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Uniting The Sun's Hale Magnetic Cycle and 'Extended Solar Cycle' Paradigms

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ABSTRACT

Through meticulous daily observation of the Sun's large-scale magnetic field the Wilcox Solar Observatory (WSO) has catalogued two magnetic (Hale) cycles of solar activity. Those two (∼22-year long) Hale cycles have yielded four (∼11-year long) sunspot cycles (numbers 21 through 24). Recent research has highlighted the persistence of the "Extended Solar Cycle" (ESC) and its connection to the fundamental Hale Cycle - albeit through a host of proxies resulting from image analysis of the solar photosphere, chromosphere and corona. This short manuscript presents the correspondence of the ESC, the surface toroidal magnetic field evolution, and the evolution of the Hale Cycle. As Sunspot Cycle 25 begins, interest in observationally mapping the Hale and Extended cycles could not be higher given potential predictive capability that synoptic scale observations can provide.

INTRODUCTION

For over four centuries solar observers have pondered the physical origins of the canonical marker of solar activity - the sunspot. It took more than 200 years after the sketching and cataloging of sunspots commenced before it was discovered that the number of sunspots waxes and wanes over an approximately 11-year period (Schwabe, 1849). A half century later, mapping the latitudinal variation of the spotted Sun yielded the "butterfly diagram," a pattern progressing from latitudes around 30° (north and south) to the equator over the 11-year period (Maunder, 1904). In the golden age of solar astronomy that followed, it was first suggested (Hale, 1908) and then demonstrated (Hale et al., 1919) that sunspots were sites of intense magnetism protruding through the Sun's photosphere and that the polarities of the butterfly's wings alternated in sign with a period of about 22 years (Hale and Nicholson, 1925). This alternating magnetic polarity cycle is synonymously identified with its discoverer, the eponymous (22-year) "Hale Cycle," or the (22-year) "Hale Magnetic Polarity Cycle." Understanding how the magnetic spots, their butterfly patterning, and the polarity flipping are tied together to drive solar activity has formed the keystone problem of observational (Babcock, 1961), theoretical (Leighton, 1969) solar- and astro-physics in the intervening century (e.g., Hathaway, 2010).

For over four decades another term describing solar activity has sporadically appeared in the literature - the "Extended Solar Cycle." The extended solar cycle (e.g., Wilson, 1987) (ESC) was used to describe an spatio-temporal extension of the sunspot butterfly pattern to higher solar latitudes (to around 55°) and further back in time (by almost a decade). A culmination of many years of painstaking observation the ESC is exhibited in prominences and filaments (e.g., Bocchino, 1933; Hansen and Hansen, 1975), 'ephemeral' (small-scale transient) active regions (e.g., Harvey and Martin, 1973), global-scale features of the Sun's corona (e.g., Altrock, 1988) and the zonal flow patterns (e.g., Howard and Labonte, 1980; Snodgrass and Wilson, 1987) of the 'torsional oscillation.' In effect, this assortment of observational phenomena created a set of spatio-temporally overlapping chevron-like activity patterns.

The concept of the ESC was 're-discovered' by McIntosh et al. in their study of extreme ultraviolet brightpoints and their associated magnetic scale (McIntosh et al., 2014, hereafter M2014). They identified a pattern of coronal and photospheric features that was greatly extended in time and latitude relative to the sunspot butterfly. They deduced that the activity bands observed were the (toroidal) magnetic bands of the Hale cycle, but no concurrent photospheric magnetic measurement was available to affirm their deduction. The core inference of their study was that the spatio-temporal overlap and interaction of extended activity bands observed contributed directly to the shape (the butterfly) and modulation (the amplitude) of the sunspot cycle.

Figure 1 shows the evolution of the total sunspot number, the latitudinal distribution of sunspots and the data-inspired construct introduced by M2014 that inferred the magnetic activity band arrangement and progression of the Hale Cycle and how those bands contribute to the modulation of sunspot cycles. This 'band-o-gram,' introduced in section 3 (and Fig. 8) of M2014, was intended as a qualitative, and not quantitative, illustration of the position, timing and magnetic field strength of the bands - with the emphasis on their phasing. The activity bands in the band-o-gram start their (assumed) linear progression towards the equator from 55°latitude at each hemispheric maxima, meeting and disappearing at the equator at the terminator. At the terminator the polar reversal process commences at 55°latitude, progressing poleward at their (assumed) linear rate - reaching the pole at the appropriate hemispheric maximum. So, for a list of hemispheric maxima and terminators, a band-o-gram can be constructed. The width of the bands is prescribed by a Gaussian distribution 10 degrees in latitude, commensurate with those observed in the coronal brightpoints originally studied by M2014.

DATA & METHOD

The Wilcox Solar Observatory (WSO) began collecting daily low spatial resolution observations of the Sun's global (or mean) magnetic field in May 1975 (Scherrer et al., 1977) and a very well-known data product of WSO is the evolution of the Sun's polar cap magnetic fields (Svalgaard et al., 1978). These low-resolution synoptic observations are ideal for identifying large-scale, long-lived, patterns - reducing the effects of small-scale, rapidly changing fields of emerging magnetic regions. Following, Duvall et al. (1979) the daily WSO magnetograms are obtained by scanning boustrophedonically along 11 east- west rows (i.e., the observation of alternate rows in opposite directions - if one row is taken from left to right then the next row is from right to left). The 180" magnetograph aperture moves 90" between points in the east-west direction and 180" north or south between rows, taking a 15s integration of the Fe I 5247Å line at 195 points on the solar disk - resulting in a total of about 2 hours per daily map. Because of the large

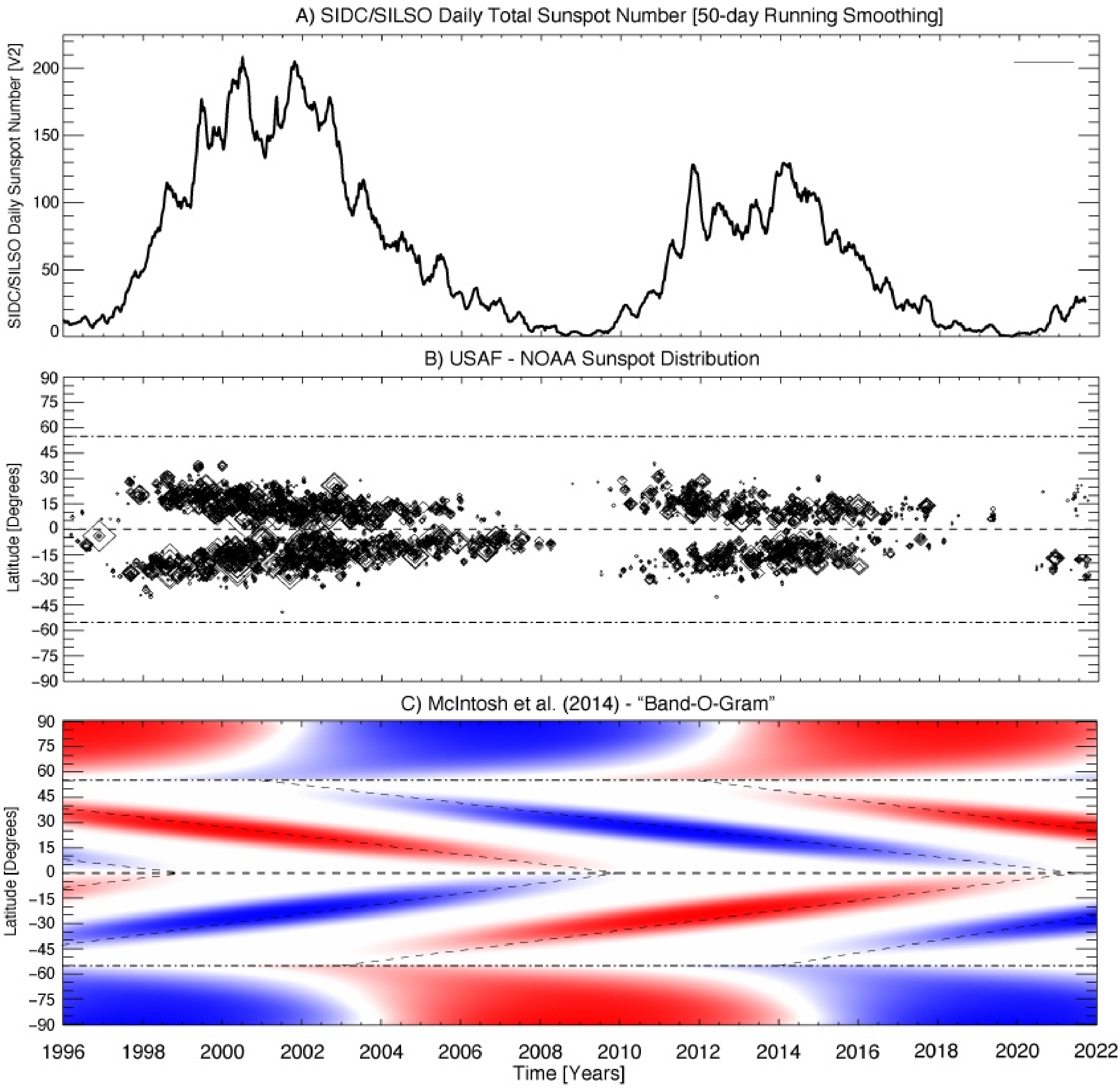

Figure 1. Sunspot evolution since 1996. Comparing and contrasting the evolution of the total sunspot number provided (panel A), the spatio-temporal distribution of sunspots provided by the US Air Force and NOAA (panel B), and a data-driven schematic of the Hale cycle evolution constructed by M2014, the band-o-gram (panel C).

aperture size of the magnetograph the regions from 70° to the poles lie entirely within the last aperture and are not resolved.

Following the method of Howard (1974) and Duvall et al. (1979), the daily WSO magnetographs can be decomposed into the poloidal and toroidal components which, according to dynamo models, are regenerated from one another, alternating and repeating in an approximately 22-year cycle (e.g., Charbonneau, 2010). The method used to perform this decomposition is detailed by (Shrauner and Scherrer, 1994), where the daily WSO magnetographs are first separated into their positive and negative magnetic field polarities which are then tracked as they cross the solar disk. They are then fitted to estimate the average east-west inclination angle of the magnetic field - or the toroidal component of the photospheric magnetic field (see Fig. 1 of Lo et al., 2010, for an illustration of the geometry).

In this paper we use the Shrauner and Scherrer (1994) derivative data product of the WSO toroidal field component in the photosphere and the WSO polar magnetic field estimate using the five central aperture pointings (central meridian $\pm$ two) in first and last rows of observations documented by Svalgaard et al. (1978).

RESULTS

An initial study of the slowly evolving behavior (Shrauner and Scherrer, 1994) noted the potential relationship with the ESC. Figure 2 contrasts four and a half decades of WSO observations with the evolution of the sunspot number over the same timeframe. Panel B shows the latitude-time variation of the WSO toroidal magnetic field component in addition to the field strength of the northern and southern polar regions.

Several features of Figure 2 are immediately visible, but perhaps the most striking are the strong overlap in time of the toroidal magnetic systems, the short transitions from one polarity to the next - evidenced through the narrow white (very near 0G) zones, the lack of field migration across the Sun's equator, and the close association of these last two features at the Sun's equator four times in the record (in 1978, 1988, 1998 and 2011). The patterns, including a strong resemblance to the ESC, are described in more detail by Shrauner and Scherrer (1994) and Lo et al. (2010).

The last of these features, synchronized zero-crossing transitions at the lowest latitudes in each hemisphere, are concurrent with events that mark the end of the Hale Cycle progressions, or termination events as they have become known, that were initially described by M2014 and explored again (in more detail) recently (McIntosh et al., 2019, hereafter M2019). The termination events are illustrated with dashed vertical lines in Figure 2. These events signify the final cancellation of the magnetic systems that were responsible for the last sunspot cycle at the equator and, near-simultaneously, a period of very rapid growth of the next sunspot cycle at mid-solar latitudes. Interestingly, M2019 also noted that these termination events at the equator were co-temporal with the start of the polar magnetic field reversal process. This process is perhaps best visualized through the observed progression of the highest latitude filaments (or polar crown filament) to the pole, the so-called "rush to the poles" (e.g., Babcock, 1961; Sheeley, Wang, and Harvey, 1989). The time at which this poleward march completes corresponds to when the measured polar magnetic field crosses zero.

In order to visually compare the WSO observations [Figure 2B] and the ESC band-o-gram [Figure 1C] (extended to cover the baseline of the WSO observations) we convert the WSO data from sine latitude to latitude and the result can be seen in Figure 3.

DISCUSSION

A general criticism of the M2014 band-o-gram is that it was based on catalogued proxies of the photospheric magnetic field through chromospheric and coronal features. Those tracked features formed by the overlapping activity bands observed were not necessarily representative of the photospheric or interior magnetic field itself. It is clear from the WSO observations that, while comparison of the observed progression with the band-o-gram is still qualitative, that there is an overwhelming correspondence of

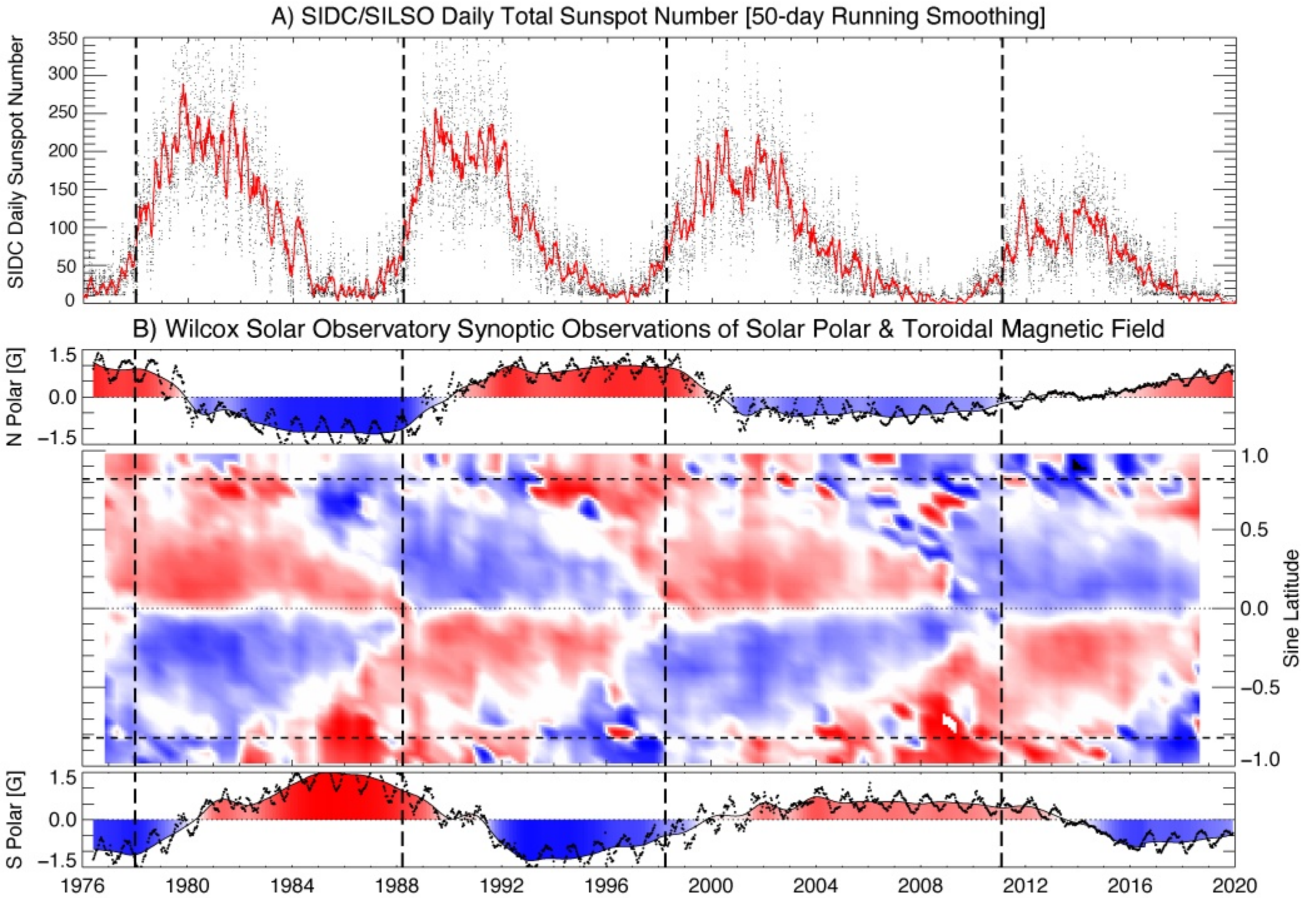

Figure 2. WSO Inferred toroidal magnetic field evolution since 1976. Comparing and contrasting the evolution of the total sunspot number (panel A), with the spatio-temporal distribution of the derived toroidal magnetic field component (central) and polar magnetic field components (above north and below south) derived from daily WSO observations (panel B). Note that the toroidal field panel is in its native sine latitude format (Lo et al., 2010). The vertical dashed lines shown in each panel mark the times of the Hale Cycle termination events studied by M2019.

the features observed in the WSO observations with those of the highly idealized band-o-gram. We note that a similar treatment of higher spatial resolution photospheric observations from the Mt Wilson Solar Observatory over a shorter timeframe yields similar correspondence (Ulrich and Boyden, 2005).

Additionally, Table 1 of Liu and Scherrer (2022) places bounds on the correspondence of the toroidal field zero-crossings (near the solar equator) with the Hale cycle terminator events determined by other means. With the 5 degree resolution of the WSO magnetograph scanning rows around the equator the zero-crossing times of the toroidal magnetic field provided correspond well with the Hale Cycle terminator times presented in Table 1 of M2019: 1978.00 [N5:1976.67, S5:1977.17]; 1988.50 [N5:1988.75, S5:1986.83]; 1997.75 [N5:1997.75, S5:1999.17]; 2011.20 [N5:2008.83, S5:2011.50].

The alternating toroidal field patterns clearly visible in the WSO observations are borne out also with considerably higher spatial resolution observations from space with SoHO/MDI and SDO/HMI (Liu and Scherrer, 2022, , see Fig. 2). In tandem, these magnetograph observations illustrate a clear pattern of the ESC that is consistent with the previous studies cited above. In a forthcoming publication we will

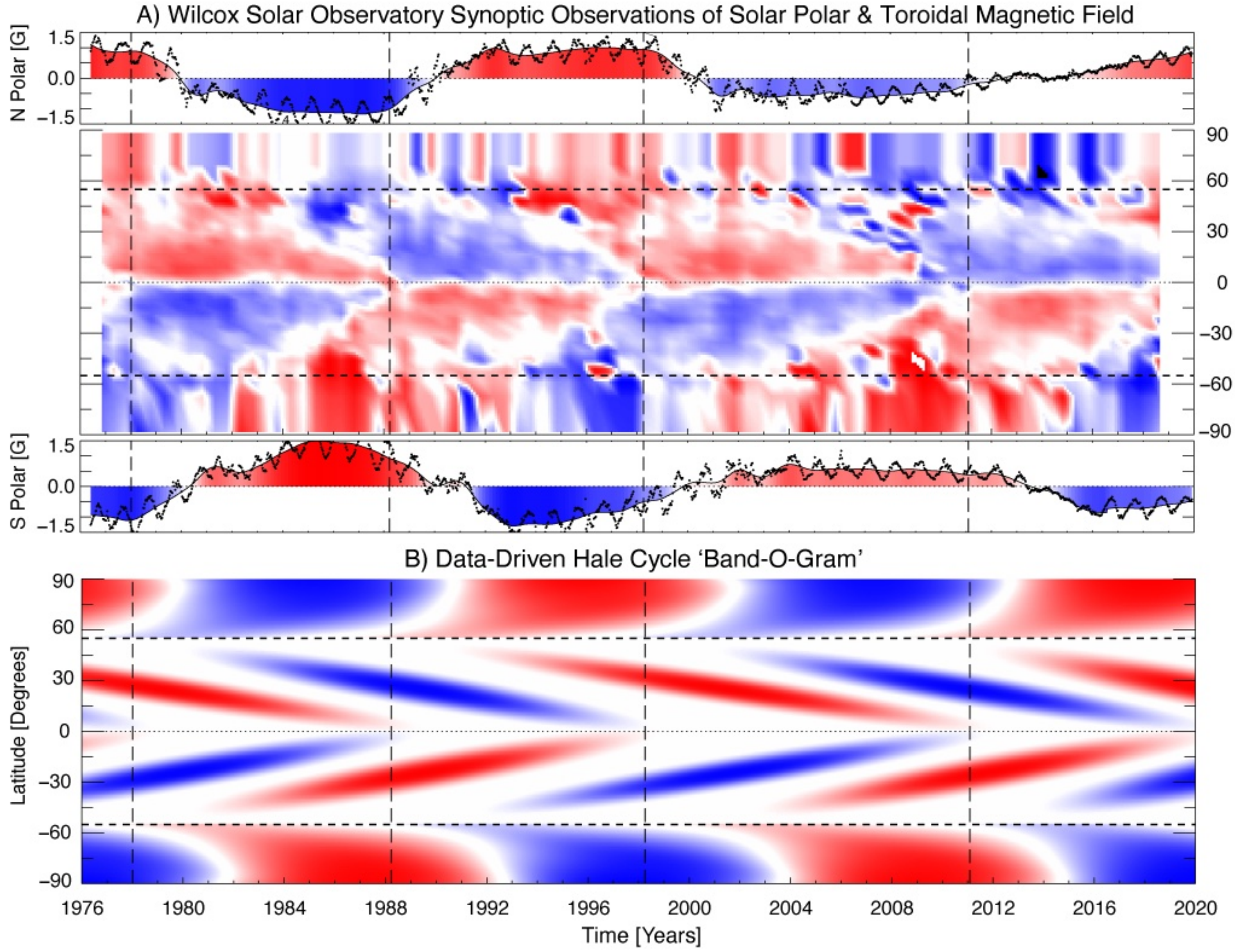

Figure 3. Comparing and contrasting the WSO toroidal field (Panel A, see Figure 2B and now expressed in latitude) and polar cap measurements with the data-inspired band-o-gram (cf. Fig. 1C) now extended to cover the WSO record. The vertical dashed lines shown in each panel mark the times of the Hale Cycle termination events studied by M2019.

utilize SDO/HMI data to explore the two most recent terminator events, including that just passed in 2021 (McIntosh et al. in preparation).

Further, it is known that the heliosphere exhibits a 'sector' structure. The sector, or Hale sector, structure reflects the polarity of the heliospheric magnetic field relative to the solar direction in a state of either being "away" from or "towards" the Sun and expresses the largest spatial scales of solar magnetism and connectivity (e.g., Hudson, Svalgaard and Hannah, 2014). Since the earliest articles about the sector structure the solar cycle has been noted to end abruptly, within one or two solar rotations, of the time when the mean magnetic field of the Sun and the interplanetary magnetic field (IMF) become effectively unipolar, i.e. the sector structure disappears (e.g., Svalgaard and Wilcox, 1975). This highly ordered large-scale sector structure likely has its roots in the fields exhibited in the WSO magnetograms and will be the subject of a subsequent publication exploring its relationship with the terminator and other phases of the ESC (e.g., Leamon, McIntosh and Title, 2022).

CONCLUSION

The meticulous daily synoptic scale observations of the WSO have captured almost two complete 22-year Hale cycles. These observations have permitted a mapping of the Sun's photospheric toroidal magnetic field component over that timeframe. Key features of the WSO observations compare directly to the data-inspired schematic of the ESC that was conceived to illustrate how the activity bands of the ESC can interact to shape the latitudinal progression of sunspot cycles and their amplitude. The WSO observations should unambiguously unify the Hale magnetic cycle and the ESC as being, physically, one and the same and indistinguishable. As Lo et al. (2010) and M2014 inferred, there is predictive capability in these synoptic analyses through the ESC - providing strong indicators of the current progression and potential evolution of upcoming solar activity at the decadal scale, beyond those amenable through the analysis of sunspots. This result demonstrates the intrinsic power of synoptic observations at a time when it is becoming increasingly difficult to sustain such efforts.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTION STATEMENT

All authors conceived the experiment, P.S., L.S. and S.M. analyzed the results. All authors reviewed the manuscript.

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