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REVIEW
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Improving the Medium-Term Forecasting of Space Weather: A Big Picture Review From a Solar Observer's Perspective

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We have improved considerably our scientific understanding of the key solar drivers of Space Weather, i.e., Coronal Mass Ejections, flares, in the last 20+ years thanks to a plethora of space missions and modeling advances. Yet, a major breakthrough in assessing the geo-effectiveness of a given CME and associated phenomena still escapes us, holding back actionable medium-term (up to 7 days) forecasting of Space Weather. Why is that? I adopt a two-pronged approach to search for answers. First, I assess the last 20+ years of research on solar drivers by identifying lessons-learned and paradigm shifts in our view of solar activity, always in relation to Space Weather concerns. Then, I review the state of key observation-based quantities used in forecasting to isolate the choke points and research gaps that limit medium-term forecasting performance. Finally, I outline a path forward along three vectors—breakthrough capabilities, geo-effective potential, and actionable forecast—with the strongest potential to improve space weather forecasting horizon and robustness.

Keywords: Sun, space weather, flares - Sun, coronal mass ejection, forecast

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1. INTRODUCTION

The Sun is a cauldron of activity. Its radiative, magnetic and plasma outputs vary at all timescales, from seconds to years to decades. The solar variability modulates the state of Earth's geospace (defined here as the region encompassing the mesosphere to the magnetosphere) and drives a range of phenomena that impact space and terrestrial infrastructure. In analogy to terrestrial weather, we denote as Space Weather (SWx) geospace phenomena that occur on relatively short timescales (of the order of a few days or less) and refer to longer timescale phenomena (months to years) as Space Climate.

Within the last 20 years or so, the increasing recognition of the impact that extreme SWx events have on critical systems, such as electric power, communications, and transportation (Baker and Lanzerotti, 2016, and references therein) has transformed SWx from a narrow research topic to a worldwide societal concern. recently, the term has outgrown its original Earth-centric definition to describe the solar influence on other planets and objects (natural or man-made) within the solar system and, under the term "exoplanet SWx," the influence of stars on their exoplanets.

Here, I focus on forecasting terrestrial SWx over medium timescales (from hours to days in advance) and review the role of solar drivers on improving the forecast accuracy. This is a practical choice. SWx expresses the reaction or behavior of geospace, which is a highly complex and non-linear system. We are still a long way from understanding this system in sufficient detail to be able to predict its behavior. Understanding, however, the inputs to the system—the solar drivers—seems a more tractable problem. My objective is to provide a "big picture" overview of where do we stand now, how did we get here, and how could we move forward to improve the quality of the solar driver inputs (and hence the accuracy of SWx forecasting).

The paper begins with a short review of important lessons-learned from recent missions (section 2) and proceeds to identify three key paradigm shifts in our view of solar activity and in the interpretation of the observations (section 3). It then discusses the choke points in forecasting of several key observational parameters and the research gaps from which they arise (section 4). The paper concludes, in section 5, with a list of measurement strategies for moving forward. Hopefully, this information could assist in targeting research or hardware development efforts that can lead to robust improvements in SWx forecasting accuracy within the next decade or so.

2. LESSONS-LEARNED FROM THE RESEARCH ON SOLAR DRIVERS

The rise of SWx to societal prominence has been largely fueled by the great advances in our capabilities to observe the Sun-Earth system in the last 25 years, starting with the launch of the Solar and Heliospheric Observatory (SOHO; Domingo et al., 1995) mission in 1995, followed by the Advanced Composition Explorer (ACE; Stone et al., 1998) in 1997 and the arrival of the (Wind; Acuña et al., 1995) spacecraft at the Sun-Earth L1 Lagrange point and culminating with the launch of the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al., 2008) and the Solar Dynamics Observatory (SDO; Pesnell et al., 2012) in 2007 and 2010, respectively. Although these missions were designed for research on fundamental solar and heliospheric science, they have evolved into indispensable assets for operational SWx forecasting. Their payload complements and concept of operations have influenced the strategic plans of space agencies worldwide and the designs of numerous mission proposals. SWx research is now a highly valued Heliophysics objective on par with the long-standing research objectives of coronal heating and the acceleration of the solar wind. But, *why is that?*

The answer is fundamental for devising a successful strategy to move forward in SWx[1] forecasting. I argue that the transformational shift in Heliophysics research priorities was brought about by a series of key measurement capabilities and discoveries from the aforementioned missions and in particular from coronal and heliospheric imaging. I consider these as lessons-learned since they form the foundation basis of any future plan of action. I should note some practical caveats driven by the limited available space for this review. First, the discussion and assessments concern solely SWx issues and leave out much of the exceptional research on many other Heliophysics topics. Second, the review focuses on the most important solar phenomena that drive short-term SWx; namely, Coronal Mass Ejections (CMEs) including their shocks, flares, and Solar Energetic Particles (SEPs). Third, I will provide limited background information on the physical properties or the SWx importance of the drivers. The discussion proceeds in, roughly, the order of importance or impact of each lesson-learned.

[1]for brevity, SWx will refer to the solar drivers, hereafter, unless explicitly mentioned otherwise.

2.1. "24x7"

Before SOHO, space-based observations were performed from low-Earth orbit with a nominal duty cycle of about 50 min per the 96-min orbit. While this concept of observations was sufficient to establish CMEs as a rather regular phenomenon, it was inadequate for capturing with clarity their life cycle and connections to other forms of solar activity. SOHO pioneered uninterrupted remote observations of solar and coronal activity owing to its placement around the Sun-Earth L1 Lagrange point. The continuity of *synoptic* observations, particularly from full-disk telescopes, such as the Extreme Ultraviolet Telescope (EIT; Delaboudiniere et al., 1995), the Michelson Doppler Imager (MDI; Scherrer et al., 1995), and Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al., 1995), began to clarify the connections between photospheric magnetic flux and coronal structure evolution and erupting events, led to the creation of extensive and detailed databases of CMEs (e.g., Gopalswamy et al., 2009) and subsequently to the realization of CMEs as the main SWx driver (Gopalswamy, 2009).

2.2. Observations in EUV and Visible Light

LASCO was the first "nested" coronagraph to fully cover the inner to outer corona. Up until the start of SOHO science operations, the concept of operations for EIT considered it as context imager in support of the higher priority spectroscopic experiments on board. LASCO and EIT were expected to acquire a handful of images per day but the reality turned out to be very different. With the first observations of propagating EUV waves (Moses et al., 1997) and the direct association of front-side EUV activity to an Earth-directed CME (Thompson et al., 1999), the combination of EUV full disk and coronagraphic observations became the indispensable tool for detecting the occurrence, source region, and approximate extend (roughly) of a CME. The end result is that both visible light coronagraphs and full disk imagers have become baseline instruments on NOAA's SWx operational infrastructure, replacing soft X-ray imagers whose operational utility was based on the previous "paradigm" of flares as the primary agents of SWx (more discussion under Paradigm 2 in section 3).

2.3. Multi-Viewpoint Imaging

The success of SOHO led to the development and launch of the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al., 2008) mission devoted directly to the study of CMEs and their associated phenomena, such as shocks and SEPs. The mission objectives were built around the "EUV imager plus nested coronagraph" payload but extended it with two novel

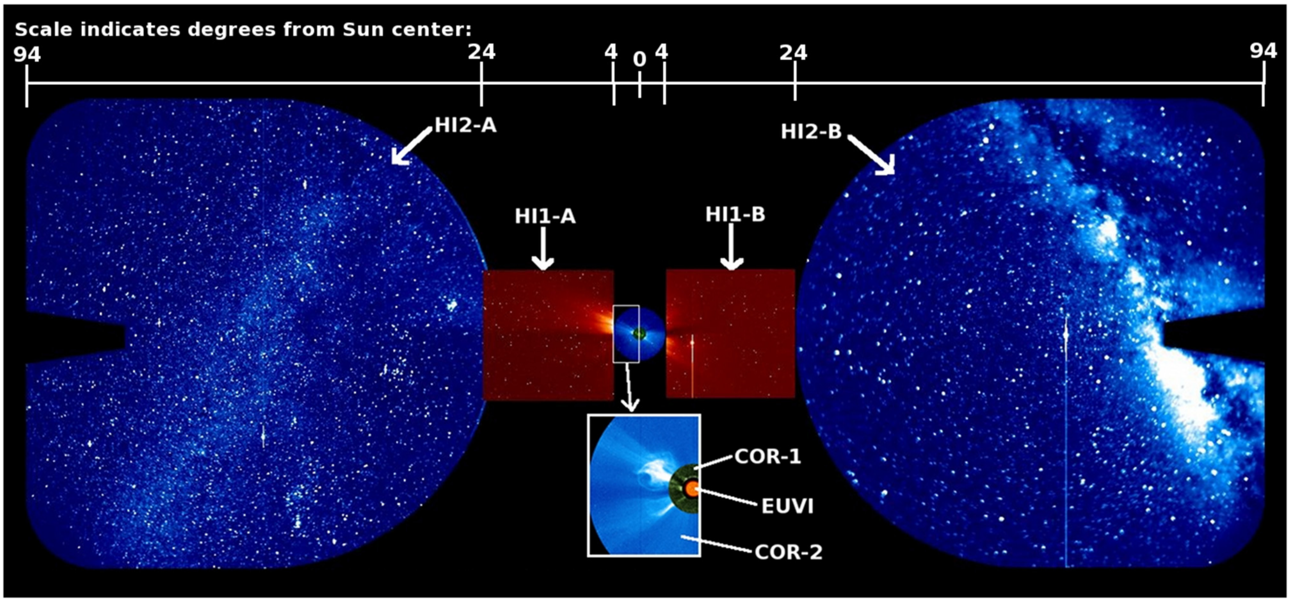

FIGURE 1 | Overview of the imaging capabilities available by the combined SECCHI payloads on the STEREO-A(head) and -B(ehind) spacecraft.

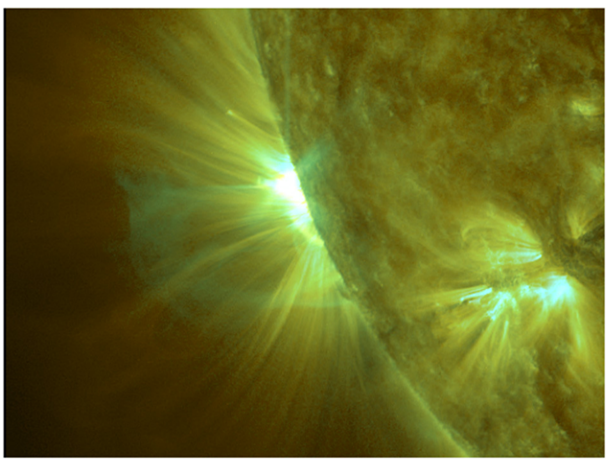

FIGURE 2 | SDO/AIA composite of 131 Å (silver) and 171 Å (gold) channels demonstrating the detection of a hot flux rope (HFR) during an eruptive flare on 29 November, 2020. The snapshots were taken at 12:48:30 UT (171 Å) and 12:48:57 UT (131 Å). The temperature of the elongated structure is likely 10 MK because it is detected only in 131 Å. See Nindos et al. (2020), for more examples.

"firsts." STEREO was the first mission to attempt 3D stereoscopy and reconstruction of astrophysical phenomena by deploying two spacecraft with nearly-identical payloads, on Earth-leading and trailing orbits, respectively, with gradually increasing inter-spacecraft angular separations of 22°/year. The other STEREO "first" was the deployment of visible light telescopes to image the inner heliosphere along the Sun-Earth line (SEL). The combined imaging payload, named the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008), consists of an EUV Imager (EUVI), two nested coronagraphs (COR1, COR2), and two heliospheric imagers (HI1, HI2) and is capable of imaging, without interruptions, the full Sun-Earth space (**Figure 1**). STEREO has enabled routine 3D reconstructions of CMEs from the first moments of their eruption (e.g., Patsourakos et al., 2010), uncovering a hitherto unnoticed phase of lateral super-expansion (Patsourakos and Vourlidas, 2012), to the inner heliosphere (Poomvises et al., 2010) spurring a blooming of empirical and physics-based efforts to model the CME propagation and internal magnetic structure (e.g., Vourlidas et al., 2019, and references therein). The 3D information afforded by the multi-point imaging *and in-situ* measurements led to major insights in the origins and propagation of SEPs. STEREO revealed that SEPs undergo surprisingly wide longitudinal spread (e.g., Anastasiadis et al., 2019, and references, therein), which is likely due to the large extent of the CME shocks, even in the low corona (e.g., Lario et al., 2017). The latter finding was made possible thanks to our ability to 3D reconstruct both the shock and driver CME (Vourlidas et al., 2013, and references, therein) and even extract the physical properties at the shock remotely (e.g., Kwon and Vourlidas, 2018).

2.4. Imaging From Away the Sun-Earth Line (SEL)

The STEREO passage and observations from the L4 and L5 Lagrange points in 2009 crystallized the importance of off-SEL observations for tracking Earth-bound CMEs and CIRs (e.g., Harrison et al., 2017) and ignited strong advocacy for SWx monitoring and research from L5 (Webb et al., 2010; Vourlidas, 2015; Pevtsov et al., 2016), including concrete mission designs (Gopalswamy et al., 2011) to the point where a mission to L5 is now considered the logical next step for improving SWx forecasting (Pulkkinen et al., 2019). Quadrature observations between the STEREO and SOHO imagers and coronagraphs, offer a straightforwad way to assess and correct projection effects in the kinematics of Earth-directed CMEs (e.g., Makela et al., 2016). The off-SEL viewpoint of STEREO-A was responsible for the discovery of the so-called "stealth" CMEs (Robbrecht et al., 2009). "Stealth" CMEs are generally slow events with low geoeffective potential in principle, but see Mishra and Srivastava (2019) and Zagainova et al. (2020) for counter examples. However, they still represent expulsions of large amounts of magnetized plasma in the heliosphere and their presence should be included in operational heliospheric models to properly assess the forecasting efficiency of these models, It should be noted that Earth-bound "stealth" CMEs are virtually impossible to detect from an Earth or L1 viewpoint. Given the observing challenges, it is unsurprising that a quantitative assessment of the geo-effectiveness of CMEs is currently lacking.

2.5. Hot Flux Ropes

Perhaps Solar Dynamics Observatory (SDO; Pesnell et al., 2012) mission's singular contribution in shaping SWx research was the detection of "hot flux ropes" (HFRs: **Figure 2**) in the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) 131 Å EUV channel (Cheng et al., 2011; Reeves and Golub, 2011). Deployed for the first time in the SDO mission, the 131 Å channel images primarily cool plasmas in Fe VIII (∼ 0.4 MK) but it is dominated by Fe XXI (∼ 11 MK) during flares (O'Dwyer et al., 2010). The fact that HFRs show only or most clearly in 131 Å (hence missed or rather went unnoticed e.g., Figure 6 in Vourlidas et al., 2012 by previous EUV experiments) along with the realization that they appear minutes (Zhang et al., 2012) or even *hours* (Patsourakos et al., 2013; Nindos et al., 2020) before the eruption opens a new perspective on how the coronal system evolves toward eruption. More crucially for medium-term forecasting, it offers the possibility to (1) isolate and better study the likely strongest magnetic structure of the erupting CME, and (2) develop a prediction capability if confined flares are indeed the tell-tale signs of HFRs formation ahead of an eventual eruption as suggested by Patsourakos et al. (2013) and Nindos et al. (2020). Deeper analyses of the phenomenon, including assessments on their appearance in other EUV wavelengths, are needed and should hopefully be forthcoming.

2.6. Sympathetic Eruptions

The long-standing question on whether eruptions (flares and CMEs) from different locations are causally linked has been finally put to test thanks to the wide longitudinal coverage afforded by SDO and STEREO. The observations showed (Schrijver and Title, 2011), and modeling supported (Török et al., 2011), that a CME over one polarity inversion line (PIL) can trigger eruptions (referred to as "sympathetic") over adjacent PILs. While the details remain to be worked out, numerical modeling indicates that the "seed" CME may trigger the subsequent eruptions via its effect on the global magnetic field, either by removing magnetic field or modifying its topology, (Jin et al., 2016). The implications for SWx forecasting are twofold: (1) the earlier CME(s) change the ambient density and magnetic field, altering the characteristic speeds of the medium and influencing the trailing event's kinematics and shock generation ability. The earlier events could also enhance the suprathermal particle background by accelerating particles out of the ambient medium thus increasing the SEP output from the trailing event(s) (e.g., Gopalswamy et al., 2002, 2015; Kahler and Vourlidas, 2014); (2) further out, "sympathetic" eruptions may interact with each other and/or change magnetic connectivity thus impacting the performance of operational forecasting models (Lugaz et al., 2017).

3. PARADIGM SHIFTS

The measurement capabilities and discoveries just described have transformed our view of solar eruptive activity over the last two cycles but I have not yet explained how. It is no easy task to crystallize the extraordinary amount of research on solar eruptions into a set of "paradigm shifts." I can discern three major "paradigms" (with SWx implications) that have undergone fundamental shifts due to the observations discussed in the previous section:

- Paradigm 1: *"Extreme Space Weather is expected during high sunspot number cycles."* The smoothed sunspot number (SSN) has been traditionally used as the indicator of solar activity levels. So much so that NOAA, NASA and the International Space Environmental Services (ISES) convened a Solar Cycle Prediction panel to forecast the next solar cycle SSN levels. Since higher SSN indicates more flares and CMEs, we have become accustomed to expect extreme SWx during strong (high SSN) cycles and to "lower our guard" during weak cycles. This is not, however, the lesson we should draw from the last cycle. Solar Cycle 24 (SC24) was the weakest cycle of the last 100 years and, more importantly for this discussion, the weakest cycle during the space era. While solar wind reached its lowest values ever measured (McComas et al., 2013), the cosmic ray background reached records values raising serious concerns on the viability of human deep space exploration during weak cycles (Schwadron et al., 2018). Although Earth experienced weaker geomagnetic storms than in SC23 (Manoharan et al., 2018) and only two Ground Level Enhancement (GLE) particle events, the CME rate was largely the same (Lamy et al., 2017). A likely reason for the absence of strong SWx events may be the lower rate of fast and/or wide CMEs in SC24 (Gopalswamy et al., 2020). However, STEREO's wide inner heliospheric coverage indicate that many more GLE-level events likely occurred, some even stronger than SC23 events (Cohen and Mewaldt, 2018) but Earth was not magnetically connected to them (Gopalswamy et al., 2014). Crucially, STEREO measured the strongest magnetic fields in an interplanetary CME (Russell et al., 2013; Liu et al., 2014) on July 23, 2012—an event that could have rivaled the *Carrington 1859 event*, the archetypal extreme SWx event, if it was Earth-directed (Ngwira et al., 2013). In addition, a series of large eruptions from active regions 2673 and 2674 in September, 2017 (in the declining phase of a weak cycle) caused a host of SWx phenomena from Earth to Mars (e.g., Chertok et al., 2018; see other papers in the Space Weather Journal special issue). Although by no means complete (the passage of active region 1429 in March 2012 marked another period of intense activity, e.g., Patsourakos et al., 2016), these arguments should make the lessons learned clear; namely, (1) a Carrington-level event can occur at *any* cycle, even in the weakest cycle in 100 years, (2) weak cycles are as dangerous for human space exploration as stronger cycles, and hence (3) the sunspot number is an unreliable proxy—I would even call it a "red herring"—we should instead focus on individual regions and try to understand how regions like 1429, 1520, or 2674 (anti-Hale, δ-spot) form and evolve, if we want to address extreme SWx.

- Paradigm 2: *"Flares and CMEs evolve at different spatial and temporal scales."* Although CME and flares (eruptive flares, at least) are closely related, they are generally approached with different mentalities. Flares are characterized by a sharp brightness increase (rise time of $\sim 5-10$ min) in heavy element emissions (e.g., Fe), implying heating to temperatures of 10s MK, in small-scale (order of arcseconds) loop systems, followed by a gradual increase in area and intensity before an hours-long return to pre-flare intensity levels (Benz, 2008). The brightness increase, small flare loop area, and (mostly) radiation effects contrast sharply with the usually hour-long acceleration, solar-radius spatial scales, and mass motions of CMEs. It is unsurprising that the two phenomena were studied in isolation, with different tools and models, and by different communities. The dichotomy extends to their SWx effects, particularly in the origin of SEPs (e.g., Reames, 2013) leading to a linear "flare-CME-SEP" paradigm of the solar SWx timeline.

  This turns out to be a rather simplistic, and potentially misleading, approach as the high quality and rapid cadence EUV imaging observations have demonstrated. The discovery of EUV waves (Thompson et al., 1999) and post-CME rays (Ciaravella et al., 2002) and their singular connection to eruptive flares (e.g., Long et al., 2017, and references therein) indicated a closer spatial and temporal relation between magnetic energy release and both flare and CME development that previously realized (Longcope and Beveridge, 2007; Qiu et al., 2007); see also Patsourakos et al. (2020), and references therein. In my opinion, a paradigm-shifting advance was the identification of the EUV wave driver with a *"super-expansion"* phase in the very first stages of CME formation (Patsourakos and Vourlidas, 2012). During this hitherto unknown phase, the injection of poloidal flux into the forming magnetic flux rope (MFR) leads to a fast lateral expansion of the nascent CME expands at speeds of about 1,000 km/s, reached within 5 min. These speeds are sufficient for driving shocks (manifested as EUV waves and metric type II bursts) and hence can accelerate SEPs to high energies. Importantly, the temporal profile of the "super-expansion" phase is similar to the impulsive phase of the flare, occurring in close proximity, though not always simultaneously (e.g., Patsourakos et al., 2010; Cheng et al., 2014). The "super-expansion" phase neatly integrates a host of disparate phenomena variously attributed to flares or CMEs, such as expanding flare ribbons, short-lived metric Type-II bursts, EUV waves, and even the somewhat puzzling detection of separate sites of γ-ray and Hard X-ray emission (Lin et al., 2003), implying separate ion and electron acceleration sites (Pomoell et al., 2008). I propose, in other words, that flares, CMEs and the highest energy and possibly even the "seed" populations of SEPs, should be viewed as co-located phenomena, of *initially* similar spatio-temporal scales, powered by the magnetic energy released via reconnection within extended current systems in the corona.

- Paradigm 3: *"All projections are created equal."* Any type of coronal imaging is subject to projection as the observed emission is optically thin, whether it arises from spectral line emission or scattering processes. Up until 2007, 30+ years of single viewpoint observations, all from the Sun-Earth line, had led to a certain degree of complacency regarding the effects of projection in our view of solar structures. Techniques to recover the unprojected quantities, and ensuing uncertainties, such as loop heights or CME speeds, were (and continue to be) commonplace, yet they had not been validated in any comprehensive manner. The underlying assumption that the observations capture a representative view of the actual 3D structure of the object of interest, went unchallenged. But what happens if it is not a valid assumption? What if, say, the halo-like feature in a coronagraph image is not the result of an Earth-directed CME but a chance co-temporal ejection of two oppositely-directed CMEs that pose no SWx threat? Or what if an Earth-directed CME happens to propagated behind the occulter until it leaves the field of view of a coronagraph?

  It was difficult to answer such questions and, in essence, to check the validity of much of previous studies without *observations from multiple vantage points*. The STEREO mission offered us that opportunity in 2007. The two STEREO viewpoints, often with a third one from LASCO, revealed a much more nuanced, and oftentimes surprising reality. For example, a single CME (Magdalenić et al., 2014) may be three CMEs (Colaninno and Vourlidas, 2015); halo CMEs are actually a manifestation of the shock and not the CME itself (Kwon et al., 2015); evidence for an entrained MFR or prominence material in a CME is a matter of viewpoint (e.g., Figures 6, 7 in Vourlidas et al., 2017); an MFR can have the textbook "slinky"-like helical morphology, or not, depending on its orientation before eruption (e.g., Figure 3 in Vourlidas, 2014). More importantly for our discussion here, the detection of an Earth-directed CME can only be guaranteed from off-SEL observations (e.g., **Figure 3** and Vourlidas et al., 2020a). In other words, "all projections are not created equal." The viewpoint matters and must be selected wisely. For SWx, the off-SEL viewpoints are more important the SEL ones, since the former can help decipher the CME structure.

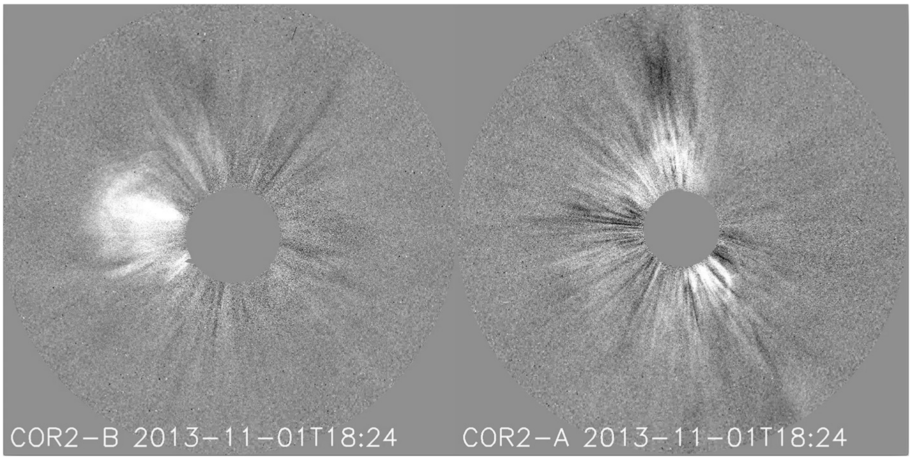

FIGURE 3 | An example of a projection effect with SWx implications. **Left**: Snapshot of a CME from COR2 on STEREO-B. **Right**: Simultaneous snapshot from COR2 on STEREO-A (69° away). The event, barely visible in COR2-A, lacks a clear halo appearance and may not have been classified as a COR2-A directed event without the COR2-B observations. The movie is available online from the COR2 catalog.

TABLE 1 | Forecasting status of key quantities used to assess the Geo-effectiveness of the main solar drivers of space weather.

Quantity	Observational inputs	Forecasting status	Choke points
CME/shock			
Direction (Hit/Miss)	Source region / flare location, 3D CME reconstruction	85%*	Deflection in low corona, IP evolution
Time-of-arrival	Speed in corona or inner heliosphere	9.8 ± 2 h[a]	IP propagation, CME/shock front shape at 1 AU
Speed-on-arrival	Speed in corona or inner heliosphere	± 200 km/s*	Same as above
Density	CME mass	Unknown	IP propagation, small-scale structure of CME/shock sheath
Magnetic configuration	Radio emission, 3D CME reconstruction, coronal magn. field extrapolations	~ 30 min (L1 *in-situ* meas.)	Coronal origin, evolution (< 3 Rs), IP propagation
Flares			
SXR class	Photosph. magn. field, flaring history	TSS ~ 0.4[c]	Energy storage/release in corona
Intense radio bursts[b]	Ground-based radio antennas	No forecasting capability	Unknown physics
SEP			
Onset time	TypeII/III, flare (CME) occurrence & class (speed)	4 h $>$ 10 MeV, 1 h $>$ 100 MeV	High cadence imaging in the inner corona (< 3 Rs), "seed" particle observations, magnetic connectivity
Peak intensity	Same as above	Within ~ 1 order of magnitude	Same as above
Intensity profile	Same as above	9 h ($>$ 10 MeV), 33 h ($>$ 100 Mev)	Same as above

[a] *Vourlidas et al. (2019).*
[b] *Next Step Space Weather Benchmarks Report (2019).*
[c] *TSS, True Skill Statistic (Leka et al., 2019).*

4. FORECAST "CHOKE POINTS" AND GRAND CHALLENGES

These research developments have advanced the sophistication and performance of forecasting models and have informed the strategy for the SWx operational infrastructure. But we still have some way to go. This is not solely driven by the solar driver observations. Accurate and actionable SWx forecasting is far more challenging than terrestrial weather. A key reason is that the geospace is a vast, complex, and sparsely sampled system compared to the troposphere. Another reason is the non-linear reaction of geospace to the solar inputs. The solar driver inputs, and the focus of this paper constitute only the third agent in the SWx problem.

In **Table 1**, I summarize the quantities most commonly used to assess the geo-effectiveness of the three solar drivers of

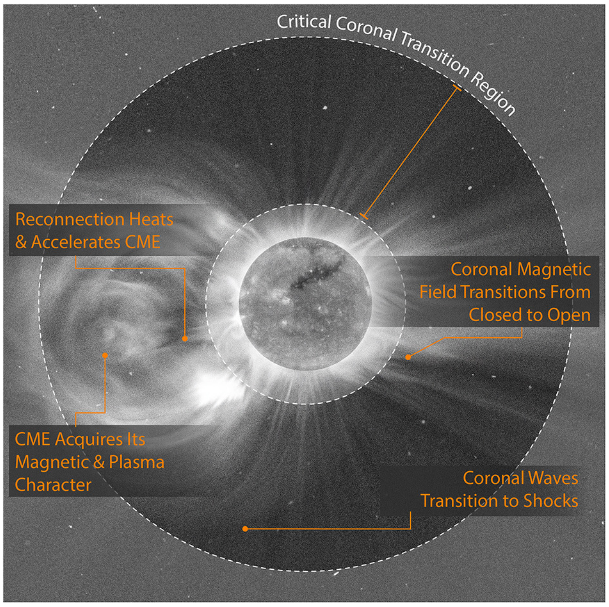

FIGURE 4 | Several important physical transitions during solar eruptions, directly relevant to SWx, occur within the inner corona—the region between 1.3 and 4 Rs, roughly. However, this critical coronal range remains poorly studied (more details in Vourlidas et al., 2020d).

concern; flares, CMEs, and SEPs. The parameter list is not meant to be exhaustive. For each quantity, **Table 1** provides a brief list of observational inputs used to forecast the quantity, the current forecasting accuracy, and the main issues that hinder the forecast. The selection of these "choke points" is based on my experience and understanding of the related literature, observational limitations and modeling requirements. I expect some disagreements on the details, but **Table 1** hopefully expresses the broad consensus on this area.

A key observation to draw from **Table 1** is that many "choke points" are common across all solar drivers. In fact, all "choke points" stem from incomplete physical understanding of the three lifetime phases of any transient; namely, the pre-eruptive phase, the formation phase, and the interplanetary (IP) propagation phase. Understanding these phases better would naturally lead to improved forecasting. To get started, we first need to consider the challenges (always in regards to SWx forecasting) that we are facing now. These *gland challenges* are as follows:

- *Pre-eruptive Phase:* The main challenge is to uncover the *coronal* magnetic configuration of the pre-eruptive structure and how it evolves toward eruption. This is a high-stakes challenge as the answer will enable prediction of both flares and CMEs (and consequently shocks and SEPs) from a few hours to possibly days before, Although we have learned a great deal on how flares and CMEs evolve over the last 20 years or so (Green et al., 2018), we are not yet close to addressing this challenge. The reason is rather simple; eruptions are (1) magnetically driven and (2) originate in the corona where we have few ways of measuring magnetic field. Thus, we cannot observe/measure many of the quantities important to coronal energy storage and release, such as magnetic free energy, helicity, or currents. Patsourakos et al. (2020) reviewed the subject in detail and put forth a range of ideas for moving forward.
- *Formation Phase:* As discussed earlier, most CMEs undergo their formation and acceleration phases in the inner corona (below 4 Rs). It is where shocks form and the highest energy particles are accelerated. Although the flare-related brightenings are smaller spatial scale phenomena restricted to the low corona, their eruptive manifestations, such as current sheets and the particles accelerated in them, can reach much higher. **Figure 4** summarizes the richness of the physical processes relevant to SWx in this coronal region (the specifics are not discussed here due to space constraints). Yet, this region remains poorly understood, mostly because it is visible in its entirety only during eclipses while it is only partially accessible at other times by disparate instruments, either coronagraphs (down to 1.5 Rs or so) or EUV imagers (up to 1.5 Rs). There are no comprehensive spectroscopic measurements of its physical state (density, temperature, composition) either. The importance of the inner corona is discussed in some detail in a white paper by Vourlidas et al. (2020d).
- *IP Propagation Phase:* It has been only 10 years since we started routine measurements of the IP propagation of transients (CMEs, shocks, SIRs) thanks to the operation of the heliospheric imagers on the STEREO mission. The discoveries and remaining challenges are reviewed by Manchester et al. (2017). The IP propagation affects most of the SWx-relevant properties of the solar drivers. Improvements in this area will benefit SWx forecasting across a wide range of users. There are essentially three challenges relevant to forecasting: (1) CME-solar wind interactions that are important for shocks, SIRs, and slower CMEs. They tend to affect the time and speed of transient at its 1 au arrival and possibly the direction of propagation; (2) CME-CME interactions that can lead to magnetic field compression and strengthening of the shocks, as they propagate through the slower CME (Lugaz et al., 2017) , which is an issue of SWx relevance closer to the Sun, as well (e.g., Liu et al., 2014); and (3) CME internal forces, namely the interplay between the magnetic forces of the entrained flux rope with the surrounding plasma and magnetic pressure (e.g., Yeh, 1995). The force balance of a CME is not well-understood. For example, *in-situ* measurements at 1 AU suggest the CME flux ropes are force-free, yet estimates from coronagraphic observations suggest the opposite (e.g., Subramanian et al., 2014). Large-scale studies indicate that only 65–70% of events within 15 Rs follow self-similar expansion (Balmaceda et al., 2020).

5. PATH FORWARD

The identification of the forecast "choke points" and the research challenges they originate from, allows us to define measurement strategies for addressing these challenges. In the following, I organize these strategies according to the three phases: pre-eruptive, formation, and propagation. However, I list them according to their perceived SWx impact to emphasize the different value to SWx operations of each evolutionary phase:

- *Breakthrough Capabilities:* Predicting (reliably) the onset of a flare or a CME within a few hours of its occurrence will be a major breakthrough in SWx. To understand the pre-eruptive state, we must follow the flow of magnetic energy and helicity upwards from the photosphere and its storage in the corona, as well as, the reaction of the ambient field to this energy/helicity flow. **Multi-height vector magnetic field measurements**, from photosphere to (at least) the upper chromosphere, in active regions (because they host the most energetic eruptions), can provide the required information on energy and helicity flow and coronal currents. They will also provide strong constraints for coronal field extrapolations leading to robust 3D reconstructions of the magnetic morphology of the pre-eruptive structures thus removing the need for the much more difficult direct coronal field measurements (for more information and ideas see Patsourakos et al. 2020). The measurements could be achieved by a $>$ 1-m telescope with a visible-to-near infrared (NIR) magnetograph, perhaps launched as a balloon payload.

  The reaction of the ambient field and the slow rise of the system, which is typical before an eruption, can be captured via **off-limb spectroscopic measurements** in the UV and/or EUV, up to about 2.5 Rs or so. Doppler, temperature and density measurements will help constrain the force balance evolution of the system toward eruption and provide 3D information of the erupting structures and their interplay with the ambient magnetic systems. While ground-based off-limb spectroscopy in the visible and NIR could provide these measurements (e.g., McIntosh et al., 2019) and improve our understanding of the physics of eruption, they are of little direct use for SWx operation. SWx-relevant eruptions can only be measured and monitored from platforms away from the Sun-Earth line (SEL), such as around the Sun-Earth L4 and L5 Lagrangian points.
- *Geo-effective potential:* The majority of the energy release and the magnetic configuration of the erupting CME occur during the formation stage. The shocks (and accelerated particles) and magnetic content of the CME are established in that phase. In other words, understanding the formation phase will improve forecasting of the geo-effective potential of a solar transient. A straightforward improvement will come from emulating solar eclipses to provide **uninterrupted coronal coverage** from the solar surface to 10-15 Rs. A long boom visible coronagraph or an expanded version of a formation-flying coronagraph (Galano et al., 2018) can provide such an eclipse-like field of view. The addition of a wide-field EUV imager/coronagraph could fill in the gap from the disk to the inner corona and provide additional density and temperature information, depending on the channel selection. Detailed physical properties, however, can only be obtained via **off-limb spectroscopy** in the UV/EUV to 2–5 Rs (e.g., Ko et al., 2016), heights inaccessible for ground-based visible-NIR spectroscopy. Again, the best viewing locations for SWx operations are off-SEL, which would necessitate the development of small volume/simple spectrograph and coronagraph concepts. Radio spectroscopy can play an important role in this area by tracking interplanetary shocks in the kHz-MHz range or probing CME magnetic fields via Faraday rotation measurements (e.g., Vourlidas et al., 2020b). Carley et al. (2020) reviews extensively the SWx-related radio infrastructure upgrades under way. Finally, **stereoscopic EUV imaging with vector magnetic field measurements** of Earth-facing active regions can provide strong (and possibly early) constrains of the erupted field strength and configuration by comparing before after magnetic field extrapolations and stereoscopy, as discussed in Schrijver et al. (2015).
- *Actionable Forecast:* Resolving the issues surrounding the propagation of solar transients in the inner heliosphere is the most direct way to obtain actionable forecasts in the near-term. IP propagation is a concern for almost all solar drivers of interest; CMEs, shocks, SIRs, and SEPs. To understand it, we need to overcome a major barrier—the sparse coverage of the vast Sun-Earth space. I can see three ways to overcome this: (1) Obtain **off-SEL high signal-to-noise ratio (SNR) heliospheric imaging** to enable tracing of the magnetic flux rope entrained in the CME and cleaner separation of the sheath and CME structures. Better observations of the kinematic and dynamic evolution of these features will increase understanding of CME-solar wind and CME-CME interactions, as we discussed in section 4 (see also the "path forward" discussion in Vourlidas et al., 2019); (2) design missions for **distributed particles and fields measurements from 0.7 to 1 AU** to provide $\sim$ 24-h forecasting horizon of magnetic and kinematic parameters of incoming transients; and (3) obtain **multi-point particles and fields measurements with a $<$ 8° angular separation** to investigate the medium-scale structure of these transients, preferably upstream of L1 (Lugaz et al., 2018).

  All three measurement types are achievable with current spacecraft technologies and sufficient investment. A more comprehensive solution that is scientifically rewarding but technically challenging will come from **off-SEL**, and particularly **off-ecliptic heliospheric imaging** (Gibson et al., 2018) to image directly deflections and interactions in the ecliptic without the ambiguities that plague imaging from within the ecliptic.The proper combination of ecliptic and off-ecliptic imaging of the solar surface to the extended corona offers a particularly ground-braking capability—**the 4π coverage** of the solar atmosphere. (Vourlidas et al., 2018; Berger et al., 2019). The resulting measurements will impact research and forecasting across the whole SWx enterprise (e.g., Vourlidas et al., 2020c).

In closing, I reiterate that I did not intent to provide an exhaustive review of all possible obstacles and remedies for improving the medium-term forecasting of SWx. Such gap analyses require careful consideration and community-wide input. Thankfully, both NOAA and NASA are in the midst of such efforts as of this writing. The aim of the paper is twofold: (1) capture the status of our physical understanding of solar drivers and their SWx effects from a research perspective and (2) demonstrate that there is a clear and executable path forward. All that is left is to put this plan in motion as resources and opportunities arise across the world. Space Weather is a concern for all humans as we try to expand our footprint in space.

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AV was the sole contributor to this paper.

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