Comparing the Performance of a Solar Wind Model from the Sun to 1 au Using Real and Synthetic Magnetograms

Kalpa Henadhira Arachchige1,2,5,6, Ofer Cohen1,2,5,6, Andres Munoz-Jaramillo3, and Anthony R. Yeates4

1 Lowell Center for Space Science and Technology, 600 Suffolk Street, Lowell, MA 01854, USA; kalpa_henadhiraarachchige@student.uml.edu
2 Department of Physics & Applied Physics, University of Massachusetts Lowell, Lowell, MA 01854, USA
3 Southwest Research Institute Boulder, Boulder, CO, USA
4 Department of Mathematical Sciences, Durham University, Durham, DH1 3LE, UK

Abstract

The input of the solar wind models plays a significant role in accurate solar wind predictions at 1 au. This work introduces a synthetic magnetogram produced from a dynamo model as an input for magnetohydrodynamics simulations. We perform a quantitative study that compares the space weather modeling framework (SWMF) results for the observed and synthetic solar magnetogram input. For each case, we compare the results for extreme ultraviolet images and extract the simulation data along the Earth trajectory to compare with in situ observations. We initialize the SWMF using the real and synthetic magnetograms for a set of Carrington rotations within solar cycles 23 and 24. Our results help quantify the ability of dynamo models to be used as input to solar wind models and thus provide predictions for the solar wind at 1 au.

1. Introduction

The importance of space weather forecasts has increased with the growth of our society’s dependence on space technology. Currently, in situ observations at 1 au from the Advanced Composition Explorer (Stone et al. 1998) and global imaging of the Sun by, e.g., the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) and the Solar Dynamics Observatory (Pesnell et al. 2012) provide observational constrains for a limited space weather forecast.

To improve forecasting capabilities, numerical models play a vital part in predicting solar wind conditions from the corona up to 1 au. Early simplified potential field models (Altschuler & Newkirk 1969) and the first magnetohydrodynamic (MHD) model (Kopp & Pneuman 1971) provided the first steady-state, global structure of the solar corona (SC) taking into account the solar wind and the Sun’s open magnetic field that determines the interplanetary magnetic field (e.g., McComas et al. 2007). Modern global MHD models for the ambient SC and solar wind extend their domain from the Sun to 1 au, taking into account coronal heating and thermodynamics and solar wind acceleration (e.g., Linker et al. 1990; Mikic et al. 1999; Usmanov et al. 2000; Odstrcil 2003; Cohen et al. 2007; Lionello et al. 2014; van der Holst et al. 2014; Merkin et al. 2016; Feng et al. 2017; Hinterreiter et al. 2019; Hazra et al. 2021). While the modeled solar wind conditions at 1 au have improved, and forecasts can be obtained in real time, modeled forecasts are still limited due to limited resolution near the Earth and the dependence on the magnetogram input data (most of these models require magnetogram data to constrain their inner boundary).

The input magnetogram data heavily influence reproducing accurate, realistic solar wind predictions at 1 au. Specifically, model predictions are only available after the magnetogram data have been acquired. In this paper, we investigate a new input for solar wind MHD models, which is derived from the 3D kinematic dynamo (Kd3) code (Yeates & Muñoz-Jaramillo 2013). In Kd3, the bipolar magnetic regions (BMRs) are generated by imposing velocity perturbations, where the main advantage of this code is that it can study both cycle propagation and photospheric evolution simultaneously. The code is modified to produce the surface magnetic field distributions, i.e., synthetic magnetograms.

In this paper, we use the threaded field line model (TFLM; Sokolov et al. 2021) and the latest version of the Alfvén wave solar atmosphere model (AWSoM; van der Holst et al. 2014) within the space weather modeling framework (SWMF; Tóth et al. 2012) to predict the global coronal structure and solar wind conditions at 1 au using real and synthetic magnetogram data. Thus, this paper aims to demonstrate how well the synthetic magnetograms perform as input for MHD models over real magnetograms. We stress that our goal here is not to test the performance of the MHD model against real data but rather to compare its results using the real and synthetic input data. We use synthetic magnetograms produced by the Kd3 model for a number of Carrington rotations (CRs) over solar cycles 23 and 24 and test how similar the modeled conditions are compared to the case of the real magnetograms. A reasonable agreement means that the Kd3 model could provide data for the future state of the Sun’s photospheric field. Thus, MHD models could provide space weather forecasts for the ambient solar wind even before the magnetogram data are available.

We describe our modeling approach and setup in Section 2 and show the results in Section 3. We then discuss the usability of the synthetic magnetograms in Section 4 and conclude our findings in Section 5.
2. Model Description

2.1. Model Description

We use the AAWSoM to obtain steady-state solutions in the SC. AAWSoM serves as the SC module in the SWMF (Toth et al. 2012). Using the SWMF, the SC module is coupled with a module for the inner heliosphere (IH), driving its inner boundary conditions. The end result is a steady-state solution over the CR that extends from the Sun to 1 au. Both the SC and IH modules are versions of the BATS-R-US MHD code (Powell et al. 1999).

AAWSoM uses Alfvén wave turbulence formalism to heat the SC and accelerate the solar wind, where the Alfvén wave turbulent pressure \( P_A = \frac{1}{2} (\omega_+ + \omega_-) \) is included in the momentum and energy equations, where \( \omega_+ \) is the energy density for the wave propagating along the magnetic field, and \( \omega_- \) is the wave propagating in the opposite direction. In our simulations, we use the single-fluid MHD equations, even though two-temperature mode may improve the model’s performance against observations. In addition to the Alfvén wave turbulent pressure, the model consists of detailed thermodynamics effects, such as radiative cooling and electron heat conduction, which assist in enhancing the performance of reproducing the extreme ultraviolet (EUV) and X-ray images of the corona. The SC component uses a stretched spherical grid from 1 to 24 \( R_\odot \), and the TFLM (Sokolov et al. 2021) to calculate thermodynamics in a 1D manner very close to the inner boundary. This enables one to overcome an extremely small grid size in the 3D model. The IH component uses a Cartesian grid from 18 to 215 \( R_\odot \), and it is driven by the SC solution through its inner boundary using a buffer grid between the two modules. For detailed information about the SWMF and SC–IH coupling, we refer the reader to Tóth et al. (2012) and Sachdeva et al. (2019).

2.2. Model Inputs

AAWSoM is driven by the radial magnetic field distribution on the photosphere (magnetograms). The magnetogram is used to calculate the 3D potential magnetic field (Altschuler & Newkirk 1969), which serves as the initial, non-MHD magnetic field. Alfvén wave energy is introduced at the coronal base in the form of pointing flux, \( S_{Bx} / B_\odot \), which is a free parameter in the model. This energy heats the corona and accelerates the wind. Another free parameter in the model is the transverse correlation length of the Alfvén waves, \( L_\perp \sqrt{B} \), which parameterizes the dissipation of the wave energy in the plasma. The \( L_\perp \sqrt{B} \) is responsible for the turbulent cascade caused by the partial reflection of forward-propagating Alfvén waves (see van der Holst et al. 2014 for a complete description of the AAWSoM parameters).

In this work, we optimize the values of these free parameters for each CR in order to get the best agreement with 1 au data using the observed magnetogram. We then use the same values to obtain a steady-state solution driven by the associated synthetic magnetogram. Both magnetogram data are in the form of spherical harmonics, and these coefficients are calculated up to the order of 90. Table 1 shows the parameterization values used for each CR.

2.2.1. Real Magnetogram

Magnetograms are synoptic observations of the Sun’s photospheric radial magnetic field. These maps provide observations for the entire disk of the Sun during one solar rotation of 27.27 days, known as CR. In this study, we use synoptic magnetograms provided by several observatories, including the Michelson Doppler Imager (MDI), the Global Oscillation Network Group (GONG), and the Synoptic Optical Long-Term Investigation of the Sun (SOLIS) observatory. These observatories use the Zeeman effect to detect the strength and polarity of the magnetic field at the Sun. However, there are problems and errors associated with real magnetograms that might affect the final output obtained from the models. For more details about these errors, refer to Section 4.1 in MacNeice et al. (2018). Table 2 shows the list of modeled CRs and the magnetogram data used for each CR. These CRs occurred during solar cycles 23 and 24.

2.3. Synthetic Magnetogram Using Kd3

We use the improved Kd3 code to generate the surface field distribution of the Sun for selected CRs to simulate the synthetic magnetogram case. The Kd3 code is a 3D flux transport model with a radial dimension that allows flux emergence and subduction to allow a more realistic evolution of the magnetic field. The fundamental governing equation for Kd3 is the magnetic induction equation (Yeates & Muñoz-Jaramillo 2013):

\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \nabla \times (\eta \nabla \times B). \tag{1}
\]

The above equation is solved using a finite difference scheme by imposing localized velocity perturbations and prescribing a turbulent diffusivity profile \( \eta \). Active regions at the solar surface emerge out of a toroidal magnetic field at the tachocline, and the properties of these regions are reproduced by calibrating the velocity perturbations. This velocity has three components: an outward radial velocity that transports the magnetic flux from the tachocline to the solar surface, a diverging component that expands the rising tube with increasing heights, and a vortical...
flow to capture the net effect of helical turbulence on the rising tube. The advantage of this model is that it can generate the emergence and decay of BMRs, which can be used to identify the Sun’s active regions in a CR. This method avoids the problems associated with depositing artificial flux tubes (Muñoz-Jaramillo et al. 2010; Hazra & Nandy 2013), and the location of the emerging flux tubes is chosen based on the distribution of the magnetic field at the bottom of the convection zone (Yeates & Muñoz-Jaramillo 2013).

2.3.1. BMR Database and Input in Kd3 Simulation

We drive flux emergence in Kd3 using a BMR database constructed from NSO synoptic magnetograms (Whitbread et al. 2018; Whitbread 2019). This database contains the flux, latitude, longitude, and dipolar moment of each region as observed in each CR.

As described in Yeates & Muñoz-Jaramillo (2013), we only use the latitude, longitude, and dipolar moment to determine the moment, place, and tilt of the flux emergence. The magnetic flux is not specified, but it is determined only by the availability of toroidal flux inside the convection zone. At the moment, our flux emergence is completely deterministic and reflects the historical observations provided by our BMR data sets. In future work, we plan to drive flux emergence statistically based on toroidal field conditions in the convection zone.

2.3.2. Dynamo Simulation Parameters and Setup

We use the same simulation parameters and setup as in Yeates & Muñoz-Jaramillo (2013). These parameters were optimized to match the spatiotemporal distribution of the toroidal field at the base of the convection zone and the observed distribution of BMRs in the photosphere of subsequent cycles.

The initial conditions for the simulations of isolated tubes are described in Section 4.1 in Yeates & Muñoz-Jaramillo (2013) and consist of an empirical formalism of a purely toroidal field layer in the tachocline. For each isolated flux tube, a velocity field perturbation is introduced to cause it to rise to the surface, where we match each flux tube with the observed magnetic flux, location, and orientation of a real active region at some particular time. This way, of course, the Kd3 model still relies on observations. Nevertheless, it is possible that these emergence parameters themselves could be modeled in the near future using, e.g., machine-learning algorithms. Our work presented here aims to provide a quantitative analysis regarding the ability of such synthetic magnetogram data to predict the solar wind conditions at 1 au.

We start our simulation at the beginning of solar cycle 20, initialized with symmetric toroidal belts with an average flux density of 250 G and a weak dipolar field. (The mathematical expressions describing our initial conditions are identical to those described in Yeates & Muñoz-Jaramillo 2013.) We then proceed to run Kd3 for four cycles, seeding emergence during each cycle using the data described above. At the moment, Kd3 is not able to match the observed varying delays between one cycle and the next. Because of this, we shift the beginning of each cycle to match the evolution of the internal toroidal field. However, once the cycle start has been prescribed, the time, latitude, longitude, and tilt of the BMR emergence are governed by observations.

Using the simulation parameters of Yeates & Muñoz-Jaramillo (2013), we perform a series of simulations to reach solar cycle 23. The procedure for all of them is the same.

1. Using the generic initial conditions described above, drive emergence using data from cycle 20.
Figure 2. Comparison of synthesized EUVs of the model with SOHO/EIT EUVs. The columns are, from left to right, 171, 195, and 284 Å. Top panels: observational SOHO/EIT images. Middle panels: synthesized EUVs of the model driven by the real magnetogram. Bottom panels: synthesized EUVs of the model driven by the synthetic magnetogram. The images are generated for CRs (a) 1925, (b) 1957, (c) 1989, (d) 2021, (e) 2009, (f) 2086, (g) 2112, (h) 2151, and (i) 2164.
2. Let the simulation continue in order to determine the best time alignment between emergences of cycle 21 and the evolution of the future internal toroidal field.

3. Reset the simulation, but this time run it with emergences from both cycle 20 and cycle 21 (delaying the beginning of cycle 21 emergence to the optimal time identified above).

Figure 3. OMNI data (black) and SWMF results for solar wind parameters driven by real (red) and synthetic (blue) magnetogram data for CRs (a) 1925, (b) 1957, (c) 1989, (d) 2021, (e) 2069, (f) 2086, (g) 2112, (h) 2151, and (i) 2164.
4. Let the simulation continue in order to determine the best time alignment between emergences of cycle 22 and the evolution of the future internal toroidal field.

5. Repeat steps 3 and 4 for cycles 22 and 23.

2.3.3. Toroidal to Poloidal Field in Kd3

The advective emergence of flux from within the convection zone by Kd3’s advective bubbles serves two purposes: (1) it
transports flux that is originally located within the convection zone, and (2) it imparts a tilt to the emerging flux bundle, creating a poloidal component. Yeates & Muñoz-Jaramillo (2013) found that this poloidal field is more than sufficient to seed the toroidal field of the next cycle via meridional flow, turbulent pumping, turbulent convection, and differential rotation. No additional source is necessary. In other words, Kd3 works as a self-sustained, pure Babcock–Leighton dynamo (once we add the advective mechanism that transports flux to the surface) by shearing and subducting the toroidal field generated out of the collective emergence of BMRs.

2.4. Simulations

For each CR, we first obtain a steady-state MHD solution using the real magnetogram input, where we modify AWSoM’s free parameters to obtain the best match to 1 au in situ observations. We then keep the model parameters the same when obtaining a solution using the synthetic magnetogram to keep the model consistent for both cases. For a side-by-side comparison of the real and synthetic maps, we refer the reader to Figure 1. For each steady-state solution from the Sun to 1 au, we extract the solution of the IH module along the orbit of the Earth during that CR. This extraction can be directly compared against 1 au in situ observations for CRs 1925, 1957, 1989, 2021, 2069, 2086, 2112, 2151, and 2164. We compare the SWMF simulated results with in situ observations at 1 au obtained from the OMNI database7 and SOHO/EIT8 images.

3. Results

We present steady-state solar wind simulations driven using real and synthetic magnetogram inputs for a selected set of CRs within solar cycles 23 (CR 1925, 1957, and 1989) and 24 (CR 2021, 2069, 2086, 2112, 2151, and 2164). We compare the SWMF simulated results with in situ observations at 1 au.

### Table 3

| CR     | \(B\) (nT) | \(T\) (K) | \(N_e\) \((\text{cm}^3)\) | \(U_r\) \((\text{km s}^{-1})\) |
|--------|------------|----------|----------------|-----------------|
| 1925   | 5.21       | 65,351   | 8.40           | 390.98          |
| 1957   | 7.14       | 140,764  | 5.19           | 474.05          |
| 1989   | 7.60       | 124,390  | 5.43           | 450.56          |
| 2021   | 5.55       | 79,191   | 6.24           | 391.60          |
| 2069   | 4.16       | 98,334   | 4.62           | 465.53          |
| 2086   | 4.02       | 60,093   | 5.08           | 384.09          |
| 2112   | 5.16       | 105,658  | 4.26           | 452.72          |
| 2151   | 5.18       | 57,371   | 6.86           | 367.48          |
| 2164   | 6.08       | 86,197   | 6.66           | 417.58          |

### Table 4

| CR     | \(B\) (nT) | \(T\) (K) | \(N_e\) \((\text{cm}^3)\) | \(U_r\) \((\text{km s}^{-1})\) |
|--------|------------|----------|----------------|-----------------|
| 1925   | 2.55       | 44,974   | 5.00           | 46.96           |
| 1957   | 3.13       | 83,490   | 5.54           | 113.86          |
| 1989   | 2.84       | 84,996   | 5.11           | 91.78           |
| 2021   | 2.42       | 65,720   | 3.82           | 76.63           |
| 2069   | 1.56       | 62,607   | 3.13           | 95.30           |
| 2086   | 2.02       | 49,045   | 3.48           | 72.05           |
| 2112   | 2.08       | 84,401   | 3.13           | 103.93          |
| 2151   | 2.26       | 45,943   | 4.37           | 64.44           |
| 2164   | 3.21       | 67,643   | 5.62           | 111.47          |

#### 3.1. EUV Images

The SC steady-state MHD solution holds the steady-state density and temperature structure for the particular CR. The SC has a tool to create synthetic line-of-sight (LOS) images in the EUV and X-ray bands by integrating the electron density square along the LOS, taking into account the local response function that is calculated from atomic databases (e.g., CHIANTI; Dere et al. 1997). For more information about the synthetic LOS images, we refer the reader to Downs et al. (2010).

For each solution, we generate synthetic LOS images as observed from the Earth during the center of the CR in the 171, 195, and 284 Å bands. Figure 2 shows the comparison for the SWMF-synthesized EUVs obtained from the real and synthetic magnetogram inputs with observed LOS images for CRs 1925, 1957, 1989, 2021, 2069, 2086, 2112, 2151, and 2164. The observation time for all

---

7 https://omniweb.gsfc.nasa.gov
8 https://umbra.nascom.nasa.gov/eit
Rotations coincides with the central meridian times of the real and synthetic maps used for the simulations. Each subplot set (associated with each CR) includes the 171 (left column), 195 (middle column), and 284 Å (right column) bands for the observed (top row), real magnetogram (middle row), and synthetic magnetogram (bottom row). Figures 2(a)–(c) visualize the EUVI comparison for the CRs within solar cycle 23, while Figures 2(d)–(i) show the comparison for CRs within solar cycle 24. Overall, both magnetograms do a reasonable job of reproducing the observed images, reproducing most of the large-scale bright features and coronal hole locations reasonably well. However, the synthetic magnetograms produce a blurry version of the real magnetogram, as they do not capture the small-scale features that may appear in the real magnetogram. There also seems to be some small shift in the synthetic magnetograms that may be related to the timing of the dynamo solution with the start/end time of the CR.

3.2. OMNI Data

We compare the SWMF predicted solar wind parameters at 1 au (using the two magnetogram inputs) with real in situ observations. The in situ observations include the hourly averaged solar wind conditions. Figure 3 shows the comparisons of simulation results at 1 au for the selected CRs within solar cycles 23 and 24. From top to bottom, the panels show the total magnetic field ($B$), plasma temperature ($T$), plasma number density ($N_p$), and plasma bulk speed ($U$). Each panel shows OMNI data (black) and the simulated solar wind using real (red) and synthetic (blue) magnetograms. Panels (a)–(c) show the solar wind comparisons at 1 au for CRs 1925, 1957, and 1989, respectively, within solar cycle 23, and panels (d)–(i) show results for CRs 2021, 2069, 2086, 2112, 2151, and 2164 within solar cycle 24.

Despite the fact that our goal here is not to validate the MHD model but rather to focus on comparing the results from the two magnetogram inputs, one should expect a reasonable performance of the SWMF. However, the 1 hr, point-by-point comparison shown in Figure 3 may undermine the model’s performance, as it represents a comparison of a global model, with a rather large grid size near the Earth, with a single point of measurement in time and space. Instead, we choose to quantify the model’s performance in a more statistical manner. For each data set (OMNI data, real, and synthetic magnetogram), each
CR, and a given parameter, we create a probability distribution of the 1 au values over the duration of the CR ±2 weeks. Then, instead of comparing the time series, we compare these distributions by defining their statistical properties—their mean and standard deviation. Figure 4 shows the probability density distributions for each solar wind parameter obtained from SWMF results driven by real (red) and synthetic (blue) magnetograms, compared with OMNI data (black) for the selected CRs. For each distribution, we calculate the mean values and the standard deviation to measure the spread and center point of the particular case and parameter. Tables 3 and 4 summarize the mean and standard deviation values. Figure 5 shows the mean values of each parameter of the distributions for SWMF results plotted against those of the OMNI observations. Figure 6 shows similar plots for the standard deviation.

4. Discussion

This paper introduces surface field maps (synthetic magnetograms) produced by the Kd3 code as a new input for solar wind MHD simulations. To validate the new input, we first optimize the SWMF for the real magnetogram input. We have shown that this input could potentially reproduce the solar wind parameters at 1 au and the LOS EUVIs with a reasonable agreement with predictions made by real magnetograms for some CRs.

When looking at the comparisons obtained for LOS EUVIs (see Figure 2), we find that the synthetic magnetogram could reproduce the EUVIs in reasonable agreement with observations. However, it could not provide as much detailed information on the lower corona as the real magnetogram. In general, EUV-bright regions are produced by the magnetogram’s active regions, and the dark coronal holes are produced by the open magnetic field regions, typically dictated by the lower-order magnetogram component. When considering an EUV comparison for CR 1925 (Figure 2(a)) centered on 1997 July 29, it is quite clear that the real magnetogram provides a better result than the synthetic magnetogram. However, the synthetic magnetogram result clearly captures the bright feature on the limb, as seen in the observations. On the other hand, for the CR 2086 comparison (Figure 2(f)) centered on 2009 August 6, the synthetic magnetogram reproduces additional bright features, which are not in the SOHO/EIT observations.

Figure 6. Correlation between the standard deviations of the solar wind parameters obtained from SWMF and OMNI observations at 1 au for CRs 1925, 1957, 1989, 2021, 2069, 2086, 2112, 2151, and 2164.
However, the real magnetogram result perfectly captures the observed images while reproducing the coronal hole morphology and the bright feature observed from 1 au. The overestimation here is because of the uncertainty of the Kd3 code in reproducing the bright features of the Sun at a period with very few active regions. So, when imposing velocity perturbations, the code amplifies the tiny bright spots of the Sun as large plumes.

Moreover, considering the EUVI for CR 2069 (Figure 2(e)) centered on 2008 April 29, we see that the synthetic magnetogram result was unable to capture the coronal hole morphology quite well, as shown in the real magnetogram simulated images. However, it captures the bright feature on the limb as observed in the SOHO/EIT images. The above-mentioned three rotations are for a period of solar minimum, occurring in solar cycles 23 (CR 1925) and 24 (CRs 2069 and 2086). All of the other rotations (occurring during a solar maximum) show a reasonable agreement with the real and synthetic magnetograms in terms of the active regions and coronal hole morphology. Looking at the comparison for CR 1957 (Figure 2(b)) centered on 1999 December 18, both SWMF-synthesized EUVIs show an offset in the location of the bright features of the Sun. Other than that, all other rotations (Figures 2(c), (d), (g), (h), and (i)) show a reasonable agreement, with the synthetic magnetogram images being a blurry version of the real magnetogram images. This is expected, as the synthetic magnetograms do not provide sharp, clear active regions. We plan to dedicate a future study to investigating how the sharpness of the active regions in the synthetic magnetograms can be improved, perhaps with an increased model resolution or a postprocessing image sharpening of the output magnetogram.

To observe the comparison statistically, we performed calculations for the rms error (RMSE), which compares the quantitative behavior of the EUVI between the model-synthesized and observed images. We refer the reader to Table 5 for the values of the RMSE. From Table 5, we see that the RMSEs for the model-synthesized images driven using the real and synthetic magnetograms are in excellent agreement. The RMSE between the observed and model-synthesized images using a synthetic magnetogram is slightly higher than the real magnetogram. However, for all cases, the RMSE values are on the order of less than ~0.3, implying that the model captures the coronal hole morphology and the bright regions of the corona in good agreement with the SOHO/EIT observations for both real and synthetic magnetogram inputs. Further, to observe how the EUVI RMSE comparison stands for each phase of the solar cycle, we categorized the nine rotations we used for the simulations under each phase (see Table 6). Here we performed an average RMSE analysis for EUV bands 171, 195, and 284 Å (see Figure 7).

From Figure 7, we see that for all bands, the RMSE is higher for the rising phase of the solar cycle, overall rising, and the maximum phase, showing consistent results for both real and synthetic magnetogram cases. Interestingly, the RMSE values obtained for the synthetic magnetogram in the 284 Å band are lower than for the real magnetogram comparison. From the quantitative point of view, for all phases, we see that the synthetic magnetogram does a better job synthesizing the EUVI than the real magnetogram in the 284 Å band. The 195 Å result implies that the real and synthetic magnetograms synthesize the EUVI consistently with the observations from SOHO/EIT.

| CR | Wavelength (Å) | Obs.–Real | Obs.–Syn. | Real–Syn. |
|----|---------------|-----------|-----------|-----------|
| 1925 | 171 | 0.1913 | 0.2388 | 0.1309 |
| 195 | 0.1579 | 0.1899 | 0.1235 |
| 284 | 0.1581 | 0.1667 | 0.0917 |
| 1957 | 171 | 0.2760 | 0.2881 | 0.2184 |
| 195 | 0.2280 | 0.2436 | 0.1628 |
| 284 | 0.2414 | 0.2570 | 0.1169 |
| 1989 | 171 | 0.1594 | 0.1748 | 0.1303 |
| 195 | 0.2068 | 0.2429 | 0.0957 |
| 284 | 0.2337 | 0.2418 | 0.1128 |
| 2021 | 171 | 0.2435 | 0.2669 | 0.1230 |
| 195 | 0.1484 | 0.1902 | 0.1092 |
| 284 | 0.1615 | 0.1747 | 0.0902 |
| 2069 | 171 | 0.2143 | 0.1831 | 0.1377 |
| 195 | 0.1349 | 0.1649 | 0.1010 |
| 284 | 0.1463 | 0.1588 | 0.0802 |
| 2086 | 171 | 0.2471 | 0.2428 | 0.2337 |
| 195 | 0.1564 | 0.1995 | 0.1553 |
| 284 | 0.1599 | 0.1984 | 0.1296 |
| 2112 | 171 | 0.2215 | 0.2457 | 0.1628 |
| 195 | 0.1595 | 0.1996 | 0.1321 |
| 284 | 0.1651 | 0.1932 | 0.1318 |
| 2151 | 171 | 0.2793 | 0.2408 | 0.2023 |
| 195 | 0.1711 | 0.1782 | 0.1165 |
| 284 | 0.1980 | 0.2015 | 0.1339 |
| 2164 | 171 | 0.2607 | 0.3403 | 0.1699 |
| 195 | 0.1785 | 0.1897 | 0.1029 |
| 284 | 0.1691 | 0.1710 | 0.1216 |

| Phase of the Solar Cycle | CRs |
|-------------------------|-----|
| Minimum                 | 1925, 2069, 2086 |
| Rising                  | 1957, 2112 |
| Maximum                 | 1989, 2151 |
| Declining               | 2021, 2164 |

From the observation point of view, we see that the synthetic magnetogram synthesized images are worse than the observed and real magnetogram synthesized images. However, the quantitative comparison shows that the model can reproduce the EUVI in excellent agreement for both real and synthetic magnetogram inputs.

The SWMF results show that both real and synthetic magnetogram input statistically reproduces the observed solar wind parameters at 1 au reasonably well for most CRs (see Tables 3 and 4 for the mean and standard deviation of the distributions). The SWMF results for CR 1925 and 2069 (solar minimum; see Figures 3(a) and (e)) driven by the real magnetogram produce solar wind that is faster than observed in OMNI observations, where this result is confirmed by the
distribution plots as well (see Figures 4(a) and (e)). Interestingly, the synthetic magnetograms for these CRs produce fast and slow wind, with a better agreement with observations compared to the real magnetogram. These solar minimum results indicate that the synthetic magnetogram could potentially reproduce the large-scale solar wind structure at 1 au (which is affected less by the active regions) quite well.

For the magnetic field comparison, we mostly find that the SWMF results underestimate the observations, which is consistent with, e.g., Cohen et al. (2008) and Sachdeva et al. (2019). However, looking at the distributions for the magnetic field, the SWMF results obtained from the real and synthetic magnetograms show similar distributions. The real and synthetic magnetogram simulation results also show an overall underestimation of the observed solar wind temperature. This is likely due to the fact that the modeled solar wind temperature represents the single-fluid MHD temperature, which may be different than the observed OMNI proton temperature. The plasma density comparison shows that for all CRs, the real and synthetic magnetogram-driven SWMF results show pretty good agreement. Figure 4 shows the summarized distributions of the solar wind parameters for the CRs representing solar cycles 23 and 24. Looking at the distributions, we find that the simulation results driven by the synthetic and real magnetograms match reasonably well, except for a few rotations. For CRs 1925 (Figure 4(a)) and 2086 (Figure 4(f)), we see that the synthetic magnetogram underestimates the solar wind parameters at 1 au compared with the real magnetogram input, which proves that the synthetic magnetogram performs well when there is a fair number of active regions on the solar surface (solar maximum conditions). These results are consistent with the EUVI comparisons and linear plots shown in Figures 2 and 3. For a more quantitative description of the distributions, please refer to Tables 3 and 4.

To further investigate the statistical performance of the model, we perform two additional statistical tests, the Kolmogorov–Smirnov (K-S) test and the Wasserstein distance calculations (Earth movers’ distance). The K-S test measures the degree of separation between the cumulative distribution of the two samples. In this work, we selected the null hypothesis $H_0$ by stating that the real and synthetic magnetogram simulated distributions are identical. We calculated test statistics $D$ (see Table 7), and we found that the obtained $p$-value for each solar wind parameter is $\approx 0$, which rejects the $H_0$ stating that the alternative hypothesis $H_a$ is true. In other words, the K-S test states that the distributions are not identical or from a similar population. We calculated the test statistics using the `scipy.stats.ks2samp`9 Python module. Even though the results from the K-S test did not confirm promising similarities of the two distributions, we identify a positive trend by looking at the cumulative distribution plots, where we found that the calculated values for the test statistics $D$ are small (see Table 7).

Figure 8 shows the cumulative distributions for all CRs representing the solar wind parameters, including the values of the $D$ statistics. The $D$ statistics provide the maximum vertical difference between the real and synthetic magnetogram-driven cumulative distributions. The statistics for each CR are summarized in Table 7. In Figure 8, we have interpreted the percentages by how much the distributions are off to the maximum of the other. The worst-case result is for the temperature distribution in CR 2086 (Figure 8(f)), and the observed value is 72.51%. Further investigating the cumulative distributions, we identify that the results we stated earlier for CRs 1925 (Figure 8(a)) and 2086 (Figure 8(f)) are consistent with the linear and probability density distribution plots. Overall, the cumulative distributions show that both inputs reproduce the plasma speed and density at 1 au in a good agreement. Cumulative distributions for CRs 2112 (Figure 8(g)) and 2151 (Figure 8(h)) show exceptional
agreement with each other, thus supporting our previous finding that synthetic magnetograms reproduce the solar wind at 1 au better during solar maximum.

To test the two probability density distributions in the horizontal direction, we perform the Wasserstein distance (Earth movers’ distance) calculations (see Table 8). This test deduces the minimum work where one distribution is required to change into the other (Chen et al. 2021; List 2021). To calculate the distance, we use the `scipy.stats.wasserstein_distance` Python function.
The comparison was for the simulation results obtained from the real and synthetic magnetograms. The values for each case are displayed in Figure 9 and Table 8. From Table 8, we see that the Earth movers’ distance values for the solar wind speed for CRs 1925, 2069, and 2086 that occurred in a solar minimum condition are high compared to the other rotations that occurred in a solar maximum.

These calculations confirmed the underestimation of the synthetic magnetogram input in reproducing solar wind at 1 au for CRs 1925 (Figure 9(a)) and 2086 (Figure 9(f)). Overall, we...
Table 8

| CR       | B (nT) | T (K)   | N_p (cm⁻³) | U₁ (km s⁻¹) |
|----------|--------|---------|------------|-------------|
| 1925     | 2.68   | 21,076.16 | 4.58       | 140.40      |
| 1957     | 4.18   | 5069.85  | 9.69       | 60.36       |
| 1989     | 2.20   | 16,617.00 | 3.01       | 30.79       |
| 2021     | 0.59   | 4408.33  | 3.40       | 49.88       |
| 2069     | 0.54   | 20,973.92 | 0.98       | 107.61      |
| 2086     | 0.38   | 32,972.21 | 3.87       | 207.23      |
| 2112     | 0.62   | 8579.07  | 0.87       | 48.74       |
| 2151     | 0.85   | 4879.25  | 1.98       | 68.66       |
| 2164     | 1.38   | 13,680.20 | 4.10       | 88.11       |

The calculated Wasserstein distances are small compared to the scale of each solar wind parameter, which means that the real and synthetic magnetogram distributions show good agreement when quantifying in the horizontal direction. Observing all of the statistical results, we see that the simulated solar wind parameters obtained for the CRs representing solar cycle 24 show better agreement with observations than those in solar cycle 23. We obtained the mean values and standard deviations for each solar wind parameter from the distributions (see Tables 3 and 4). Figures 5 and 6 show the linear relations for the mean and standard deviations for each solar wind parameter obtained for CRs 1925, 1957, 1989, 2021, 2069, 2086, 2112, 2151, and 2164. We do not see a strong correlation between the model-simulated solar wind parameters with OMNI observations from the plots. However, by looking at the relatively close slopes of both Figures 5 and 6, we see that there is a good linear relationship between the real and synthetic magnetogram results.

5. Conclusion

We study whether synthetic magnetograms can be used to predict the ambient solar wind at 1 au by comparing their performance against real magnetogram data. The comprehensive study and analysis conclude that synthetic magnetograms could initialize solar wind models for future space weather predictions as an alternative to the observed magnetograms in reproducing realistic solar wind conditions at 1 au. Overall, looking at the results, we conclude that the synthetic magnetogram performs better in reproducing 1 au results when a certain number of active regions are present on the solar surface or in a solar maximum. We plan to dedicate future study to investigating how synthetic magnetograms can be improved to provide better predictions for the solar wind at 1 au.

We thank an unknown referee for the useful comments. This work is supported by NASA HSR grant 80NSSC20K1354. Simulation results were obtained using the (open-source) Space Weather Modeling Framework, developed by the Center for Space Environment Modeling at the University of Michigan with funding support from NASA ESS, NASA ESTO-CT, NSF KDI, and DoD MURI. The simulations were performed on the Massachusetts Green High-Performance Computing Center (MGHPCC) cluster supercomputer. We thank Dr. Soumitra Hazra for his suggestions that improved this paper.