

# Solar Cycle Observations

Aimee Norton<sup>1</sup>, Rachel Howe<sup>2\*</sup>, Lisa Upton<sup>3</sup> and Ilya Usoskin<sup>4</sup>

<sup>1</sup>HEPL Solar Physics, Stanford University, CA,94305-4085, USA.

<sup>2\*</sup>School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.

<sup>3</sup>Southwest Research Institute, Boulder, CO, 80302, USA.

<sup>4</sup>Sodankylä Geophysical Observatory and Space Physics and Astronomy Research Unit, University of Oulu, 90014, Finland.

\*Corresponding author(s). E-mail(s): [r.howe@bham.ac.uk](mailto:r.howe@bham.ac.uk);

Contributing authors: [aanorton@stanford.edu](mailto:aanorton@stanford.edu);

[lisa.upton@swri.org](mailto:lisa.upton@swri.org); [ilya.usoskin@oulu.fi](mailto:ilya.usoskin@oulu.fi);

## Abstract

We describe the defining observations of the solar cycle that provide constraints for the dynamo processes operating within the Sun. Specifically, we report on the following topics: historical sunspot numbers and revisions; active region (AR) flux ranges and lifetimes; tilt angles; Hale and Joy's law; the impact of rogue ARs on cycle progression; the spatio-temporal emergence of ARs that creates the butterfly diagram; polar fields; large-scale flows including zonal, meridional, and AR in-flows; short-term cycle variability; and helioseismic results including mode parameter changes.

**Keywords:** Sunspots – 1653, Solar Cycle – 1487, Dynamo – 2001, Helioseismology – 709

## 1 Introduction

The fact that sunspot numbers rise and fall over the course of roughly 11 years has been reported since the mid 1800's ([Schwabe, 1844](#)). One hundred and eighty years later, astronomers still can not provide, or agree upon, a rigorous and precise explanation of the solar dynamo. So we optimistically carry on the observations, modeling and discussions to aid us in deciphering one of

the fundamental, unsolved problems in astrophysics: how do dynamos operate within the Sun and the stars? And what are the physical processes that cause variations in solar and stellar cycle amplitude? For a general introduction to the evolution of solar dynamo theory, see Charbonneau & Sokoloff (2023) (insert arXiv reference).

The discovery of the solar cycle by Schwabe (1844) likely inspired Wolfe to take daily observations of the Sun, thus beginning the crucial, historical recording of the sunspot number. See Section 2 for the history, and recent revision, of the sunspot numbers. Studies of individual ARs and their properties began with sunspot drawings and daily observations, but AR research was revolutionized by Hale (1908) who demonstrated their magnetic nature, as discussed in Section 3.

In addition to sunspot numbers, the area occupied (both umbral and umbral plus penumbral area) and the position of the sunspots has been recorded since 1874, beginning at the Royal Observatory, Greenwich and later continuing via the National Oceanic and Atmospheric Administration (NOAA) and the US Air Force (USAF). The distribution of sunspot area as a function of latitude revealed that two sunspot bands existed on either side of the heliographic equator and that these bands moved equatorward in time. This pattern is known as the butterfly diagram, see Section 4. The large-scale dipole field that dominates at cycle minimum, and is a reliable precursor for the next cycle amplitude, is best-studied through the accumulation of small-scale flux at the poles, as discussed in Section 5.

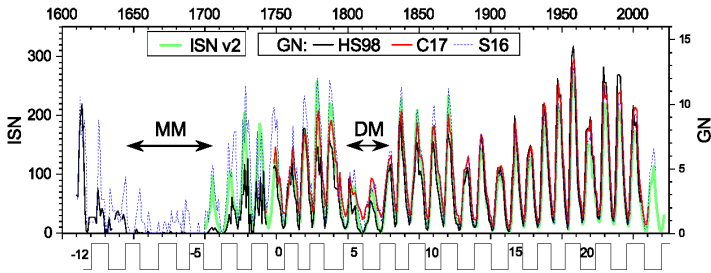
The magnetic nature of the solar cycle is only a part of the story. The behavior of large-scale flows inform us of the kinetic perturbations associated with the dynamo, including torsional oscillations, meridional flow and AR in-flows as discussed in Section 6. Finally, short-term cycle variations and helioseismic mode parameter changes are mentioned in Sections 7 and 8, respectively. Discussions in this chapter are intentionally brief, or omitted, since the purpose is to introduce the observations that inspired the up-to-date research. .

## 2 Sunspot Number

The sunspot number (SN) is a synthetic (not physical) quantitative index of solar activity which is historically widely used because of its simplicity and long (more than 400 years) available dataset. The SN is not equal to the *number of sunspots* (denoted as  $s$  below) but includes also the weighted number of sunspot groups  $g$ , using the formula introduced by Rudolf Wolf in the middle of the 19th century:

$$SN = k \cdot (10 \cdot g + s), \quad (1)$$

where  $k$  is a scaling factor reducing the data quality (related, e.g., to the quality of the used instrumentation) of individual observers to that of the reference one (usually Rudolf Wolf or Alfred Wolfer are considered as the reference observers). A single spot on the Sun forms also one sunspot group leading thus to SN=11. The classical Wolf's method uses observations of only one, so-called



**Fig. 1** Annual sunspot activity for the last centuries according to different recent reconstructions: International sunspot number series version 2 (green ISN v2 curve, LHS axis) obtained from SILSO; Number of sunspot groups (RHS axis), according to HS98 – Hoyt and Schatten (1998); C17 – Chatzistergos et al (2017); S16 – Svalgaard and Schatten (2016). Standard (Zürich) cycle numbering is shown between the panels. Approximate dates of the Maunder minimum (MM) and Dalton minimum (DM) are shown in the lower panel. Modified after Usoskin (2023).

primary observer for each day. If the primary observer’s data was not available for a day, secondary, tertiary, etc. observers were used, but always only one per day (see Waldmeier, 1961). This makes the SN series easy to calculate but leaves no way to verify it nor to estimate its uncertainty. This forms the so-called *Wolf* or Zürich SN series (WSN or *Z*). The WSN was continuously produced by Zürich Observatory using roughly nearly the same, with minor modifications, techniques. The main shortcoming of the WSN is that it is not transparent and cannot be presently revisited, corrected or verified, since only the final product has been published while raw data were hand-written in log books. These old log books are being digitized now making it potentially possible to revise the WSN in the future (Friedli, 2020).

The production of the SN series was ceased in the 1980s in Zürich and smoothly transmitted to Brussels (Sunspot Index and Long-term Solar Observations project, SILSO – <http://sidc.be/silso>), where it is continued in the form of the International Sunspot Number, ISN (Clette et al, 2007). SILSO continues using the same formula (Eq. 1) for ISN but changed the methodology so that not only a single primary observer’s data, but a weighted sum of all available data are used for each day.

For more than a century, the WSN was the golden standard’ in solar studies, but then several problems had been identified, including impossibility of its update with newly recovered data. Hoyt and Schatten (1998) developed a new index, called *Group sunspot number*, GSN (or GN), based on a weighted sum of the number of sunspot groups reported for each day by all possible observers. They neglected the number of individual spots as less reliably detected. Hoyt and Schatten (1998) added a lot of new data not known to R. Wolf and his successors and, most importantly, published the entire database of raw data, making it possible to assess the uncertainties and add or revise the data if needed. This also allows evaluation of the related uncertainties. The database

of individual historical observations is continuously updated at <http://haso.unex.es/?q=content/data> (Vaquero et al, 2016).

After a careful study, several issues have been found in the WSN/ISN dataset, such as discontinuous transitions between different observers or changed methodology (e.g., Leussu et al, 2013; Clette et al, 2014). These obvious discontinuities have been ad-hoc corrected in the revised ISN series, which have been also normalized to A. Wolfer as the reference observer – the latter leads to a scaling factor of 1.667 with respect to the classical WSN. This forms the ISN version 2 dataset which is considered as a current version (Clette and Lefèvre, 2016), as shown by the green curve in Figure 1. A new revision of the ISN, version 3, is pending in the near future as the first consensus dataset using the best of our present-day knowledge.

Independently of the WSN/ISN, the methodology has been revisited for the GSN series, starting from the raw-data database. Several new approaches have been developed in this direction. One was made by Svalgaard and Schatten (2016) who performed a daisy-chain ‘backbone’ GSN composition following the classical scheme of linearly scaling individual observers between each other (blue dotted curve in Figure 1). The daisy-chain approach was further improved by Chatzistergos et al (2017) who accounted for non-linear relations between data from overlapping observers and composed a new GN series (red curve in Figure 1). A principally new approach has been developed recently (Usoskin et al, 2016; Willamo et al, 2017) that uses the active-day (days with at least one sunspot observed) fraction as the metrics of the observer’s quality, quantified via the acuity threshold, viz. the minimum size of sunspot group to be detected by the observer.

Of special interest is the level of solar activity during the Maunder minimum of 1645–1715 (Eddy, 1976): while the present paradigm is that it was nearly sunspot free (e.g., Usoskin et al, 2015; Carrasco et al, 2021), some estimates predict low but still significant sunspot activity (Svalgaard and Schatten, 2016; Zolotova and Ponyavin, 2015). However, a consistent analysis of the multitude of other data, such as cosmogenic isotopes, auroral records, solar eclipse observations, confirms the very low level of solar activity during the Maunder minimum (e.g., Usoskin et al, 2015; Asvestari et al, 2017; Carrasco et al, 2021; Hayakawa et al, 2021), implying particularly that the reconstruction by Svalgaard and Schatten (2016) is too high in the 18th century.

Thus, at present there is a zoo of SN and GN reconstructions, as shown in Figure 1. Generally, they are all consistent after about 1870 but somewhat disagree for the period between 1749–1870, with the difference being indicative of the systematic uncertainties. The GSN series by Hoyt and Schatten (1998) and by Svalgaard and Schatten (2016) can be considered as conservative lower and upper bounds, respectively, while other models lie between them. A consensus-based SN reconstruction is presently not available but it is under consideration by the research community.



**Fig. 2** (Left) Hale's law describes how bipolar magnetic regions in one hemisphere tend to have the same leading magnetic polarity while those in the other hemisphere have the opposite leading polarity. This leading polarity switches from one Solar Cycle to the next, i.e., cycle  $N$  ( $N+1$ ) shows the expected polarity for Cycle 24 (25). The average tilt angles between the magnetic polarities, depicted by red lines, increase with increasing latitudes. (Right) HMI magnetograms from Cycles 24 (2012.04.21) and 25 (2022.05.15) show the manifestation of Hale's and Joy's law on any given day with orange-red (green-blue) colors identifying the location of negative (positive) polarity.

## 3 Active Regions

### 3.1 Hale's Law

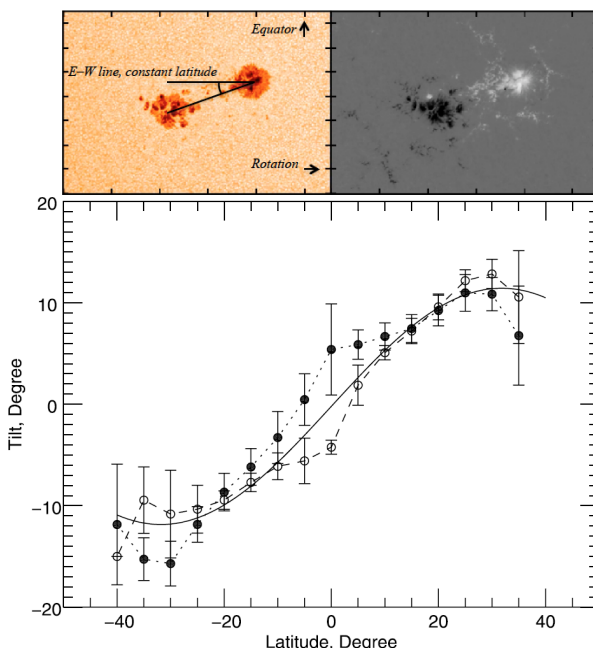
Hale (1908) realized that magnetic fields were the cause of sunspots after observing the Zeeman splitting of a spectral line from the light originating in a sunspot. He also noted that sunspots appeared in pairs of positive and negative magnetic polarity and that the leading polarity in each hemisphere changes from one sunspot cycle to the next. This is known as Hale's polarity law, see Figure 2. While Hale's law is straightforward, it has profound implications for the solar dynamo. It implies that the large-scale organization of the magnetic field in the interior is mostly toroidal (East-West) in orientation and oppositely directly across the equator. The sunspot group that makes up a bipolar magnetic region is known as an AR (AR). ARs adhere to Hale's law  $\sim 92$ – $95\%$  of the time (Wang and Sheeley, 1989; McClintock et al, 2014; Li, 2018; Muñoz-Jaramillo et al, 2021).

### 3.2 Flux Ranges and Lifetimes

ARs are part of a spectrum of magnetic bipoles that emerge into the photosphere and have a smooth, distribution function in regards to size and total absolute flux values ranging from  $10^{18}$  to  $10^{23}$  Mx. Ephemeral regions are smaller, short-lived regions with flux less than  $1 \times 10^{20}$  Mx and have a lifetime of hours, i.e., shorter than a day (Hagenaar et al, 2003). Small regions appear as pores with flux in the range of  $1 \times 10^{20}$  to  $5 \times 10^{21}$  Mx. Larger sunspots develop well-defined penumbra and have  $5 \times 10^{21}$  to several  $\times 10^{23}$  Mx. They live on the order of several weeks to several months. Typically, the flux emergence period is 15 – 30% of the total lifetime (van Driel-Gesztelyi and Green, 2015), usually 3–5 days for an average-sized AR (Harvey-Angle, 1993; Norton et al, 2017) after which there is a plateau of stability before the flux begins to decay.

### 3.3 Tilt Angles

Bipolar sunspot pairs are, on average, oriented so that the leading sunspot (with respect to rotation) is closer to the equator than the following sunspot, see Figure 3 for an example, and also the red lines connecting the bipolar sunspot pairs in Figure 2, with the angle being a measure of the orientation of the bipolar magnetic region’s axis with respect to the East-West direction. On average, the tilt angles increase with latitude and this trend was named “Joy’s Law” by Zirin (1988), see Figure 3. Tilt angles are of interest in dynamo studies since the tilt is crucial in flux-transport dynamo models where it plays a role in the formation and evolution of polar fields (see, e.g., Wang and Sheeley (1991); Dikpati and Charbonneau (1999a)). Tilts serve as an observable feature of the conversion of toroidal magnetic field into poloidal, i.e., the  $\alpha$ -effect, and the reversal of axial dipole between cycles. There are two dominant, physical explanations for the origin of Joy’s law. First, as proposed by Babcock (1961), the tilt angle observed in the photosphere reflects the directional components of the global magnetic field at depth and is a direct consequence of the “winding



**Fig. 3** The majority of ARs emerge in nearly an E-W orientation with a tendency for the leading spot (with respect to rotation) to be closer to the equator. A southern hemisphere AR is shown (top) as observed in SDO/HMI intensity and magnetogram. Joy’s law describes how the tilts, on average, increase with increasing latitude. (Bottom) Mean tilt of magnetic bipoles as a function of latitude from Cycles 15–24 from Mt. Wilson Observatory daily sunspot drawings with magnetic polarity indicated. RMS of mean tilt shown as error bars with even (open circles, dashed line) and odd cycles (filled circles, dotted line) as well as a fit to all data (solid line). Lower image reproduced with permission from Tlatova et al (2018), copyright from Springer Nature.

up” of the poloidal field in the solar interior. Second, Wang and Sheeley (1991) propose that Joy’s law is a result of the Coriolis force acting on flows within the flux tube as it rises through the convection zone.

Joy’s law is weakly adhered to and only becomes obvious after much averaging. A study by Wang and Sheeley (1989) with over 2500 bipolar magnetic regions reported that 16.6% had no measurable tilts, 19% were anti-Joy, 4.4% were anti-Hale. That is a whopping 39.9% of regions that were not obeying Joy’s law. The data are so noisy that Joy’s law can not be recovered for Cycle 17 (Cycle 19) in the northern (southern) hemisphere, respectively (McClintock and Norton, 2013). The scatter is thought to have a physical origin, the buffeting of flux tubes by convective motions (Fisher et al, 1995).

Simulations of thin flux tubes rising through the convection zone with the Coriolis force acting on flows within the flux tube have been able to recreate both Joy’s law and its scatter (D’Silva and Choudhuri, 1993; Fan, 2009; Weber et al, 2011) with scatter increasing for flux tubes that spend a longer time rising. Thin flux tube modeling has become less popular with the rise of 3D global dynamo modeling capability. While the results of the 3D models show some promise of producing bipolar magnetic regions that adhere to Hale and Joy’s law (Nelson et al, 2013), there is certainly no consensus as to which models most accurately represent solar conditions and recreate tilt angle distributions.

A list of observational aspects of tilt angles are as follows: the dependence on latitude differs between cycles and hemispheres (Dasi-Espuig et al, 2010; McClintock and Norton, 2013; Tlatova et al, 2018), there is evolution as the AR emerges and decays so the time of measuring a tilt angle matters (McClintock and Norton, 2016; Schunker et al, 2020), scatter is higher during the first day of emergence (Schunker et al, 2020), the value tends to settle near the end of emergence (Stenflo and Kosovichev, 2012; Schunker et al, 2020), there are conflicting reports as to whether the tilts show a dependence on magnetic flux as predicted in thin flux tube modeling (Fisher et al, 1995; Stenflo and Kosovichev, 2012; Jiang et al, 2014; McClintock and Norton, 2016; Schunker et al, 2020), the scatter in the tilt values has a dependence on flux but not latitude (Fisher et al, 1995), the mean and median tilts of regions near the equator are not zero indicating that forcing a fit for Joy’s law through the origin may be unphysical, an inflection point in the fit of tilts as a function of latitude occurs around 30° in both hemispheres (Tlatova et al, 2018), the smallest bipoles appear to have negative tilts (Tlatov et al, 2013), and the anti-Hale regions may not simply be the tail of the distribution of tilt angles as Muñoz-Jaramillo et al (2021) reports they prefer an east-west orientation and have a distribution distinct from the ARs that follow Joy’s law.

Improvements in tilt angle measurements and databases is ongoing work. Traditional determinations of Joy’s law have been based on white-light images because magnetograms only became routinely available in the mid-1960s. White-light studies yield median tilt angles that are smaller and increase less steeply with latitude (lower slopes) than those obtained from magnetic data

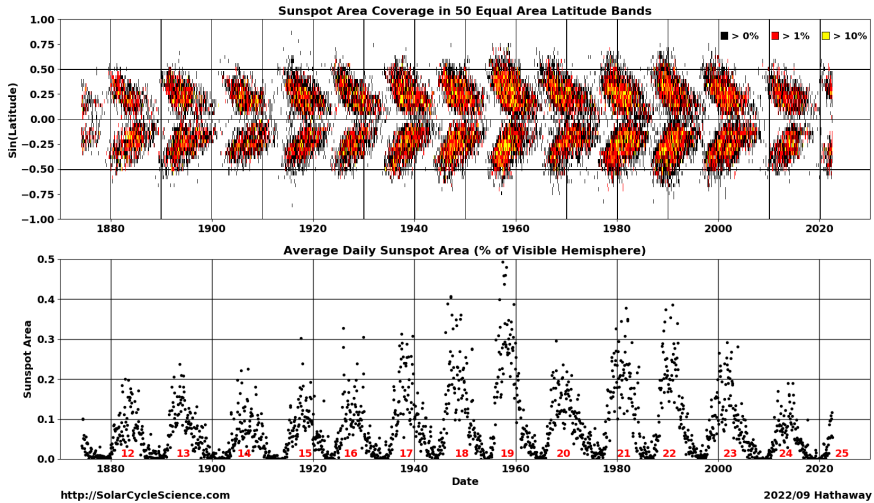
as shown by Wang et al (2015), who also pointed out that a substantial fraction of tilts determined from white-light data were erroneous since they were from sunspots of the same polarity. In addition, if plage is included in the calculation, the tilt angle is usually higher. Given the errors in tilt angle determinations prior to routine magnetograms, and inconsistent methodologies (i.e., tilt angles determined including only umbra versus those determined using umbra, penumbra and plage), it is not clear if long-term trends of tilt angles using only white-light data are valid.

An anti-correlation between area-weighted mean tilt angles (normalized by latitude) and cycle strength was shown by Dasi-Espuig et al (2010) for cycles 15-21, indicating that the surface source for the poloidal field becomes weaker for stronger cycles, potentially limiting the strength of the next cycle, and providing a feedback mechanism (“tilt-quenching”) that prevents runaway solutions to the cycle amplitude. However, McClintock and Norton (2013) could only recover the Dasi-Espuig et al (2010) result for the Southern hemisphere, not the Northern, and the Cycle 19 outlier value dominated the fit for the Southern hemispheric data. Nevertheless, non-linear feedback mechanisms that affect average tilt angles appear effective. Surface flux-transport modeling by Cameron and Schüssler (2012) and Jiang et al (2010) incorporated the effect of AR inflows into surface flux transport models and found that strong cycles produce strong in-flows which result in a lower tilt angle and decreased resulting axial dipole moment. Another proposed mechanisms that affects the average tilt angle of a cycle is a thermal perturbation of the overshoot region as explored by Işık (2015).

### 3.4 Rogue Active Regions

The progression of any solar cycle, including the polarity reversal and gradual strengthening of the polar caps responsible for the axial dipole moment, is punctuated by the appearance of unusually influential ARs. The term “rogue AR” was coined by Nagy et al (2017) who reported that a single rogue bipolar magnetic region in their simulations was found to have a major effect on the development of subsequent solar cycles, either increasing or decreasing the amplitudes, and in extreme cases, triggering a grand minimum. Petrovay et al (2020) formulated an algebraic method that consists of summing the ultimate contributions of individual ARs to the solar axial dipole moment at the end of the cycle. Nagy et al (2020) then proposed the AR Degree of Rogueness (ARDoR) quantity that is the difference between the final contribution to the axial dipole moment from an individual AR and an ideal contribution from a region at the same latitude that has an expected tilt angle prescribed by Joy’s Law and separation of opposite polarity footpoints typical for an AR of similar flux. Nagy et al (2020) performed a statistical analysis of a large number of simulated activity cycles and ranked the ARs from most to least influential, i.e. by decreasing values of ARDoR. They showed that the top 50 influential ARs of any given cycle are sufficient to reproduce the final dipole moment of that cycle. Rogue ARs have a variety of characteristics but their rogueness is



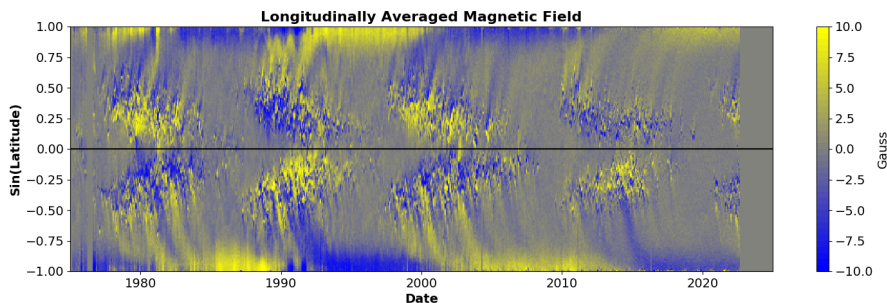


**Fig. 4** Butterfly diagram shows sunspot area from the Royal Greenwich Observatory, color coded as a percentage of the solar disk, plotted as a function of time and sine latitude (top panel). For reference, the total sunspot area is also plotted as a function of time (lower panel). Figure courtesy D.H. Hathaway via [www.solarcyclescience.com](http://www.solarcyclescience.com).

commonly determined by having a very large amount of flux, an abnormal tilt angle such as being anti-Hale, an unusually large separation distance between the polarities, or being very close to the equator.

## 4 The Butterfly Diagram

When the location of sunspots or ARs are plotted as a function of latitude and time, a beautiful pattern emerges that resembles butterfly wings. This so called “Butterfly Diagram”, first depicted by [Maunder \(1904\)](#), shows sunspot bands of activity in both the Northern and Southern hemispheres. Modern depictions include a third dimension, the fractional area of the sun covered by sunspots, see Figure 4. Inspection of the butterfly diagram reveals that early in the cycle, ARs begin emerging at mid-latitudes (approximately 30 degrees) and as the cycle progresses the emergence moves closer to the equator. This equatorward progression of AR emergence is known as Spörer’s Law ([Maunder, 1903](#)). Larger cycles tend to begin emergence at higher latitudes than weaker cycles. The width of the “Butterfly wings” also changes over the course of the cycle and is proportional to the strength of the solar cycle ([Ivanov and Miletsky, 2011](#)), producing a tapering of the wings at both the start and the end of the cycle. The asymmetry between the northern and southern hemispheric cycle progression was noted by [Sporer \(1894\)](#) and [Maunder \(1904\)](#) with unequal sunspot activity persisting for several years. [Norton et al \(2014\)](#) showed that the asymmetry was never more than 20% in amplitude or timing using many parameters, meaning that the hemispheres are strongly coupled to



**Fig. 5** The magnetic butterfly diagram shows the latitudinal distribution of the magnetic field as a function of time. The magnetic field is averaged over all available longitudes and over each Carrington Rotation using data from SOLIS/MDI/HMI. The color indicated the sign of the polarity, with yellow (blue) for positive (negative) radial magnetic fields. Figure courtesy D.H. Hathaway via [www.solarcyclescience.com](http://www.solarcyclescience.com).

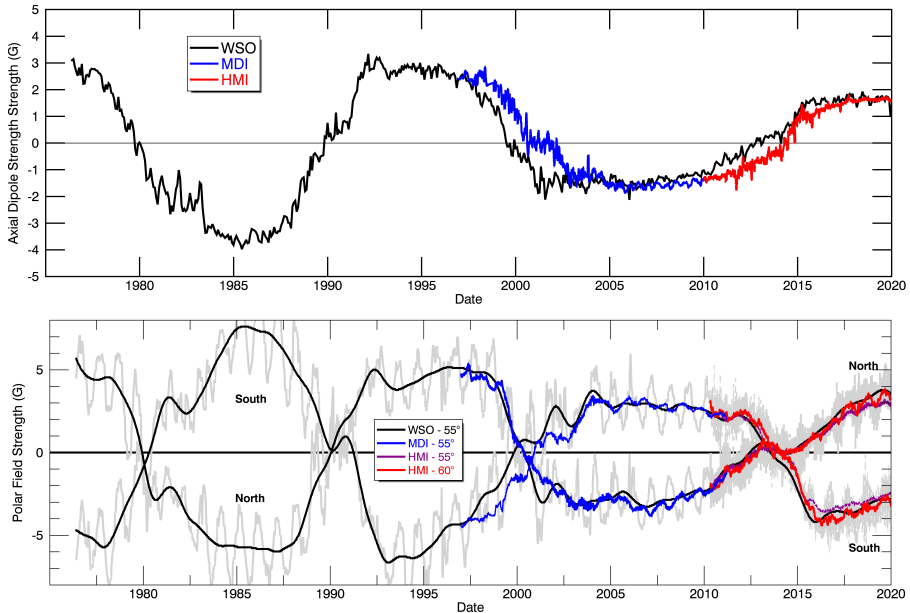
$\approx 80\%$ . Typically the cycles overlap in time by about one-two years, with the new cycle beginning at mid-latitudes before the previous cycle has finished. However, this overlap is proportional to the strength of the following cycle such that the weakest cycles have little to no overlap with the previous cycle.

While the traditional Butterfly Diagram is created in statistical manner by plotting the sunspot area as a function of latitude and time, a similar plot can be created by plotting the average magnetic field instead (Harvey, 1994). This “Magnetic Butterfly Diagram”, see Figure 5 reveals several other characteristics of the solar cycle. Most notable, are the appearance of Joy’s Law and Hale’s law. Each wing displays a leading polarity on the southern edge and the opposite following polarity on the northern edge (Joy’s Law). The wing polarity is opposite across hemispheres and switches from one cycle to the next (Hale’s law). In addition to the butterfly wings, streams of flux can be seen emerging from the wings and moving towards the poles. They are most prominent during solar cycle maximum and are dominated by the following polarity flux (though intermittent leading polarity streams are also present). These streams are a signature of the pole-ward meridional flow transporting residual AR flux to the polar regions. This process forms strong flux concentrations at the poles, i.e. the polar fields, that reverse polarity near the time of solar maximum.

## 5 Polar Fields

During solar minimum, the Sun’s magnetic field resembles that of a dipole, with opposite polarity magnetic field concentrations at the poles. This dipolar magnetic field acts as the seed field for the solar cycle described in Chapters 1 and 13 of this book.

The Sun’s polar magnetic fields can be measured by averaging the magnetic field strength over the polar cap to get the flux density over each polar region or by calculating the axial dipole moment of the magnetic field configuration. The latter provides a single value for the state of the Sun’s global magnetic



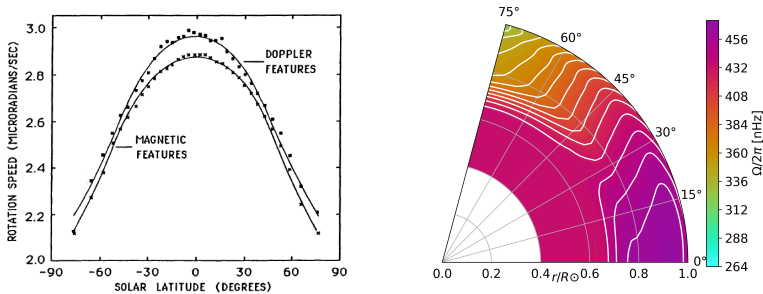
**Fig. 6** The Sun’s polar fields measured by the axial dipole moment (top) and by the average field strength over the polar caps (bottom). Data smoothed over 13 Carrington Rotations is shown from WSO in black, SOHO/MDI in blue, and SDO/HMI in purple and red. WSO and MDI averaged polar fields are measured from  $55^\circ$  and above, while HMI is shown for both  $55^\circ$  and  $60^\circ$  (purple and red) and above. For reference, the unsmoothed WSO and HMI measurements are shown in grey in the polar field plot, highlighting the annual signal caused by the changing inclination of the Sun over Earth’s yearly orbit.

field as a whole, while the former provides additional information about the differences between the North and South hemispheric polar magnetic field.

The Wilcox Solar Observatory (WSO) has been measuring the Sun’s line-of-sight magnetic field daily since 1976 and has provided measurements of both the polar field strength and the axial dipole since that time<sup>1</sup> (Svalgaard et al, 1978; Hoeksema, 1995), as shown in Figure 6. The axial dipole component of the Sun’s magnetic field as measured by WSO is shown in Figure 6 (top panel). The axial dipole moment is an integrated quantity that measures the axisymmetric component of the large-scale photospheric magnetic field. The polar field strength, bottom panel in Figure 6, is defined as the flux density of the magnetic field above a specific latitude. For WSO this is limited by the spatial resolution and taken to be the line of sight field strength measured in the highest most pixel, which is taken to be between  $55^\circ$  and the poles (but the actual latitude range varies with the Earth’s orbit). Space based missions have a better resolution and in the case of HMI<sup>2</sup> calculate the polar fields as the inferred radial component of the magnetic field measured at  $60^\circ$  and above

<sup>1</sup><http://wso.stanford.edu/Polar.html> courtesy of J.T. Hoeksema.

<sup>2</sup><http://jsoc.stanford.edu/data/hmi/polarfield/> courtesy of Xudong Sun.



**Fig. 7** Left: Differential rotation measured by feature tracking (from [Snodgrass and Ulrich, 1990](#), ©the AAS, reproduced by permission). Right: Solar rotation profile from 2D inversions of HMI helioseismic observations, averaged from 2010 to 2022.

([Sun et al, 2015](#)). While the improved resolution does mitigate the projection effects, a residual annual oscillation (gray lines in the bottom panel in [Figure 6](#)) is evidence that there is still uncertainty in these measurements. While the flux density over each polar region offers insight into hemispheric asymmetries, the innate ambiguity associated with this measurement may make the axial component of the Sun’s magnetic dipole a better metric for solar cycle prediction ([Upton and Hathaway, 2014](#)).

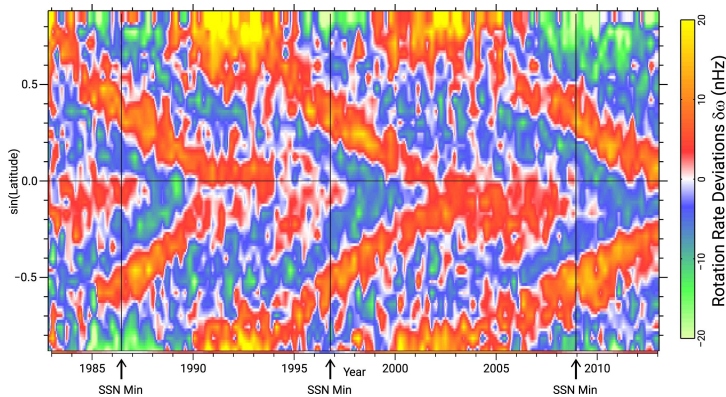
The polar fields are out of phase with the sunspot number, with the reversal occurring near the time of solar cycle maximum. The peak in the polar field strength typically occurs at or just before solar cycle minimum. The amplitude of the polar fields at the time of solar cycle minimum is proportional to the amplitude of the next solar cycle. Measurements of the Sun’s polar fields over the have proven to be successful predictor of the following cycle amplitude ([Schatten et al, 1978](#); [Svalgaard et al, 2005](#); [Petrovay, 2010](#); [Muñoz-Jaramillo et al, 2013](#)). The physical basis of this is rooted in the phenomenological dynamo model proposed by [Babcock \(1961\)](#). In this description, the Sun’s global magnetic field begins in a dipolar configuration. The magnetic field in the convection zone is sheared by differential rotation, causing the magnetic field to become buoyant and rise to the surface, thus forming sunspots. For a detailed account of Babcock model, see Chapter 13 of this book ([Cameron and Schüssler, 2023](#)).

## 6 Flows

For a detailed account of the plasma flows in the Sun, see Chapter 10 of this book.

### 6.1 Solar Rotation Profile

The mean solar differential rotation profile is well known. At the surface it can be measured by tracking features such as sunspots, revealing that the rotation rate is highest at the solar equator and decreases towards the poles ([Figure 7](#), left). A good review of these measurements has been made by [Beck \(2000\)](#).

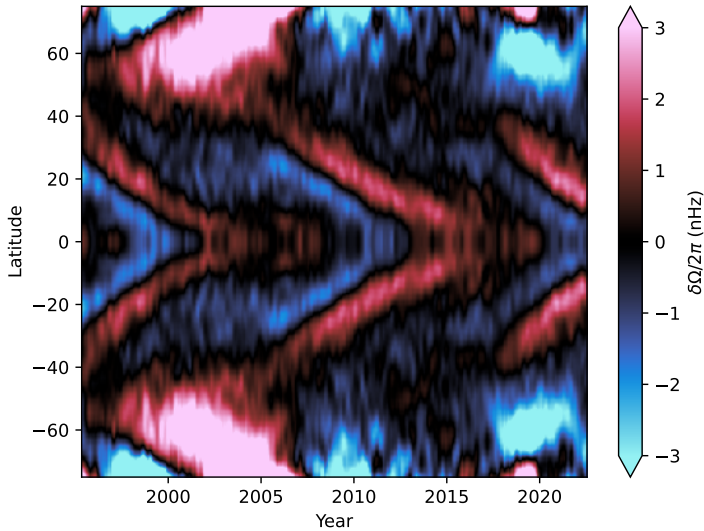


**Fig. 8** The torsional oscillation in Mount Wilson surface Doppler observations, adapted from Ulrich et al (2022) under the <http://creativecommons.org/licenses/by/4.0> license.

Helioseismology (see, for example, Thompson et al, 1996; Larson and Schou, 2018) has revealed the interior rotation profile (Figure 7 right). It features a near-surface shear layer where the rotation rate increases with depth down to about  $0.95 R_{\odot}$ . Below this layer, differential rotation persists through the bulk of the convection zone, approximately constant on radial lines although the isorotation contours tend to lie at about a 25-degree angle to the rotation axis over a wide range of latitudes (Gilman and Howe, 2003). There is another shear layer or “tachocline” at the  $0.71 R_{\odot}$  base of the convection zone, which is narrower in reality than it appears in most helioseismic profiles due to the finite resolution of the inversions; the consensus (see Table 2 of Howe, 2009, and references therein) is that the thickness is around  $0.05 R_{\odot}$ , but at least one estimate (Corbard et al, 1999) puts it as low  $0.01 R_{\odot}$ . Below the tachocline, in the radiative interior, there is roughly rigid rotation down to the limits of reliable measurement at around  $0.2 R_{\odot}$ . (e.g. Eff-Darwich and Korzennik, 1998; Couvidat et al, 2003), although the former authors note that it is possible that the nuclear-burning core is rotating somewhat faster than the bulk of the radiative interior).

## 6.2 Zonal Flows: Torsional Oscillations

The solar rotation profile is modulated by a pattern of bands of faster- and slower-than-average rotation, which can be considered respectively as prograde or retrograde flows, and which migrate in latitude in synchrony with the solar cycle. This pattern was first observed, and dubbed the “torsional oscillation”, by Howard and LaBonte (1980) in surface Doppler observations at the Mount Wilson Observatory. The Mount Wilson observations continued until 2013, and Figure 8 from Ulrich et al (2022) shows the pattern over three solar cycles. The main feature is the band of faster rotation in each hemisphere that moves from mid-latitudes towards the equator between one solar minimum and the next; as pointed out by Howard and LaBonte (1980), the latitude of maximum flux falls close to the edge of this belt. These flows are relatively weak compared to



**Fig. 9** Zonal flow map from helioseismic inversions of GONG, MDI, and HMI data, at a target depth of  $0.99 R_{\odot}$ , with a temporal mean over the whole dataset subtracted at each latitude. Reproduced from [Howe et al \(2022\)](#) under the <http://creativecommons.org/licenses/by/4.0> license.

the mean solar rotation, with amplitudes close to the surface of less than ten meters per second, or a fraction of a per cent of the equatorial rotation rate.

With the advent of systematic, long-term helioseismic observations from the Global Oscillations Network Group (GONG: [Harvey et al, 1996](#)) and the Michelson Doppler Imager (MDI: [Scherrer et al, 1995](#)), it became possible to measure the solar rotation and its temporal changes below the photosphere. The flow patterns were seen in helioseismic data in the rising phase of Solar Cycle 23 by [Schou \(1999\)](#), and [Howe et al \(2000\)](#) found that the patterns penetrated at least 0.08 solar radii into the convection zone; subsequent work, for example by [Vorontsov et al \(2002\)](#), suggested that the variation in rotation involves most of the bulk of the convection zone. A strong band of faster flow migrating from mid-latitudes towards the poles was reported on by [Antia and Basu \(2001\)](#) in data from early in Solar Cycle 23.

Because the mid-latitude rotation begins to speed up before significant surface activity is seen, the flow pattern towards the end of one solar cycle can give some indication of the timing of the following one, as reported by [Howe et al \(2009\)](#) for Cycle 24 and [Howe et al \(2018\)](#) for Cycle 25. In particular, the time at which the main belt of faster rotation reaches a latitude of around 25 degrees seems to coincide with solar activity becoming widespread in a new cycle. The strong poleward branch seen in Cycle 23 was not repeated in Cycle 24 ([Howe et al, 2013](#)). This seems to be associated with small but significant deceleration at higher latitudes, possibly related to the weaker polar

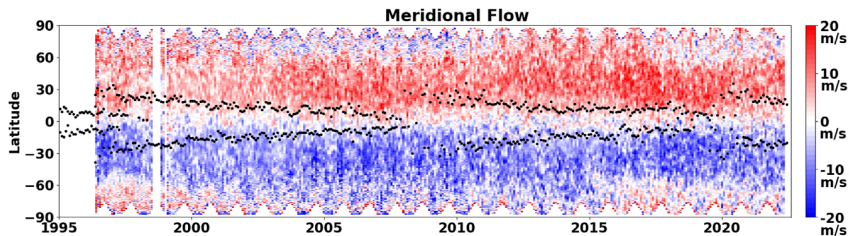
fields in Cycle 24 (Rempel, 2012). Figure 9 shows the flow residuals from inversions of GONG, MDI, and HMI data, as reported by Howe et al (2022). We note that the global helioseismic inversions can only show the North–South symmetric part of the flow pattern, while the surface measurements and those from local helioseismology (e.g. Komm et al, 2018; Lekshmi et al, 2018) can distinguish the two hemispheres. The relationship between the flow pattern and magnetic butterfly diagram is complex, but Lekshmi et al (2018) found that the asymmetry of the flows is related to, and is a leading indicator of, the magnetic asymmetry.

### 6.3 Meridional Flows

The solar meridional flow is the North-South motion of the plasma. At the surface this flow plays a critical role in the solar dynamo by transporting residual flux from ARs to the poles in order to generate the magnetic field to initialize the solar cycle. This plasma flow moves from the equator to the poles in each hemisphere with an amplitude of  $\sim 10 - 20 \text{ m s}^{-1}$ . The meridional flow is 1-2 orders of magnitude weaker than the differential rotation (relative velocities of  $\sim 200 - 250 \text{ m s}^{-1}$ ) and the convective flows (velocities of  $\sim 500 \text{ m s}^{-1}$  for supergranules and  $\sim 3000 \text{ m s}^{-1}$  for granules), making it the most challenging plasma flow to constrain. However, it is typically measured in the same manner as (and along with) the Differential Rotation. Independent measurement techniques can often give very different measurements, thought to be a consequence of the different depths sampled by each technique. For an in depth review, see Hanasoge (2022) and references therein.

High resolution continuous magnetic data from space-based observatories (i.e., SOHO/MDI and SDO/HMI) have ushered in a new era, paving the way for meridional flow measurements with unprecedented spatial and temporal resolution, revealing that the amplitude and structure vary with the solar cycle (Gizon, 2004; González Hernández et al, 2008a; Hathaway and Rightmire, 2010). The meridional flow measured by magnetic pattern tracking (Hathaway et al, 2022) for the last two solar cycles (see Figure 10) shows that the meridional flow is the strongest at solar cycle minimum and weakens during solar minimum. This weakening of the meridional flow was more pronounced during the stronger Solar Cycle 23 than it was for the weak Solar Cycle 24. The relative magnitude of this cycle dependent change in the flow speed is illustrated in the left panel of Figure 11. This modulation of the meridional flow by the presence of ARs may serve as a nonlinear feedback mechanism for regulating the solar cycle, as described in the next section.

Another aspect of the meridional flow, are the quite contentious of high latitude equatorward flows, sometimes referred to as polar counter-cells. The possibility of these flows was suggested by Ulrich (2010); Hathaway and Rightmire (2010), but later dismissed (Rightmire-Upton et al, 2012) as an instrumental artifact because they were not originally present in high resolution HMI data. However, more recent analysis (Hathaway et al, 2022) now



**Fig. 10** The evolution of the meridional flow measured by magnetic pattern tracking of MDI/HMI data over the last two cycles is shown in the left panel (adapted from [Hathaway et al \(2022\)](#)).

suggests these flows may have returned and are now observed in the HMI measurements (see Figure 10). As of yet, their appearance does not seem to have a solar cycle dependence but rather to occur somewhat sporadically. Resolving these structures unambiguously remains a challenge for several reasons. First and foremost, these flows only appear to be  $\sim 1 - 2 \text{ m s}^{-1}$ , an order of magnitude weaker than the already difficult to measure standard meridional flow. Secondly, they appear at latitudes above  $60^\circ$ , where the radial component of the magnetic field is not well resolved and signal to noise is small. While advancement in the measurement techniques may eventually shed some light on this ambiguous aspect of the meridional flow, a mission to directly observe the poles with a Doppler-magnetograph may ultimately be needed to fully resolve these controversial flows.

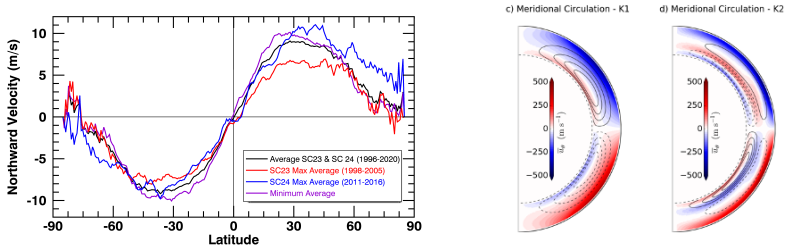
In order to satisfy mass conservation, the meridional flow must have an equatorward return flow at some depth, and thus is also referred to as the meridional circulation. In addition to generating the polar fields at the surface to initialize the solar cycle, the meridional circulation in the interior is believed to play an important role in setting the period of the cycle ([Dikpati and Charbonneau, 1999b](#)). Long thought to be a single circulating cell in each hemisphere, modern observations are challenging that notion ([Hathaway, 2012](#); [Zhao et al, 2013](#)). Understanding the implications of different possible configurations (e.g., see the right panel of Figure 11) of the meridional return flow in the solar interior has become an integral focus of dynamo modelers ([Bekki and Yokoyama, 2017](#); [Stejko et al, 2021](#)). For a more in depth discussion on this, refer to [Hazra et al \(2023\)](#).

## 6.4 Active Region Inflows

Inflows towards AR belts are observed by local helioseismic techniques (e.g., ([Gizon et al, 2001](#); [Zhao and Kosovichev, 2004](#); [Haber et al, 2004](#); [González Hernández et al, 2008b](#))) and these flows are observed from approximately  $10^\circ$  from the AR with amplitudes up to  $50 \text{ m s}^{-1}$  of horizontal velocities. The AR inflows modulate the N-S meridional flow which is on the same order of magnitude.

The explanation for the inflows is a geostrophic flow caused by increased radiative loss in the AR belt ([Gizon and Rempel, 2008](#)). [Gottschling et al](#)





**Fig. 11** The average meridional flow profiles for different time periods measured by magnetic pattern tracking of MDI/HMI data is shown in the left panel. The red (blue) represents the flow during cycle 23 (24) maximum. The purple line represents cycle minimum during Solar Cycle 23 and 24. The black line represents an average over both cycles. Two possible, idealized meridional circulation patterns are shown in the right panel, adapted from [Stejko et al \(2021\)](#) (have requested permission to reproduce image which we expect to have shortly): the classical single-cell with a deep return flow (labeled K1) and a double-cell circulation profile with a stronger return flow (labeled K2).

(2022) studied the evolution of the AR inflows and reports that converging flows are present one day prior to emergence and that these pre-emergence flows do not depend on latitude or flux. A prograde flow of about  $40 \text{ m s}^{-1}$  is found at the leading polarity during emergence ([Birch et al, 2019](#); [Gottschling et al, 2022](#)) with the increase in amplitudes of the inflows occurring between 1–4 days after emergence.

One important consequence of AR inflows is that they slow the flux diffusion, advection, and cancellation ([De Rosa and Schrijver, 2006](#)). Surface flux transport modeling highlights how AR inflows may modulate the amplitude of the global magnetic field in several ways. First, AR inflows can limit the latitudinal separation of the AR polarities, thus weakening of the contribution of a given bipolar region to the axial dipole field ([Jiang et al, 2010](#)), or second, by increasing the cross-equatorial transport of magnetic flux in weaker cycles, when sunspots emerge at lower latitudes, which ultimately strengthens the axial dipole field ([Cameron and Schüssler, 2012](#)). For further discussion of the implementation of AR inflows into surface flux transport models, and the results thereof, see [Yeates et al \(2023\)](#) discussion on fluctuating large-scale flows.

## 7 Short Term Solar Cycle Variability (AN)

There are two significant variations seen in solar cycle data on a time period shorter than the sunspot cycle: the quasi-biennial oscillation (QBO) (1–4 years) and Rieger-type variations (50–200 days). The QBO was observed as a roughly 2-year period ([Benevolenskaya, 1995](#)) in polar field components and also manifests as the double peak in sunspot numbers observed most easily near the maximum of the sunspot cycle. This double-peak is also known as the Gnevyshev gap ([Gnevyshev, 1967](#)). A thorough look at QBOs can be found in [Bazilevskaya et al \(2014\)](#) in which the following characteristics are

listed: the QBO timescales change within the range 1–4 years with no dominant frequency; they develop in each solar hemisphere independently, but are synchronous within one hemisphere with signatures in the atmosphere and beneath the photosphere based on helioseismology; they are observed in the photospheric magnetic field in phase with other solar activity indices; the QBOs are transferred into the interplanetary medium by the Sun’s open magnetic flux. Other stars show secondary, shorter cycles with smaller amplitudes than their primary cycle (Böhm-Vitense, 2007), and one explanation is that the dynamo is fed by the deep-seated and near-surface shear layer. Another explanation is that the QBOs are caused by the interaction between the dipole and quadrupole terms of the solar dynamo (Wang and Sheeley, 2003). The Rieger type variations were first observed in gamma-ray flare activity in the 1980s with a 154 d periodicity (Rieger et al, 1984). They were subsequently shown to have many shorter periodicities and be present in sunspot number and area and photospheric magnetic field indices (Bai, 2003). The physical mechanisms responsible for the Rieger type variability may be as simple as AR evolution (Vecchio et al, 2012) or a harmonic of the QBO (Krivova and Solanki, 2002). For a review of long-term modulation of the solar cycle, see Biswas et al (2023)

## 8 Helioseismic Mode Parameter Changes

The frequency (e.g. Woodard and Noyes, 1985; Libbrecht and Woodard, 1990; Elsworth et al, 1990), amplitude (e.g. Elsworth et al, 1993), and lifetime (Chaplin et al, 2000; Komm et al, 2002) of the acoustic modes used in helioseismology all vary with the solar cycle, and they are spatially and temporally correlated with magnetic activity on a wide range of scales, with changes in low-degree modes following global activity measures such as the sunspot number and 10.7 cm radio flux (RF), while in local helioseismology we can see changes down to the scale of ARs (Hindman et al, 2000; Rajaguru et al, 2001; Howe et al, 2004). Most of these changes are believed to arise quite close to the surface, where the cavity in which the modes propagate is modified directly or indirectly by the presence of activity and the excitation and damping of the modes influenced by magnetic fields. The exact interpretation of these changes is difficult, but, for example Basu and Mandel (2004), Verner et al (2006), and more recently Watson and Basu (2020) found evidence of solar-cycle changes in the signature that the helium ionization zone at  $0.98 R_{\odot}$  makes in helioseismic frequencies. These near-surface effects dominate the changes and make it difficult to use helioseismology to infer changes in the internal solar structure or magnetic fields.

While short-lived “local” modes can be used to study local, near-surface effects on timescales as short as a day, global helioseismology requires integration times of at least a few solar rotations to obtain the necessary precision to resolve the interior structure and dynamics, and this precludes the possibility, for example, of using helioseismology to follow the rise of an individual flux tube through the convection zone. On the timescale of a solar cycle, some

marginal effects have been reported. For example, [Baldner and Basu \(2008\)](#) and more recently [Basu \(2021\)](#) found small changes in the sound speed at the base of the convection zone. The latter work reports a change of about  $2 \times 10^{-5}$  in the squared sound-speed at the base of the convection zone between solar maximum and minimum, anticorrelated with the activity level; this is just below the  $3 \times 10^{-5}$  upper limit found by [Eff-Darwich et al \(2002\)](#). Small changes in the sound-speed near the base of the convection zone were also seen by [Chou and Serebryanskiy \(2005\)](#) using a different technique.

## 9 Discussion

The traditional index of solar activity is the (group) sunspot number, which however, is robustly defined before the middle of the 19th century and particularly poor in the first half of the 18th century. The research community works hard in reconciling the sunspot dataset.

While the solar-cycle phenomena in the Sun's outer layers can be studied in great detail using a variety of observing techniques, helioseismology reveals motions – and to a limited extent structural changes – far below the photosphere. The torsional oscillation and the meridional circulation penetrate throughout the convection zone and play a crucial role in the solar dynamo. Therefore, it is imperative that we determine the structure of the meridional circulation at depth and its evolution over the solar cycle.

While we are able to infer flows at depths the great majority of solar magnetic fields remain unobserved in the solar interior. The bipolar magnetic regions observed in the photosphere represent only the “tip of the iceberg”. Until we can reliably infer magnetic field strengths and dynamics in the interior, we must rely on observations at the surface to infer dynamics, amplitude and structure of the magnetic fields at depth.

To be considered successful, solar dynamo theories and simulations must be able to reproduce, to some degree, key observations. This includes the modulation of cycle amplitude as measured in the sunspot number, the observed large-scale flows, the adherence to Hale's law, the trends and inherent scatter in the tilt angles, the equator-ward migration of the active latitudes that produces the butterfly diagram, and the evolution of the polar fields.

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