Figure 1.

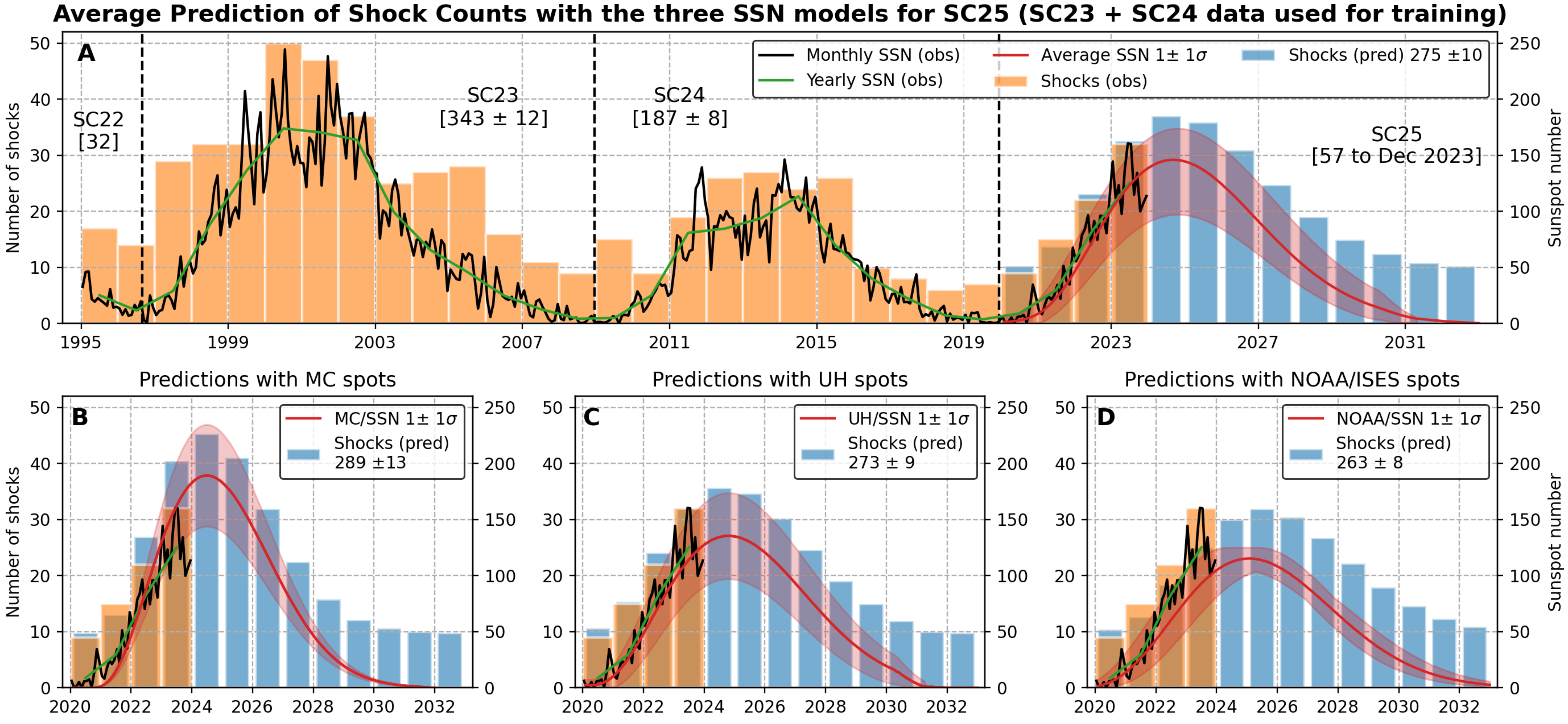
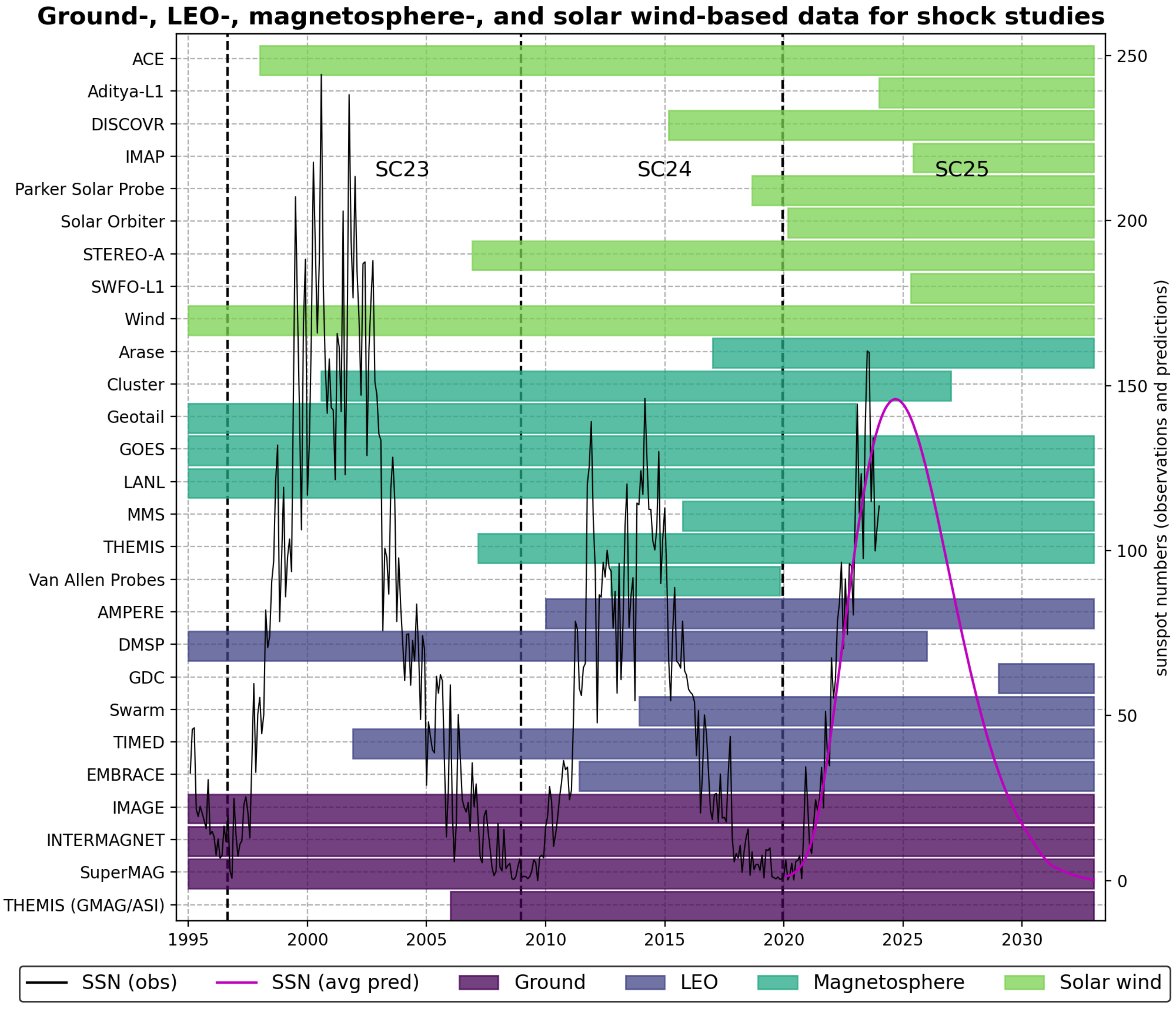

Average Prediction of Shock Counts with the three SSN models for SC25 (SC23 + SC24 data used for training)
A
Monthly SSN (obs)
Yearly SSN (obs)
Average SSN 1± 1σ
Shocks (obs)
Shocks (pred) 275 ±10
SC22
[32]
SC23
[343 ± 12]
SC24
[187 ± 8]
SC25
[57 to Dec 2023]
Number of shocks
Sunspot number
Predictions with MC spots
B
MC/SSN 1± 1σ
Shocks (pred)
289 ±13
Predictions with UH spots
C
UH/SSN 1± 1σ
Shocks (pred)
273 ± 9
Predictions with NOAA/ISES spots
D
NOAA/SSN 1± 1σ
Shocks (pred)
263 ± 8

Figure 2.


Ground-, LEO-, magnetosphere-, and solar wind-based data for shock studies
ACE
Aditya-L1
DISCOVR
IMAP
Parker Solar Probe
Solar Orbiter
STEREO-A
SWFO-L1
Wind
Arase
Cluster
Geotail
GOES
LANL
MMS
THEMIS
Van Allen Probes
AMPERE
DMSP
GDC
Swarm
TIMED
EMBRACE
IMAGE
INTERMAGNET
SuperMAG
THEMIS (GMAG/ASI)
SC23
SC24
SC25
1995
2000
2005
2010
2015
2020
2025
2030
0
50
100
150
200
250
sunspot numbers (observations and predictions)
SSN (obs)
SSN (avg pred)
Ground
LEO
Magnetosphere
Solar wind

Predicting Interplanetary Shock Occurrence for Solar Cycle 25: Opportunities and Challenges in Space Weather Research

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Key points

- Sunspot number and shock count data in SC23-24 are used with sunspot number predictions for SC25 in a supervised regression model to estimate shock occurrence in SC25

- Predictions indicate SC25 (275 events) will have ~48% more shocks in comparison to SC24 (187 events), but it will have fewer shocks in comparison to SC23 (343 events)

- SC25 will offer unprecedented opportunities for space weather research given the availability of many simultaneous data sets in the solar wind, geospace, and on the ground

Abstract

Interplanetary (IP) shocks are perturbations observed in the solar wind. IP shocks correlate well with solar activity, being more numerous during times of high sunspot numbers. Earth-bound IP shocks cause many space weather effects that are promptly observed in geospace and on the ground. Such effects can pose considerable threats to human assets in space and on the ground, including satellites in the upper atmosphere and power infrastructure. Thus, it is of great interest to the space weather community to 1) keep an accurate catalog of shocks observed near Earth, and 2) be able to forecast shock occurrence as a function of the solar cycle (SC). In this work, we use a supervised machine learning regression model to predict the number of shocks expected in SC25 using three previously published sunspot predictions for the same cycle. We predict shock counts to be around 275 ± 10, which is ~47% higher than the shock occurrence in SC24 (187 ± 8), but still smaller than the shock occurrence in SC23 (343 ± 12). With the perspective of having more IP shocks on the horizon for SC25, we briefly discuss many opportunities in space weather research for the remainder years of SC25. The next decade or so will bring

unprecedented opportunities for research and forecasting effects in the solar wind, magnetosphere, ionosphere, and on the ground. As a result, we predict SC25 will offer excellent opportunities for shock occurrences and data availability for conducting space weather research and forecasting.

Plain Language summary

Solar activity is quite correlated with sunspot numbers. Alternating periods between solar minima and minima, termed solar cycle, usually occur every ~11 years. As a result, researchers often attempt to predict sunspot occurrences for the following solar cycle. Solar perturbations occur more frequently during periods of high solar activity, and Earth-bound perturbations can disturb the Earth's magnetic field in geospace and on the ground, affecting satellites and power infrastructure. In this work, we use an artificial intelligence supervised model to predict the number of shock occurrences in the ongoing solar cycle (beginning December 2019) by training the model with observations of sunspots and solar perturbations in the previous two solar cycles (August 1996 to December 2019). Then, sunspot number predictions for the ongoing solar cycle are applied to the model, and predictions for the solar perturbations are obtained. We find that the number of predicted solar perturbations is ~50% higher than their occurrence number in the previous solar cycle (December 2008 to December 2019). Finally, we discuss how this relatively higher number of predicted solar perturbations can impact space weather research given the unprecedented number of data sets available in geospace and on the ground in the upcoming years.

1. Introduction

Interplanetary (IP) shocks are solar wind structures observed in the heliosphere (Kennel et al., 1985; Echer et al., 2003; Tsurutani et al., 2011). As IP shocks strike Earth, they cause perturbations frequently observed in geospace and on the ground, with significant implications for space weather. In geospace, IP shocks accelerate particles associated with solar energetic particle events (Tsurutani & Lin, 1985; Reames, 1999; Malandraki & Crosby, 2017); affect radiation belt dynamics (Kanekal et al., 2016, Baker et al., 2018); enhance field-aligned currents (Kasran et al., 2019; Shi et al., 2019); trigger ultra-low frequency (ULF) waves in the magnetosphere-ionosphere (MI) system (Zong et al., 2009; Hartinger et al., 2022); trigger magnetospheric substorms (Akasofu & Chao, 1980; Zhou & Tsurutani, 2001); and intensify ionospheric total electron content (TEC) (Tulasi Ram et al., 2019; Chen et al., 2023).

On the ground, IP shocks cause positive magnetic sudden impulses (SI^+) detected by low- and mid-latitude stations (Araki, 1977; Andrioli et al., 2006; Villante & Piersanti, 2011), and generate ground magnetic field variations that cause geomagnetically induced currents (GICs) (Carter et al., 2015; Oliveira & Ngwira, 2017), which can impact power transmission lines and infrastructure (Oughton et al., 2017). Therefore, keeping an updated and accurate IP shock data base with events observed upstream of the Earth at the Lagrangian L1 point is of paramount importance to the space weather community (Oliveira, 2023a).

IP shocks are frequently driven by solar wind perturbations termed coronal mass ejections (CMEs) (Bame et al., 1979; Gosling, 1997), and corotating interaction regions (CIRs) (Smith & Wolfe, 1976; Jian et al., 2006). For Earth-bound shocks observed at L1, CME-driven shocks usually have their shock normal vectors aligned with the Sun-Earth line (e.g., Byrne et al., 2010), whereas CIR-driven shocks usually have their shock normal vectors with large inclinations with respect to the Sun-Earth line following the Parker spiral structure (e.g., Balogh et al., 1999). Nearly frontal shock impacts usually trigger larger geomagnetic activity at Earth in comparison to highly inclined shocks due to highly symmetric magnetospheric compressions and the subsequent effective enhancements of the MI current systems in the former case (Oliveira & Samsonov, 2018; Oliveira, 2023b). Most of the phenomena discussed in this paper are also caused by sheaths and magnetic structures (clouds) following CMEs (Kilpua et al., 2019) and further compression effects by CIRs (Richardson et al., 2006), but our focus is on compression effects caused by shocks.

The Sun is an active star with a magnetic cycle which involves both amplitude modulation and polarity reversal in its magnetic field. The reversal of its magnetic field polarities occurs every ~11 years taking ~22-years on the average for a complete magnetic cycle which is known as the Hale cycle (Hale & Nicholson, 1925). Consequently, the Sun presents a cyclic modulation of sunspot number observations corresponding to ~11 years, which will be referred to as the solar cycle (SC) in this work (Hathaway, 2015). Solar activity cycle is produced by a magnetodydrodynamic dynamo mechanism working in its interior which involves interactions between plasma flows and fields (Hazra et al.,2023). Physical models and empirical techniques have been used with varying degrees of success in predicting the sunspot cycle amplitude (Bhowmik & Nandy 2018, Bhowmik et al., 2023) with a consensus emerging that SC25 is going to be a weak-moderate cycle slightly stronger than SC24 in terms of low sunspot numbers (Nandy, 2021). The dynamo produced magnetic fields emerge as sunspots through the Sun's surface giving rise to a plethora of activity, including energetic events that have space weather consequences thereby connecting variations that originate in the Sun to near-Earth space (Nandy et al., 2021, 2023).

At Earth, high geomagnetic activity usually occurs during periods of numerous sunspot observations (Hathaway, 2015; Vázquez et al., 2016; Chapman et al., 2020). Even though humanity has been observing sunspots by telescopes for four centuries (Stephenson, 1990; Vaquero & Vázquez, 2009), current solar cycle predictions can be quite challenging, frequently disagreeing with one another (Pesnell, 2015; Nandy, 2021). More important to our current work, IP shock occurrences are strongly correlated with sunspot observations, being more numerous during periods of solar maxima (Oh et al., 2007; Kilpua et al., 2015; Oliveira & Raeder, 2015). CME-driven shocks tend to follow the solar cycle, but CIR-driven shocks occur more often during descending phases of the solar cycle without clear correlations with sunspot numbers (e.g., Borovsky & Denton, 2006; Kilpua et al., 2015). Therefore, highly geoeffective and nearly frontal shocks tend to be more numerous during solar maxima (Oliveira, 2023a). Multi-solar-cycle analyses have shown that 3 out of 4 IP shocks are followed by magnetic storms with significant levels of geomagnetic activity (E.J. Smith et al., 1986; Wang et al., 2006; Mansilla, 2014; Fogg et al., 2023). Therefore, being able to predict IP shock occurrence as a function of solar cycle is clearly a very useful space weather forecasting tool (A.W. Smith et al., 2020).

In this work, we use the IP shock catalog provided by Oliveira (2023a) and sunspot number observations, along with previously published sunspot number predictions for SC25, to predict shock number occurrences for SC25. By using a supervised machine learning regression model, we estimate the number of shocks in SC25 to be higher than the occurrence in the notoriously weak SC24, but we find that SC25 will have fewer shocks in comparison to SC23. Moving forward, we briefly discuss the many opportunities for space weather research in the following years. Particularly in the ongoing solar cycle there are and there will be enhanced levels of simultaneous data sets collected in the solar wind, magnetosphere, ionosphere, and on the ground. One expects this period will provide unprecedented measurement numbers since the advent of the space era. As follows, Section 2 describes the data used in this article. Section 3 presents the prediction results. Section 4 briefly summarizes the main MI current systems affected by SI^+ events caused by shock compressions. Section 5 briefly discusses many topics with opportunities for space weather research, including possibilities of multipoint observations throughout the MI system and on the ground. Finally, Section 6 concludes the paper.

2. Data

In this work, we use the IP shock catalog provided by Oliveira (2023a) with 618 events from January 1995 to December 2023. The list covers nearly three decades of solar wind observations by Wind (Harten & Clark, 1995), Advanced Composition Explorer (ACE) (Stone et al., 1998), and Deep Space Climate Observatory (DSCOVR, a replacement to ACE) (Loto'aniu et al., 2022). The authors then celebrate nearly 30 years of observations from Wind, which accounts for 55% of the shock observations in the list as part of many other discoveries in astrophysics and heliophysics (Wilson III et al., 2021). The current list evolved from previous lists published by Oliveira and Raeder (2015), Oliveira et al. (2018), and Wang et al. (2010), along with online catalogs of shocks detected with Wind and ACE data located at http://www.cfa.harvard.edu/shocks/wi_data/ and http://www-ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html#shocks. The methodologies used to identify the shocks and calculate their properties, including data processing, are explained in detail by Oliveira (2023a).

The other primary data set used in this work are the sunspot number (SSN) observations provided by the World Data Center for Geomagnetism, Kyoto et al. (2015), and Long-term Solar Observations (WDC-SILSO), from the Royal Observatory of Belgium. The SSN catalog, spanning over three centuries, was revised by Clette et al. (2023), who recalibrated the data by updating previous scaling factors and introducing common symbols representing the data. The SSN data set is explained by Clette et al. (2023) and routinely updated by SILSO.

Monthly sunspot number data predictions for SC25 are provided by three different sources. The first sunspot predictions were performed by McIntosh et al. (2023), who used in their study the transition of the Hale Cycle terminator that marks the SC24-25 transition in the Sun's Hale cycle (McIntosh et al., 2020). Second, we use sunspot prediction data published by Upton and Hathaway (2023). Those authors used curve fitting methods applied to the first 3-4 years of sunspot observations in SC25, which was already under way in their analysis. Finally, the third sunspot prediction data set is provided by a panel formed by three different organizations, namely NASA, NOAA, and ISES (International Space Environment Service, https://www.swpc.noaa.gov/products/solar-cycle-progression). Henceforth, these data sets will be referred to as the monthly MC, UH, and NOAA predicted sunspot number data, respectively.

3. Shock number predictions for solar cycle 25

Shock count predictions for SC25 are obtained with a supervised regression analysis method commonly used in machine learning investigations (e.g., Rong & Bao-wen, 2018). This method involves applying a nonlinear function f to an N-dimensional list of observations x to obtain predictions of y such as $y = f(x) + \varepsilon$, where ε is a stochastic error or noise term (Bishop, 2016; Camporeale, 2019). In this work, we specifically use the Python *scikit-learn*[1] package (*LinearRegression* function of the *linear_model* module), which reduces errors with the least square method by minimizing the sum of the squares of the residuals (Pedregosa et al., 2011). Supervised linear regression functions are commonly used in space weather investigations, e.g., solar flare forecasting (Benvenuto et al., 2018), predictions of several ionospheric parameters including electron density and TEC (Sai Gowtam at al., 2019; Iban & Şentürk, 2022), predictions of storm sudden commencement occurrence following IP shocks (A.W. Smith et al., 2020), and predictions of thermospheric neutral mass density (Licata & Mehta, 2022). Since (on average) sunspot number predictions for SC25 are in between the observed sunspot numbers of SC23 and SC24, we choose the previous two solar cycles for training the model. After training, fitted coefficients are applied to the model along with yearly-averaged SSN predictions (MC, UH, and NOAA) for SC25 to obtain shock count predictions for the same solar cycle.

[1] https://scikit-learn.org/stable/modules/classes.html#module-sklearn.linear_model

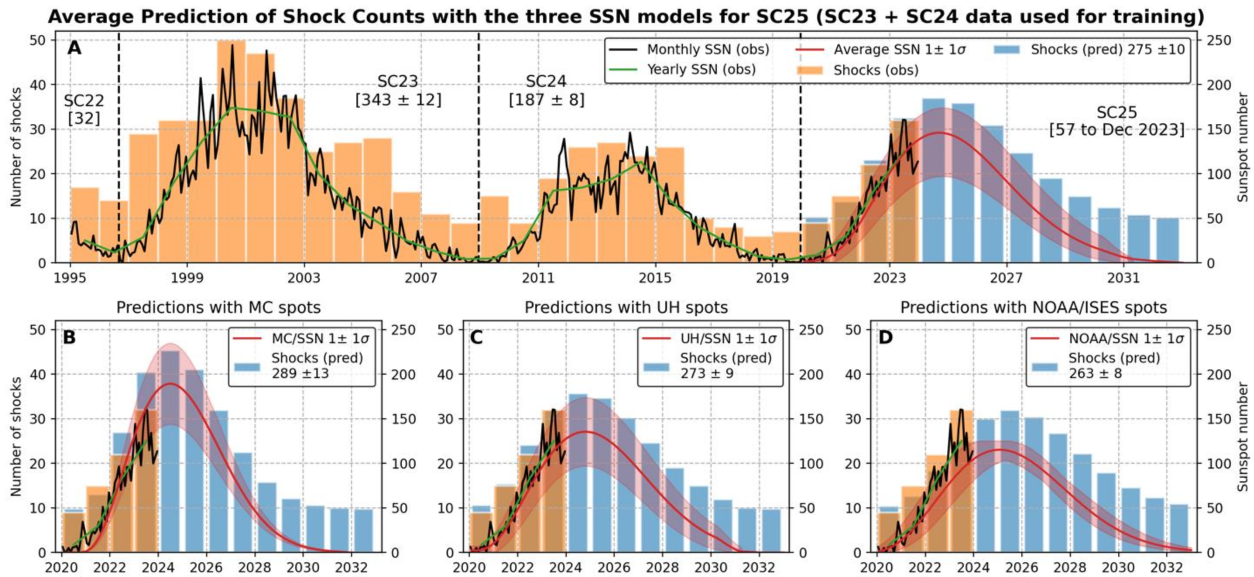

Figure 1. All panels: observed SILSO sunspot number (SSN, monthly, black; yearly, green) data; yearly shock counts from the data base provided by Oliveira (2023a) (fainted orange bars). These data are represented from 1995 to 2023 (panel A), and from 2020-2032 (panels B-D). In all panels, predictions of shock counts (fainted blue bars) for solar cycle 25 were obtained with sunspot number predictions provided by McIntosh et al. (2023) (MC, panel B); Upton and Hathaway (2023) (UH, panel C); and NOAA (panel D). The thick red lines indicate monthly sunspot number predictions obtained from the respective source (the highlighted red regions indicate $\pm 1\sigma$ estimations). Fainted blue bars in panel A show the average shock number predictions for solar cycle 25, whereas the thick red line indicates the mean sunspot number value obtained from the three sources.

In all panels of Figure 1, the solid black and green lines represent, respectively, SSN monthly and yearly observations, and the orange bars indicate yearly shock counts from the Oliveira (2023a) catalog. Panel A shows data from January 1995 to December 2023, whereas panels B-D show data from January 2020 to December 2023. The vertical dashed black lines indicate the limits from the end of SC22 to the beginning of SC25. The thick red lines indicate the MC sunspot number predictions (panel B); the UH sunspot number predictions (panel C); and the NOAA sunspot number predictions (panel D). The highlighted areas in these panels indicate $\pm 1\sigma$ estimations for the corresponding sunspot number prediction. The same in panel A indicates the mean sunspot number predictions obtained from the predicted data shown in panels B-D (thick red lines). The SC25 shock count predictions are represented by the light blue bars in panel B obtained from MC sunspot data; panel C, UH sunspot data; and panel D, NOAA sunspot data. The light blue bars in panel A indicate the mean of the three shock count predictions for SC25. The maximum monthly sunspot predictions by the models are: 184 ± 17 (MC), 134 ± 8 (UH), and 115 ± 6 (NOAA), and the average is 144 ± 10. Note this comparison is summarized in Table 1. The Supporting Information brings results obtained from similar analysis when SC23 and SC24 SSN and shock occurrence data are used for training, as well as further validations with historical F10.7 solar flux index data (1964 to 2023).

Table 1 Summary and comparison of the statistical results obtained for observations (SC23 and SC24) and predictions (SC25) for sunspot numbers (white rows) and shock occurrences (grey rows), respectively. MC represents the McIntosh et al. (2023) predictions; UH, Upton and Hathaway (2023) predictions; and the NOAA predictions. In the rightmost column, observation values are shown in normal text (SC23 and SC24), whereas the predicted mean values are shown in bold text (SC25).

	MC (# ± 1σ)	UH (# ± 1σ)	NOAA (# ± 1σ)	Obs./**Pred.** (# ± 1σ)
Max Sunspots SC23	-	-	-	244 ± 10
Shocks SC23	-	-	-	343 ± 12
Max Sunspots SC24	-	-	-	146 ± 6
Shocks SC24	-	-	-	187 ± 8
Max Sunspots SC25	**184 ± 17**	**134 ± 8**	**115 ± 6**	**144 ± 10**
Shocks SC25	**289 ± 13**	**273 ± 9**	**263 ± 8**	**276 ± 10**

The MC shock count predictions are the highest (289 ± 13) because the MC sunspot predictions are the highest. Moderate shock count predictions are obtained with UH sunspots (273 ± 9), whereas the lowest shock predictions are obtained with NOAA sunspots (263 ± 8). Therefore, shock counts are predicted to be ~40%-55% higher than the shock number occurrence in SC24 (Table 1), being on average ~47% higher. Thus, regardless of the sunspot prediction data used, the numbers of shocks occurring in SC25 are predicted to be higher in comparison to SC24 (187 ± 8), but lower in comparison to SC23 (343 ± 12). Additionally, our predictions indicate that the number of shocks in SC25 will be closer to the number of shocks in SC23 in comparison to the number of shocks in SC24 (Table 1). These results differ from the conclusions of Gopalswamy et al. (2023), who predicted that the number of CMEs observed in SC25 will also be in between the CME observation numbers of SC23 and SC24, but closer to the lower limit (i.e., SC24). Our predictions also indicate a larger number of shocks occurring during the declining phase of SC25, in agreement with SC23. Such shocks may most likely be driven by CIRs (Kilpua et al., 2015), which are not accounted for in Gopalswamy et al. (2023)'s analysis.

As shown in Figure 1A, after 2020, the average sunspot number prediction (thick red line) agrees well with sunspot observations being performed until December 2023 (monthly and yearly observations). These comparisons bring confidence to our results, as can be clearly seen in the remarkable agreement between the number of observed (78) and (average) predicted (80) shocks from 2020 to 2023 (fainted orange and blue bars, respectively).

The number of shocks predicted for SC25 are expected to be observed at low heliospheric distances, namely the Lagrangian L1 point. Based on the knowledge of shocks observed at 1 AU, we expect that the shocks observed in SC25 will mostly be driven by CMEs in comparison to CIRs (Kilpua et al., 2015). We expect this to be the case because CIR-driven shocks are more likely to be observed farther in the heliosphere, beyond 3-5 AU (Smith & Wolfe, 1976; Richardson, 2018). Additionally, the predicted CME-driven shocks are expected to be stronger than the CIR-driven shocks in SC25 (Kilpua et al., 2015).

4. MI current response to SI^+ events at different latitudes and longitudes

The first MI current promptly affected by IP shock impacts is the dayside magnetopause current, located at distances > 10 Earth radii from the ground (Chapman & Ferraro, 1931; Cahill & Amazeen, 1963). During SI^+ events, the horizontal component of the geomagnetic field increases at different latitudes due to changes in the magnetopause current associated with the dayside compression of the magnetosphere (Burton et al., 1975; Russell et al., 1994; Fiori et al., 2014). Additionally, there exist two ionospheric current systems around 100 km altitude that are usually associated with more latitudinally-localized geomagnetic perturbations that are significantly enhanced by shocks. Such currents are located at auroral regions, namely the auroral electrojet current, which is intensified by enhancements of the Region 1 current (Araki, 1977; Cowley, 2000). The other ionospheric current system affected by shocks is located at a region centered at $\pm3^{o}$ from the dip magnetic equator. This region carries an electric current named the equatorial electrojet current, which shows strong diurnal variations, with maxima typically observed during the early afternoon sector (Forbes, 1981: Lürh et al., 2004). The equatorial electrojet current is directly proportional to the Cowling conductivity through electron densities and the zonal electric field (Cowley, 2000; Kelley, 2009).

During SI^+ events, the sudden compressions of the current systems described above cause prompt variations of the horizontal component of the geomagnetic field, namely ground dB/dt variations. These geomagnetic perturbations are linked through Faraday's law (curl $\mathbf{E} = -d\mathbf{B}/dt$) to GICs (Viljanen, 1998; Boteler & Pirjola, 2017). Although dB/dt is commonly accepted as one of the most important space weather drivers of, and are frequently used as a metric for, GICs (Pulkkinen et al., 2017; Dimmock et al., 2020), actual GICs show spectral dependence of dB/dt variations due to their coupling with the three-dimensional solid Earth conductivity (Oliveira & Ngwira, 2017; Liu et al., 2019; Kelbert & Lucas, 2020; Juusola et al., 2020). Auroral dynamics is also an important space weather driver of GIC effects at high latitudes (Tsurutani & Hajra, 2023; Wawrzaszek et al., 2023). GICs can cause detrimental effects to many ground artificial conductors such as power transmission lines and infrastructure (Gaunt & Coetzee, 2007; Pulkkinen et al., 2017), oil/gas pipelines (Campbel, 1980; Gummow & Eng, 2002), railways (Thaduri et al., 2020; Patterson et al., 2023), and even submarine cables (Chakraborty et al., 2022; Boteler et al., 2024). Historical data also show that GICs caused significant damage to old telegraph wires during intense auroral activity events (Barlow, 1849; Arcimis, 1903; Silverman, 1995; Hayakawa et al., 2020a). Therefore, identifying current systems that cause GICs and being able to predict solar wind drivers (including IP shocks) that intensify currents in the MI system is of paramount importance to space weather applications and forecasting.

The geomagnetic field is often approximated to a geocentric dipole field in many regions of the magnetosphere (Laundal & Richmond, 2017). However, as shown by observations (Pavón-Carrasco & De Santis, 2016) and modeling (Finlay et al., 2020; Alken et al., 2021) of the Earth's magnetic field, there is a region where the geomagnetic field is notably weaker in comparison to the dipole field. This region is known as the South Atlantic Anomaly (SAA) region, which has been moving from South Africa to South America at a mean rate of 0.17°/year (westward) and 0.03°/year (southward) in the past four centuries (Hartmann & Pacca, 2009). The radiation belts within SAA reach the lowest altitudes (Vernov et al., 1967; Gledhil, 1976; Heirtzler, 2002). For this reason, the SAA is a region where intense energetic particle fluxes (H.S. Zhao et al., 2020; Kovář & Sommer, 2021) can pose serious threats to satellites that fly through it (Vernov et al., 1967; Heirtzler et al., 2002; Schaeffer et al., 2016; Kovář & Sommer, 2021). However, recent research performed by Liu et al. (2024) with auroral intensity observations indicates that the weakened magnetic field in the SAA subsequently weakens the corresponding longitudinal extension of the auroral structure in the SAA. This effect is not observed in the northern hemisphere. Auroral and equatorial electrojets in the SAA may contribute to ground dB/dt variations associated with GICs on the ground in the corresponding latitudes and longitudes.

In the next section we discuss how past, current, and future data sets in the solar wind, geospace, and on the ground can be used to investigate the response of the current systems discussed above to shocks. The focus is on how the predicted higher number of shocks in SC25 in comparison to SC24 may provide some new opportunities of research in the solar wind, magnetosphere, ionosphere, and on the ground.

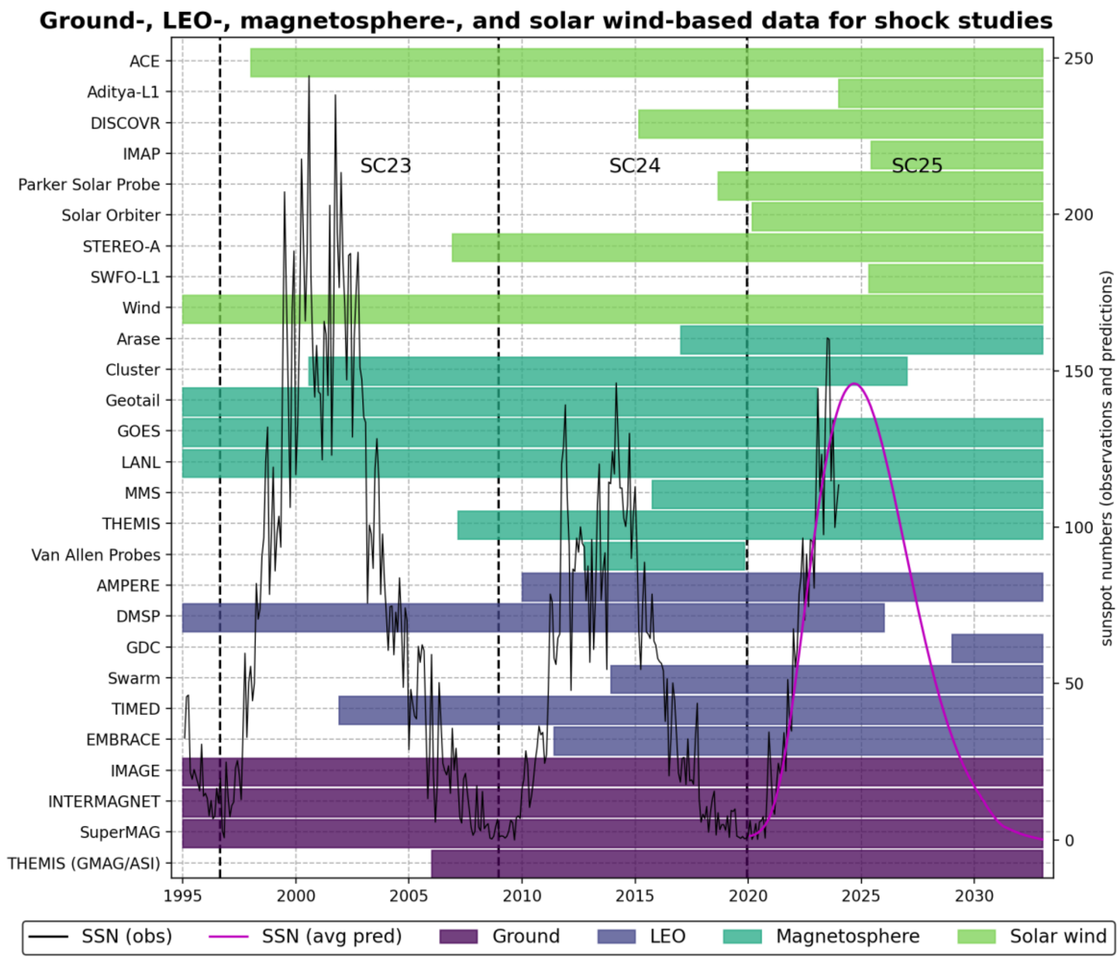

Figure 2. Chronological durations of operation and commission times for 25 ground magnetometer arrays and satellite missions whose data can be used in interplanetary shock and space weather research. Satellite missions shown in the plot operate/operated in low-Earth orbit (ionosphere and thermosphere), in the magnetosphere and solar wind (see legend). The black dashed vertical lines mark the end of SC22 to the beginning of SC25. By the end of SC25, there will be more than 20 data sets available for shock and space weather research on the ground and in space as never seen in six decades of shock studies since the first observations of collisionless shocks in the solar wind in early 1960's (Oliveira and Samsonov, 2018). The solid black and magenta lines on top of the bars indicate sunspot observations (January 1995 to December 2023) and mean sunspot predictions (January 2020 to December 2032).

5. Discussion

Here, we briefly discuss how an increased number of shocks (and possibly stronger events) observed at L1 can contribute to space weather research in different regions of the heliosphere (solar wind, magnetosphere, ionosphere, and ground). We also highlight the importance of multi-instrument studies concerning geomagnetic activity triggered by shocks considering the multi-data set availability for SC25, as shown in Figure 2. The figure shows commission times of satellites (solar wind, magnetosphere, ionosphere) and time spans of ground magnetometer deployments for many data sets during the time span of the shock catalog (Oliveira, 2023a) including the rising phase of SC25 (observations) and predictions. Some of these missions and ground data will be discussed with some detail below. In the discussion, except for missions that have already ended (Geotail and Van Allen Probes), and missions that are scheduled to be decommissioned in the following years (Cluster and DMSP), all missions are assumed to be carrying on their observations throughout SC25.

5.1 Solar wind

As a highlight mission featuring in this work, Aditya-L1, launched by the Indian Space Agency and already operational, is the first Indian mission to study the Sun (Somasundaran & Megala, 2017; Tripathi et al., 2023). Aditya-L1 carries two in-situ experiments, the charged particle detectors for measuring the solar wind (ions and electrons) and energetic particles (primarily protons and alpha particles), described by Goyal et al. (2018), and one for interplanetary magnetic field (IMF) measurements, described by Yadav et al. (2018). Some of the main goals of Aditya-L1 are to study the physics of the solar corona and its heating mechanism; the origin, development, and dynamics of CMEs; understand the origin and acceleration mechanism of solar wind and energetic particles in the solar wind; and detect/characterize space weather drivers, including IP shocks.

NOAA's Space Weather Follow-On (SWFO) mission at L1 (SWFO-L1) will also monitor the solar wind (Vargas et al., 2024). By gathering real-time data at the L1 point, NOAA aims to improve the accuracy and timeliness of space weather forecasts. The SWFO-L1 instruments are expected to be part of the broader SWFO mission, including observations in geostationary orbits by Geostationary Operational Environmental Satellite - Series U (GOES-U), which was planned for launch in 2024 (Vargas et al., 2024). The deployment at the L1 point signifies NOAA's commitment to advancing space weather forecasting capabilities, leveraging strategic positioning to gather critical data about solar activity before it impacts Earth's space environment.

NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission is designed to investigate the boundary between our solar system and interstellar space (McComas et al., 2018). IMAP's primary objective is to study the heliosphere. Specifically, IMAP aims to understand the interactions between the solar wind and the interstellar medium as well as the dynamics of cosmic rays. IMAP is planned to be launched aboard a SpaceX Falcon 9 rocket in 2024. Since IMAP will also be placed in a highly elliptical orbit around the Sun-Earth L1 point, it will provide measurements of solar wind properties and IMF as well.

Aditya-L1, SWFO-L1, and IMAP solar wind plasma parameter and IMF data will significantly contribute to the maintenance of the IP shock catalog maintained by Oliveira (2023a). Those spacecraft will join Wind and DSCOVR in providing data for shock identification and computation of shock properties. The missions join L1 at an important time because the Wind instruments, though still operational, are aging[2], and our predictions indicate more shocks will hit L1 in SC25 in comparison to SC24; therefore, having stable solar wind monitors at L1 is of paramount importance to space weather research, as well as predicting and forecasting solar wind events. In addition to Wind, DSCOVR, Aditya-L1, SWFO-L1, and IMAP at L1, Solar Orbiter (Müller et al., 2020), and STEREO (Solar Terrestrial Relations Observatory) (Kaiser, 2005) will be used for combined observations to compute shock properties in SC25. For example, Laker et al. (2024) used combined Solar Orbiter and STEREO observations to predict the arrival at Earth of a CME with high accuracy.

IP shocks also play a crucial role in CME-CME interaction. If a shock from the leading CME penetrates the preceding CME, it provides a unique opportunity to study the evolution of the shock strength and structure and its effects on preceding CME plasma parameters (Lugaz et al., 2005; Möstl et al., 2012; Liu et al., 2012). For instance, Wang et al. (2003) showed that an IP shock can cause an intense southward magnetic field of long duration in the preceding magnetic cloud, which is crucial for space weather predictions (Jurac et al., 2002). Srivastava et al. (2018) reported a case of interacting CMEs observed on 13-14 June 2012 in which the shock of the following CME led to a strong SI^+ (~150 nT) with a long duration rise time of 20 hrs. Mishra et al. (2021) suggested that the structures associated with interacting CMEs, possibly resulting from large-scale deflections, may arrive at larger longitudinally separated locations in the heliosphere. Multipoint in situ analyses highlighted that the characteristics of the same shock, propagating in a pre-conditioned medium, can be different at distinct longitudinal locations in the heliosphere (Kilpua et al., 2011). Thus, enhanced observations of IP shocks in SC25 and many solar wind monitors (Figure 2) will provide a unique opportunity with multi-point observations to study IP shocks that arrive at different locations in the heliosphere, including L1.

Accurately estimating the occurrence rate of IP shocks during different solar cycle phases is important for heliophysics space mission design. For example, a major goal of the Solar WInd Multi-Scale (SWIMS) mission, previously known as Seven Sisters (Nykyri et al., 2023), is to determine the intermediate and large-scale structure of the solar wind. For the first time, SWIMS will be able to determine simultaneously the radial evolution and azimuthal structure of CMEs, as well as capture the multi-scale properties of the heliospheric current sheet (Ness & Wilcox,

[2] https://spacenews.com/noaa-warns-of-risks-from-relying-on-aging-space-weather-missions/

1964; E.J. Smith et al., 1978; Tsurutani et al., 1995), stream interaction regions and determine the physical processes responsible for particle acceleration in these structures. The present machine learning IP shock prediction tool can be used to achieve a more accurate estimate of the amount of shock crossings during different mission phases. This is necessary to estimate the volume requirements for the burst mode data, design on-board data storage, and plan communications and downlinking schedule.

The Lunar Gateway is a space station scheduled to orbit the Moon in a Near Rectilinear Halo Orbit (NRHO) by the end of 2025 (Fuller et al., 2022). As a multi-international agency endeavor, Gateway is a key part of NASA's Artemis program, which aims to establish human presence on the Moon. Moreover, Gateway will serve as a space port to facilitate future lunar and Mars missions and deep space exploration (M. Smith et al., 2020). HERMES (Heliophysics Environmental and Radiation Measurement Experiment Suite) is the space weather instrument suite that will be continuously monitoring the lunar space environment on Gateway (Paterson et al., 2021). HERMES will support the Artemis program by providing space weather observations of the Earth's magnetospheric variabilities and solar wind interactions with the Moon. For example, Omidi et al. (2023) have demonstrated with observations and simulations that IP shocks significantly impact local density and accelerate energetic ions in the lunar tail. Since these shocks may affect the objectives of the Artemis project, it is important to be able to predict shock occurrences in SC25, even though shocks observed at lunar distances are weaker in comparison to shocks observed at L1 (Halekas et al., 2014). Moreover, the assessment of space weather phenomena is clearly highly relevant for sustainable lunar exploration activities (Fogtman et al., 2023) but are also required for future missions to Mars (Green et al., 2022). Therefore, our predictions indicate that a higher number of shocks in SC25 can generate an impact on the Artemis program objectives and on future deep space exploration missions.

5.2 Magnetosphere

Oliveira et al. (2020) and Oliveira et al. (2021) have used Magnetospheric Multiscale (MMS) magnetic field data to compute the average propagation direction of compression waves induced by shock impacts with different orientations on the magnetosphere. The authors demonstrated that the propagation direction of the compression waves is quite aligned with the propagation direction of the inducing shock impacting the magnetosphere (Collier et al., 2007). Oliveira et al. (2020) and Oliveira et al. (2021) used this supporting information provided by MMS observations in the magnetosphere to show that the subsequent geomagnetic activity following the shocks (e.g., ULF wave activity and ground dB/dt variations) were indeed triggered under very asymmetric magnetospheric compression states.

However, a statistical follow-on investigation to probe the conclusions of Oliveira et al. (2020) and Oliveira et al. (2021) is difficult to be undertaken with current data due to two reasons: first, MMS was launched during the declining phase of SC24 (September 2015), and second, SC24 was one of the weakest solar cycles since the Dalton Minimum (Figure 1A; see also Hayakawa et al., 2020b; Clette et al., 2023). Therefore, with an increased number of shocks in SC25, such a statistical analysis should be possible, eventually including magnetopause crossings observed by MMS (Dong et al., 2018; Oliveira et al., 2020; 2021). A statistical picture of the two-dimensional structure of current sheets associated with partial magnetopause crossings performed by MMS (Dong et al., 2018) may also be possible.

As mentioned in the introductory section, IP shocks are known to accelerate charged particles across its surface. Additionally, IP shocks can inject energetic electrons in the magnetosphere very rapidly, within a time scale of a few minutes or a few electron drifts (Blake et al., 1992; Baker et al., 2018; Kanekal & Miyoshi, 2021). Such energetic particles play a significant role in affecting the chemistry of the upper atmosphere with further space weather implications (Turunen et al., 2016). Although the Van Allen Probes were a successful mission to study the radiation belts (Mauk et al., 2014), Van Allen Probes operated during the relatively weak SC24 period when only ~120 shocks were observed at L1 (Oliveira, 2023a). Despite this, Schiller et al. (2016) were able to carry out a statistical analysis of IP shock effects on the subsequent energy of the injected electrons observed by Van Allen Probes and found that the highest energetic electrons occurred as a response to the strongest shocks. These results suggest that IP shocks most likely control energetic electron injections since the strongest shocks tend to be the most nearly frontal shocks (Oliveira et al., 2018). Therefore, three questions are still open: how do shock impact angles 1) affect the time duration of energetic electron injections into the magnetosphere; 2) control energetic electron injections as a function of L-shell; and 3) control the intensity of the energetic electron injections into the magnetosphere? In contrast, the exploration of Energization and Radiation in Geospace (ERG) mission, better known as Arase, a Japanese mission to study the radiation belt environment, was launched in 2017 and is still healthy (Nakamura et al., 2018; Miyoshi et al., 2022). Although some conjugate observations with Van Allen Probes and Arase data were conducted (Miyoshi et al., 2022), Arase will be able to study energetic particle injections as a function of shock impact angles with a more robust statistical sample including more and stronger shocks than the events observed by Van Allen Probes in SC24. Because Arase performs observations at higher L-shells in comparison to Van Allen Probes (Miyoshi et al., 2022), Arase will be able to sample energetic particle injections in a larger array of L-shells in comparison to Van Allen Probes.

IP shocks can also significantly impact energetic ion compositions (H^+, O^+, and He^+) within the Earth's magnetosphere. For example, Yue et al. (2016) investigated, with Van Allen Probes data when the satellites were near the equator, the increase in low-energy ions (<100 eV) associated with field enhancements caused by shocks and the related ULF wave activity. Also, observations at high latitudes have shown that sharp and sudden changes in the solar wind dynamic pressure associated with IP shocks can enhance ion outflow (e.g., Fuselier et al., 2001; Moore et al., 1999). Ionospheric outflowing ions are one of the two sources of ions in the Earth's magnetosphere (Kistler et al., 2023, and references therein). Ion outflow can come from different latitudes in the ionosphere and populate different regions in the magnetosphere. For example, at high latitudes, in the domain of open field lines, outflowing ions can reach the lobes, mantle, and cusp (e.g., K. Zhao et al., 2020), and at lower latitudes, in the domain of closed field lines, they reach the plasma sheet and the inner magnetosphere (e.g., Gkioulidou et al., 2019). Outflowing ions often have thermal energies up to a few eV, but more energetic ion outflows with energies of tens to hundreds of eV are also observed (Peterson et al., 2008). The complicated and often multi-step processes involved in generating ion outflows are, in part, the consequence of the external coupling of the magnetosphere with the solar wind. Moreover, studies of ion outflow and ion composition in the magnetosphere are crucial because cold ions can be transported and heated, influencing the ring current. The presence of cold ions can also influence reconnection rates on the dayside and affect the properties and occurrence of plasma waves such as Electromagnetic Ion Cyclotron (EMIC) waves. As shown by Zong et al. (2012), increases in ion energy spectra from ~10 eV to ~40 eV are strongly correlated with the electric and magnetic field components of ULF waves. Thus, with an enhanced number of shocks in SC25 and Arase data covering at least the extension of SC25, a statistical study to investigate how changes in energetic ion composition and their subsequent effects on the ring current and dayside reconnection may be possibly accomplished.

5.3 Ionosphere

The increase or decrease in number of shocks impacting the Earth's magnetosphere nearly directly translates into the number of geomagnetic storms which influences ionospheric variability differently in high, mid, and equatorial latitude regions. In case of increased shock numbers, the consequences on ionospheric variability are diverse ranging from increased occurrence of ionospheric storm effects (e.g., Matamba et al., 2015) to more complexity in ionospheric parameters' modelling such as TEC on both regional and global scales (e.g., Uwamahoro & Habarulema 2015). Anticipating the nature of this complexity is difficult as different storms are driven by different physical processes. It is, however, known that increases in electron density or TEC from its background values due to IP shock impacts (usually known as the positive storm effect) are more difficult to model than negative storm effects which are known to be linked to changes in thermospheric composition (e. g., Fuller-Rowell et al., 1996). Additionally, depending on local daytime, prompt penetrating electric field of magnetospheric origin can significantly alter equatorial electrodynamics. During local daytime, this leads to enhanced eastward electric fields in the equatorial regions which increases the vertical $\mathbf{E} \times \mathbf{B}$ drift resulting in expansion of equatorial ionization anomaly towards mid latitudes through equatorial ionospheric fountain effects (e.g., Tsurutani et al., 2004). Partly coupled to this, a major determinant of the occurrence of post-sunset ionospheric irregularities is the equatorial zonal electric field. Changes in the polarity and magnitude of this electric field have implications on either enhanced occurrence or suppression of these ionospheric irregularities.

A stronger solar cycle with higher number of strong shocks could contribute to the understanding of drivers triggering magnetospheric super substorms, events characterized with SuperMAG westward auroral electrojet indices SML < -2,500 nT (Hajra et al., 2016; Tsurutani & Hajra, 2015; Hajra & Tsurutaini, 2018). Although super substorm occurrences depend on pre-condition states of the magnetosphere such as intense negative IMF B_z being sustained for some time (Craven et al., 1986; Zhou & Tsurutani, 2001; Yue et al., 2010), super substorms do not necessarily take place during magnetic storms of any intensity (Tsurutani et al., 2015; Tsurutani

& Hajra, 2015; Hajra et al., 2016; Zong et al., 2021). Additionally, very intense GIC peaks at high latitudes occur during super substorms (Oliveira et al., 2021; Tsurutani & Hajra, 2021; 2023; Oliveira et al., 2024a,b). Understanding triggering mechanisms of super substorms is important because intense nighttime energetic particle injections, associated with large-scale, localized ground dB/dt variations usually occur during such events (Ngwira et al., 2018; Oliveira et al., 2021; 2024a,b). Therefore, a higher number of shocks observed during SC25 (including more fast, nearly frontal shocks) will most likely contribute to the understanding of super substorm triggering by shocks.

Multi-spacecraft measurements such as from the upcoming NASA Geospace Dynamics Constellation (GDC) mission (Rowland et al., 2023) can complement ground-based magnetometer measurements and further expand our understanding of the spatial and temporal variations of the MI current systems and waves driven by IP shocks. For example, AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) is currently used to provide global images of radial (approximate field-aligned) currents by fitting Iridium multi-satellite magnetometer measurements to a set of base functions (Anderson et al., 2000). This technique is appropriate to sample the larger scale and longer lasting currents excited by IP shocks (e.g., Shi et al., 2019; Vines et al., 2023; Oliveira et al., 2024a,b), but not for the more rapid and finer spatial scale currents and waves mentioned above. However, by incorporating additional satellite magnetometer measurements such as from GDC, thus expanding in situ magnetometer coverage, these global currents could potentially be provided more frequently and for smaller spatial scales (Vines et al., 2023), thus lending themselves to exploring the more rapid and finer scale variations related to shocks. As another example, when multi-satellite constellations such as GDC are in a string-of-pearls configuration, their repeated and rapid sampling of the same spatial region can be used to examine more rapid and localized disturbances and waves excited by IP shocks, particularly when combined with contextual ground-based observations such as magnetometers or radars (e.g., Pitout et al., 2015). Although GDC was originally planned to launch in 2029, it may be launched later due to current funding restrictions.

The Electrojet Zeeman Imaging Explorer (EZIE) mission (Yee et al., 2021; Laundal et al., 2022) is a NASA mission that aims to study the ionospheric auroral and equatorial electrojets. The three-satellite mission, planned to be launched October 2024, will use advanced imaging techniques to study the structure and dynamics of the geomagnetic field within the ionosphere. As described by Yee et al. (2017), EZIE will use the Zeeman splitting (Zeeman, 1897) of the O_2 thermal emission line at frequency of 118 GHz around 80 km altitude. Then, a vector magnetic residual $\delta\mathbf{B}$ will be obtained by subtracting the ambient magnetic field computed with a geomagnetic field model, from which an equivalent ionospheric current solution is derived to investigate the structure and evolution of currents with scale sizes of ~100-1000 km, including longitudinal variations (Yee et al., 2021; Laundal et al., 2022). By observing these currents, EZIE will improve our understanding of the mechanisms behind space weather phenomena and how they, e.g., affect satellite communications and navigation systems. Since EZIE is expected to be in orbit for 18 months and considering the spacecraft will be launched in late 2024, and accounting for the commissioning, from Figure 1, we estimate EZIE will observe 45-65 shocks with an average of 55 events for SC25 (early 2025 to mid 2026). These numbers are higher than the number of events observed in SC24 (41) in a similar period (early 2014 to mid 2015).

Therefore, we predict EZIE will have an opportunity to study a reasonable number of shock-induced substorms, hopefully including some super substorm events described above because SC25 will be stronger than SC24.

5.4 Ground magnetometer response and GICs

SC25 presents several opportunities for advancing our understanding of the complex spatial and temporal variations in the ground magnetic response to IP shocks, including the excitation of ULF waves. For example, Araki et al., (1997) noted when studying the SI^+/sudden commencement event from the 24 March 1991 IP shock/storm that 1 minute data was not adequate to characterize the event. Many other studies have reinforced this point, finding that 1-min samples are not sufficient for studying the rapid temporal variations, including pulsations, that often occur in response to IP shocks (e.g., Oliveira et al., 2020; Hayakawa et al., 2022; Hartinger et al. 2023). SC25 represents an opportunity to make progress in this area because more ground magnetometers are now collecting and publishing data with 1-s sampling intervals in comparison to past solar cycles (e.g., Love & Finn, 2011; Gjerloev, 2012), enabling more routine measurements of the rapid temporal variations excited by shocks. However, more magnetometers with denser spatial coverage are still needed to examine mesoscale currents and waves related to shocks that are localized in latitude or longitude (e.g., Araki et al., 1997). A notable gap includes mid- and low-latitude regions in North America, where magnetometer spatial coverage is relatively sparse yet large geomagnetic disturbances and GICs related to shocks can occur (e.g., Kappenman, 2003; Caraballo et al., 2019).

A higher number of IP shocks observed in SC25 could provide an opportunity to accomplish a robust statistical study using European quasi-Meridional Magnetometer array (EMMA) data (Lichtenberger et al., 2013; Del Corpo et al., 2019). EMMA, consisting of 27 stations, is made up by the extension of SEGMA (South European Geo Magnetic Array), MM100 (Magnetic Meridian 100) and the Finnish part of IMAGE (International Monitor of Auroral Geomagnetic Effects). These ground magnetic field data are then coupled with the MA.I.GIC model (Piersanti et al., 2019) for the evaluation of geoelectric field response to shock impacts. These predicted shocks for SC25 can provide a great opportunity for the use of EMMA data in a robust and solid statistical analysis of geoelectric field response to shocks as a function of magnetospheric L shells. For example, case studies and statistical analyses of ULF waves can experimentally test a hypothesis suggested by Oliveira et al. (2020), in which the shock impact angle affects the wave mode of the perturbation (nearly frontal shocks can trigger odd-mode waves only, whereas highly inclined shocks can trigger both even- and odd-wave modes). Additionally, these SC25 shock numbers can contribute to the prediction of GICs from mid- to high-latitude Europe, since GICs at such latitudes can pose significant threats to power grids (Viljanen et al., 2014; Torta et al., 2017; Tozzi et al., 2019).

New Zealand has been a particular focus in recent years, due to the relative abundance of contemporaneous magnetic field and GIC measurements (e.g., Mac Manus et al., 2017) allowing the building of validated modeling tools (Mac Manus et al., 2022). Further, in new Zealand's recent history it has experienced severe space weather effects resulting from SI^+ events; an electrical transformer failed during the initial phase of a geomagnetic storm in November 2001 caused by a fast (presumably nearly frontal) IP shock (Marshall et al., 2012; Rodger et al., 2017; Oliveira et al., 2018). The links uncovered between SI^+ events and GICs are complex, with several confounding parameters including the frequency content and orientation of the magnetic field change (e.g., A.W. Smith et al., 2022; 2024). An increasing number of shocks in SC25 promises to help to untangle these drivers. Further, we expect that a greater number of "significantly" geoeffective shocks will allow the testing of hypotheses, helping to understand the types of shock-triggered SI^+ events that are of most importance in terms of the ground impact of space weather (e.g., Oliveira et al., 2018; 2024a,b; A.W. Smith et al., 2020).

The Embrace Magnetometer Network (Embrace MagNet) was developed to provide measurements at low latitudes in a region bounded by 50° of latitude to 40° of longitude, encompassing the eastern South American sector, aiming to provide subsidies to understand geomagnetically active time evolution at low latitudes by comparing ground observations from east to west, including storm time ionospheric disturbances (Denardini et al., 2018a; 2018b). As an example, Silva et al. (2023) used Embrace MagNet to evaluate dB/dt amplitudes during geomagnetic storms. They concluded that the magnetic field variations might have additional contributions from the SAA over Embrace MagNet instruments. In this way, the perspective for SC25 having a higher number of shocks in comparison to SC24 will provide the Embrace MagNet instruments with a large number of events to better describe the MI conditions driving pulsations and geoelectric field induction at low latitudes including the SAA region.

Enhancements of the equatorial electrojet current are important because they can also generate ground dB/dt variations linked to GICs at low latitudes triggered by shocks (Carter et al., 2015; Oliveira et al., 2018; Nilam & Tulasi Ram, 2022). Although not as intense as auroral and sub-auroral dB/dt variations, these equatorial dB/dt variations can cause significant overtime effects on power transmission lines of nations located in Southeast Asia, western Africa, and South America near the magnetic equator (Moldwin et al., 2016). For example, Nilam et al. (2023) used two ground magnetometer stations in southern India named Tirunelveli (TIR, 8.6^{o}N, below the equatorial electrojet), and Alibag (ABG, 18.6^{o}N, outside the equatorial electrojet), to provide an empirical relationship between shock parameters and the stations' local time. As an example of further space weather-related applications, the empirical relationship provided by Nilam et al. (2023) can be improved by introducing shock impact angle effects since they have significant control of the geomagnetic activity triggered by shocks (Oliveira & Samsonov, 2018; Oliveira, 2023b). This analysis can be further improved by the inclusion of more shock events observed in SC25 in comparison to the analysis previously performed by Nilam et al. (2023).

Variabilities of the magnetospheric and ionospheric currents described in Section 4 usually generate induced currents in the solid Earth. As a result, geomagnetic field variations measured by ground stations capture superposed field variations generated from the ionosphere and magnetosphere and from the Earth's crust. Ionospheric equivalent currents are frequently located ~100 km above the Earth's surface, and telluric currents are located 1 m below the Earth's surface (Juusola et al., 2020; 2023). By using ground magnetometer data from the IMAGE array, Juusola et al. (2020) showed that typically internal (telluric origin) dB/dt variations dominate external (ionospheric origin) dB/dt variations because the former are much closer to the ground.

Because telluric currents are highly dependent on the local ground conductivity, interpretation of the ionospheric equivalent currents and their magnetic field in terms of solar wind drivers (including shocks) is more straightforward than interpretation of the unseparated magnetic field. Thus, more shocks in SC25 will bring an opportunity to investigate and quantify telluric and ionospheric current effects on ground dB/dt variations and their links to subsequently generated GICs (Pulkkinen et al., 2017; Dimmock et al., 2020; Oliveira et al., 2024a,b).

As discussed above, while the predictions of shock occurrences in SC25 is useful from a statistical point of view and instructive for future missions planning, this study does not advance the possibility to predict space weather phenomena. This is out of this work's scope. However, an increased number of shocks observed at L1 during SC25 will provide a great opportunity for the improvement of shock detection tools for further space weather alerts (Kruparova et al., 2013; Cash et al., 2014; Carter et al., 2022). Such alerts can be used, e.g., by power plant operators to take actions to avoid long-term detrimental effects caused GICs on ground equipment, particularly for shocks that are forecasted to impact Earth nearly frontally (Oliveira et al., 2018; 2021).

Finally, our shock count predictions and space weather research opportunities discussed in this article indicate that SC25 will be different from SC24 when comparing availability of shock events and several data sets provided by spacecraft missions in the solar wind, magnetosphere, ionosphere, and ground magnetometers. However, since space weather is highly cross-disciplinary, as also suggested by Ledvina et al. (2022), SC25 will bring great opportunities for space weather research, but risk and resiliency approaches should be considered. Ledvina et al. (2022) highlight three approaches to successfully address complex and inter-disciplinary problems in space weather to mitigate eventual risks: 1) share open-data and data science through open access and collaboration (McGranaghan et al., 2017); 2) develop cross-disciplinary science and information systems by using multi-instrument investigations (as discussed in this article) and deep-learning or artificial intelligence analyses (Camporeale, 2019); and 3) engage in citizen science, an approach that connects scientists and the general public as a collaboration to achieve scientific goals that go beyond the academia (Shirky, 2010).

6. Conclusion

In this work, we discussed two aspects of IP shock research and space weather applications. Firstly, we used sunspot number data and shock data along with three models for sunspot number predictions for SC25 to predict shock occurrence numbers for SC25. Secondly, we briefly discussed many research opportunities that already are and will be available for shock research and forecasting. We found that the number of shocks will be ~50% higher in SC25 in comparison to SC24, with predictions ranging from ~40%-55% higher. With the unprecedented number of simultaneously operating satellite missions in the solar wind, magnetosphere, and the ionosphere, along with a large number of ground magnetic field and GIC data sets, we predict SC25 will bring great opportunities for studies involving space weather research and forecasting. In addition, we predict that a stronger solar cycle will produce more nearly frontal shocks that are important for space weather research because they usually are more geoeffective than highly inclined shocks due to quasi-symmetric magnetospheric compressions (Oliveira & Samsonov, 2018; Oliveira, 2023b). Finally, we also encouraged IP shock studies involving multi-instrument analyses. However, since space weather is highly cross-disciplinary, we suggested the assessment of risk and resiliency should be considered in such studies (Ledvina et al., 2022).

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Data availability statement

The IP shock list is available at the Zenodo repository described in Oliveira (2023c). The SILSO/SSN data can be collected from the website https://www.sidc.be/SILSO/datafiles. The MC sunspot number data can be downloaded from the HELIO4CAST website https://helioforecast.space/solarcycle. The UH sunspot data are available at the Solar Cycle Science website (http://solarcyclescience.com/forecasts.html). The NOAA sunspot data are available at https://www.swpc.noaa.gov/products/solar-cycle-progression. The F10.7 solar index data used in the Supporting Information (daily and yearly data from January 1964 to December 2023) were downloaded from the NASA OMNI website (https://omniweb.gsfc.nasa.gov/form/dx1.html).

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