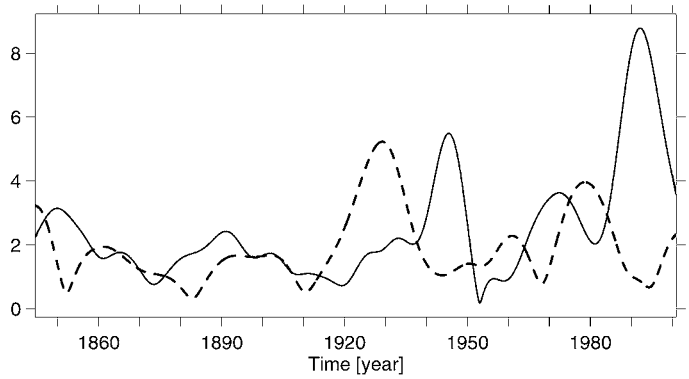

Figure 2. Filtered amplitudes (in nT) of the extended *aa* index in two mid-term periodicity bands with a period within 1.25–1.35 years (*solid line*) and 1.54–1.66 years (*dashed line*).

bands is seen even in 1840–1860s where the first strong enhancements of the mid-term periodicity were observed.

A new mid-term enhancement is seen to appear roughly every solar cycle. However, this is only an approximate rule for the last 70 years since the appearance of enhancements within the solar cycle seems to vary. While the latest enhancements mainly appeared around solar maxima or in the early declining phase, some earlier enhancements were found even around solar minima denying a clear assignment of all enhancements to one solar cycle. Accordingly, Figure 2 demonstrates a rough 22-year oscillation in the amplitude of the two mid-term periodicity bands only since 1960s while the oscillation length is slightly longer in 1930s–1960s. We note that the lower period curve in Figure 2 closely resembles the normalized spectral power curve calculated by Lockwood (2001; see their Figure 16). However, the longer period mid-term enhancements which depict a similar, roughly 22-year pattern were completely neglected in the analysis of Lockwood (2001).

An important new observation is that the power in the mid-term periodicity band (1.2–1.7 years) was consistently low from 1860s to 1920, i.e., during the low-amplitude solar cycles around the turn of the 19th and 20th centuries. This observation is against the recent result by Lockwood (2001) who found a large peak in 1.3-year power in late 1880s. However, we note that the normalization method (normalizing the 1.3-year power by background power from a larger frequency range) adopted by Lockwood (2001) erroneously enhances the 1.3-year power in late 1880s because of the extremely weak background power at this time. As seen in Figure 1, the (absolute) power at the 1.3-year period range was in fact quite weak in 1880s but the power in the neighboring frequencies (the 'background power' used by Lockwood) was even weaker. Accordingly, the strong 1.3-year peak in late 1880s calculated by Lockwood (2001) is artificial. (Finally, we note that the weak enhancement that we find in early 1890s is real but different from Lockwood's strong peak in late 1880s.)

Accordingly, the MTQP enhancements are weak during weak solar activity and strong during strong solar activity. This is true for the last nearly 160 years, including the high-amplitude times in mid-19th century, the low-activity times at the turn of the centuries and the highly active time since 1930s. (We note in passing that this relation may apply on shorter time scales, e.g., during cycle 20 which was the lowest recent cycle and had the weakest mid-term power since 1930.) This relation between solar activity and MTQP power suggests that the mid-term quasi-periodicities have a connection to the solar dynamo strength and its variations. We note that this connection can be understood in terms of the observed 1.3-year variation (Howe *et al.*, 2000) in the solar rotation period at the bottom of the convection layer. Since the magnetic flux is expected to be generated in that region, the observed variation in rotation period suggests that the magnetic flux generation is modulated at a mid-term period. As a result, the open magnetic flux and the coronal hole area would be modulated accordingly, affecting the different heliospheric parameters (e.g., solar wind, IMF, cosmic rays and geomagnetic activity), as observed in the above cited literature. Moreover, the observed relation between MTQP power and solar activity suggests that the stronger the solar dynamo is, the more variable the solar rotation rate around the tachocline is. This also suggests that the variations in the rotation rate at the tachocline are related to the magnetic flux generation and to the solar dynamo.

We note that, using its long-term connection to solar activity, the occurrence of mid-term periodicities can be used to extract information of the variation of the solar dynamo strength. It is interesting to note that the absolute minimum in the power of mid-term periodicities is found during cycle 11, i.e., slightly before the interval of the very weak sunspot cycles. This suggests that a similar disappearance of power at mid-term (1.2–1.8 years) periodicities (and, possibly, an appearance of power at a slightly longer period of about 2 years) can be expected to occur before any long-term decreases of solar activity, e.g., before the next great minimum. The importance of such a precursor signal, if verified, would be enormous.

5. Conclusions

We have studied the long-term occurrence of mid-term quasi-periodicities (period between 1.2–1.8 years) over nearly 160 years using the extended aa index of global geomagnetic activity. The mid-term periodicities appear as separate enhancements with greatly varying amplitude and a period which alternates between a slightly lower value of 1.2–1.4 years and a longer period of 1.5–1.7 years from one enhancement to another. Since a new enhancement appears roughly every solar cycle, the two mid-term period bands depict a roughly 22-year oscillation (see Figure 2).

We find that the spectral power in the mid-term period range is strong in 1840s and 1850s and since 1930, i.e., during the times of high solar activity. The alternation of the dominant period has proceeded during both of these high-activity times. Contrary to earlier results, we find that the mid-term periodicity power is low during the low-activity time from 1860s to 1920s. Accordingly, the long-term evolution of the power in the mid-term period range follows the overall solar activity and thus reflects the strength of the solar dynamo. The recently found 1.3-year variation in the solar rotation speed at the bottom of the solar convection layer (Howe *et al.*, 2000) suggests that the magnetic flux generation is modulated at a mid-term periodicity, leading to the observed mid-term variations in the different heliospheric parameters. Moreover, the relation between mid-term power and dynamo strength observed here suggests that the stronger the solar dynamo is, the more variable the tachocline rotation rate is. We also noted that a sudden disappearance of mid-term periodicity power may be used as precursor for long-term decreases of solar activity, e.g., for the next great minimum.

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