The Interaction of Coronal Mass Ejections with Alfvénic Turbulence

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Abstract. We provide a first attempt to understand the interaction between Alfvén wave turbulence, kinetic instabilities and temperature anisotropies in the environment of a fast coronal mass ejection (CME) near the Sun. The impact of a fast CME on the solar corona causes turbulent energy, thermal energy and dissipative heating to increase by orders of magnitude, and produces conditions suitable for a host of kinetic instabilities. We study these CME-induced effects with the recently developed Alfvén Wave Solar Model, with which we are able to self-consistently simulate the turbulent energy transport and dissipation as well as isotropic electron heating and anisotropic proton heating. Furthermore, the model also offers the capability to address the effects of fire hose, mirror mode, and cyclotron kinetic instabilities on proton energy partitioning all in a global-scale numerical simulation. We find amplified turbulent energy in the CME sheath, along with strong wave reflection at the shock combine to cause wave dissipation rates to increase by more than a factor of 100. In contrast, wave energy is greatly diminished by adiabatic expansion in the flux rope. Finally, we find proton temperature anisotropies are limited by kinetic instabilities to a level consistent with solar wind observations.

1. Introduction

Alfvén waves are regularly measured in situ in the solar wind, [2] and have more recently been remotely observed in the solar corona [6], where their energy is sufficient to heat and accelerate the solar wind. Based on these and similar observations, theories have been developed, which describe the evolution and transport of Alfvénic turbulence, e.g., [28, 20, 30, 31]. To self-consistently describe the heating and acceleration of the solar wind in response to turbulence, several extended magnetohydrodynamical (MHD) have been developed [25, 24, 4, 26, 12]. The recently developed Alfvén Wave Solar Model (AWSoM), [23, 27, 21] extends prior simulation capability with a three-dimensional solar corona/solar wind model that incorporates low-frequency Alfvén wave turbulence with three-temperature thermodynamics that captures the electron temperature in addition to resolving the anisotropic proton temperature into components parallel and perpendicular to the magnetic field.

AWSoM has already been used to study thermal structure of the steady state corona, and has been shown capable of explaining coronal non-thermal line-broadening with the turbulent motions of Alfvén waves [22]. The same work has shown it possible to explain the charge state composition of the slow wind with temperature evolution of plasma on open field lines at coronal hole boundaries. Manchester et al. [17] and Jin et al. [9] have employed AWSoM (in two-temperature mode [26, 27]) to study the coupled electron-proton temperature structure of coronal mass ejections (CMEs). These works found protons heated by the shock and energy
transferred to electrons by Coulomb collisions low in the corona where the collision frequency is high. Brief thermal coupling allowed electrons to attain no more than 10% of the maximum temperature of the protons, while electron thermal conduction allowed this heat to rapidly propagate ahead of the CME on open magnetic field lines forming a precursor of hot electrons ahead of the shock.

Here, we simulate the effects of CMEs and CME-driven shocks on the transport and dissipation of Alfvén wave turbulence as well as shock heating and Joule heating with the three-temperature version of AWSoM [27, 21]. We consider low-frequency Alfvén waves, which are assumed to dissipate below the ion cyclotron frequency. Wave amplitudes are prescribed at the lower boundaries to match observed wave motions in the low corona [6]. Our work follows that of Adhikari et al. [1] who first applied a detailed one-dimensional steady state turbulent model [29] to simulate quasi-parallel and quasi-perpendicular interplanetary shocks. In contrast to Adhikari et al., our turbulent transport is simpler with a phenomenological treatment of the wave dissipation, with a prescribed correlation length inversely proportional to the magnetic field strength as opposed to a time evolving formulation. The wave spectrum is not captured, so we only evolve the total forward and backward propagating wave energy densities. The partitioning of dissipated wave energy between electrons and protons is fixed so information about the wave spectrum is not required. The only turbulence parameters are the wave energy densities, the correlation length and the reflection rate. Our wave reflection model is essential the same formulation of Matthaeus et al. [20]. In this case, the energy of the dominant wave is transferred to the counter-propagating minor wave, with the reflection coefficient controlled by the gradient of the Alfvén speed.

We these simplifications, we extend the Adhikari et al. study in several significant ways. First we determine how turbulence depends on enhanced wave reflection at the shock surface, which increases turbulent dissipation. Second, our model addresses temperature anisotropies caused by preferential perpendicular proton heating at shocks and current sheets. Third, we include the effects of three kinetic instabilities: fire hose, mirror mode, and cyclotron instabilities. These modes are included to limit temperature anisotropies with thresholds that are dependent on the proton temperature ratio and plasma $\beta$. Finally our three-dimensional model includes the entire structure of the CME-driven disturbance, including sheath region and magnetic flux rope. This is the first time such kinetic physics has been incorporated into a global numerical model of a CME propagating through the solar corona, which allows us to address both particle heating, Alfvén wave damping, and their nonlinear coupled interaction.

2. Model Description

2.1. Coronal Model: AWSoM

The simulations are performed with the Alfvén Wave Solar Model (AWSoM), a global magnetohydrodynamic model from the upper chromosphere to the corona and the heliosphere in which the coronal heating and solar wind acceleration are driven with low-frequency Alfvénic turbulence [27]. AWSoM is able to address the coupled evolution of Alfvén turbulence with the magnetized plasma of the corona and solar wind in a global context. The model extends to a temperature minimum of 50,000K so that energy in the lower corona can be transported back to the upper chromosphere via electron heat conduction where it is lost via radiative cooling. The electron and proton plasma is described with a single fluid with three temperatures, an isotropic electron temperature and an anisotropic proton population with separate temperatures parallel and perpendicular to the magnetic field. The model employs heat conduction only for electrons with constant adiabatic index ($\gamma = 5/3$) and adiabatic indices of two and three for parallel and perpendicular pressures.

Alfvénic turbulence is described with two wave populations that propagate parallel and anti-parallel to the magnetic field with enhanced turbulent dissipation where populations coexist
at balanced levels. At the inner boundary, the Poynting flux of the outbound Alfvén waves is assumed to be proportional to the magnetic field strength. These outward propagating waves experience partial reflection on field-aligned Alfvén speed gradients and vorticity of the background. The nonlinear interaction between these oppositely propagating Alfvén waves results in an energy cascade through the inertial range to the smaller perpendicular gyro-radius scales, where the dissipation takes place. The apportioning of the dissipated wave energy to the electron and proton temperatures depends on kinetic physics that is not included in our model. The AWSoM model does possess a partitioning strategy based on the dissipation of kinetic Alfvén waves (KAWs). In particular the model employs the stochastic heating mechanism for the heating of the protons [3]. However, for this study, we use a simpler uniform partitioning strategy in which 40% of the wave dissipation is transferred to electron heating while the remaining 60% is used to heat the perpendicular proton temperature. Future work will examine the consequences of the self-consistent energy partitioning.

In the AWSoM model, we solve the MHD equations with proton temperature anisotropy augmented with equations for the low-frequency Alfvén wave turbulence. We employ a simplified, phenomenological form of the full turbulence transport equations that were first introduced by Zank et al. [28] and subsequently developed over the years [20, 29, 30, 31]. The following are a subset of the turbulence transport equations. For a full description of the numerical model, the reader is referred to van der Holst et al. [27]:

- The time evolution of the proton pressure is solved for the parallel proton pressure $P_{i\parallel}$ and the averaged ion pressure $P_i = (2P_{i\perp} + P_{i\parallel})/3$

$$
\frac{\partial}{\partial t}\left(\frac{P_i}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2\mu_0}\right) + \nabla \cdot \left[\left(\frac{\rho u^2}{2} + \frac{P_i}{\gamma - 1} + \frac{B^2}{\mu_0}\right)u + P_i u \cdot B - \frac{B(u \cdot B)}{\mu_0}\right]
= -u \cdot \nabla (P_e + P_A) + \frac{N_i k_B}{\tau_{ei}} (T_e - T_i) + Q_i - \rho \frac{GM_\odot}{r^3} \cdot u,
$$

$$
\frac{\partial P_{i\parallel}}{\partial t} + \nabla \cdot (P_{i\parallel} u) + 2P_{i\parallel} b \cdot (\nabla u) \cdot b = \frac{\delta P_{i\parallel}}{\delta t} + 2\frac{N_i k_B}{\tau_{ei}} (T_e - T_{i\parallel}) + 2Q_{i\parallel},
$$

where $T_{i\parallel}$ is the parallel proton temperature obtained from the equation of state $P_{i\parallel} = N_i k_B T_{i\parallel}$ and $P_i = P_{i\perp} I + (P_{i\parallel} - P_{i\perp}) bb$ is the ion pressure tensor. The second term on the right hand sides of Equations (1) and (2) are the collisional energy exchanges with the electrons. The third term on the right hand side are the heating functions $Q_i$ and $Q_{i\parallel}$ for the averaged ion and parallel ion pressure, respectively. The first term on the right hand side of Equation (2), $\delta P_{i\parallel}/\delta t$, is for the relaxation of the pressure anisotropy by the parallel firehose, mirror, and ion-cyclotron instabilities [21]

- The electron pressure

$$
\frac{\partial}{\partial t}\left(\frac{P_e}{\gamma - 1}\right) + \nabla \cdot \left(\frac{P_e}{\gamma - 1} u\right) + P_e \nabla \cdot u = -\nabla \cdot q_e + \frac{N_i k_B}{\tau_{ei}} (T_i - T_e) - Q_{\text{rad}} + Q_e,
$$

in which $Q_e$ is the electron coronal heating.

- The wave energy density $w_{\pm}$ (+ parallel to $B$, - antiparallel)

$$
\frac{\partial w_{\pm}}{\partial t} + \nabla \cdot [(u \pm V_A) w_{\pm}] + \frac{w_{\pm}}{2} (\nabla \cdot u) = \mp R \sqrt{w_{\pm} w_{\mp}} - \Gamma_{\pm} w_{\pm},
$$

where

$$
\Gamma_{\pm} = \frac{2}{L_\perp} \sqrt{\frac{w_{\pm}}{\rho}},
$$
is the phenomenological dissipation rate. The signed reflection rate \( R \) is derived as

\[
R = \min [R_{\text{imb}}, \max(\Gamma_\pm)] \begin{cases} 
1 - 2\sqrt{\frac{w_-}{w_+}} & \text{if} \quad 4w_- \leq w_+, \\
0 & \text{if} \quad 1/4w_- < w_+ < 4w_-, \\
2\sqrt{\frac{w_+}{w_-} - 1} & \text{if} \quad 4w_+ \leq w_-.
\end{cases}
\]

(6)

\[
R_{\text{imb}} = \sqrt{[(V_A \cdot \nabla) \log V_A]^2 + (\mathbf{b} \cdot [\nabla \times \mathbf{u}])^2}.
\]

(7)

For this particular simulation, we model the solar corona for Carrington Rotation number 2052, corresponding to the time period 2006 December 12 to 2007 January 08. We use GONG synoptic magnetograms to specify the magnetic field in the inner boundary of the model. To describe the time evolution of the turbulence, the following parameters are set. The Poynting flux at the inner boundary is proportional to the magnetic field, with proportionality constant \( 3 \times 10^5 \) J/m\(^2\)sT. The outward propagating wave energy density is specified to match this energy flux in accordance with the local flow and Alfvén speeds. The single prescribed correlation length is set equal to \( 1.5 \times 10^5 \sqrt{T(B)} \) m (where \( B \) is in Tesla), such that it scales with the diameter of a given flux tube.

### 2.2. CME Model: EEGGL

In order to simulate the CME, we employ the Gibson-Low flux rope model [7] with parameters specified by the Eruptive Event Generator Gibson-Low (EEGGL). This tool was developed by Jin et al. [11] and recently installed at the Community Coordinated Modeling Center (CCMC). Parameters are chosen to produce a fast CME with a speed of 1600 km/s certain to produce a fast-mode shock in the surrounding corona and solar wind. Without regard to any observed event, we select an active region from which to launch the CME. For these circumstances, EEGGL provides the following parameters: longitude = 45.5°, latitude = -6.5°, orientation = 330.7°, rope radius = 0.22 \( R_s \), and magnetic strength of 146 Gauss. The grid is uniformly refined in a spherical wedge in the path of the CME extending form 1.15 to 22 \( R_s \) and -30° to 60° latitude and 20° to 90° longitude. This background grid provides 1.0 degree resolution in latitude and longitude and radial resolution that varies from 0.01 to 0.25 \( R_s \). Two additional levels of grid refinement (increasing resolution by a factor of four) are applied to the CME’s path of propagation, which is sufficient to capture the shock and sheath structures.

### 3. Results

The flux rope and its entrained plasma are linearly superimposed in the closed field of the active region in a state of force imbalance. The flux rope expands rapidly and is ejected from the corona where it produces a fast CME that drives a fast-mode shock through the corona. This simulation is similar to earlier work [16, 14, 17, 9, 18, 10], however here we consider for the first time the interaction of the CME with the Alfvénic turbulence and proton temperature anisotropy.

We begin here with a detailed description of the interaction of the CME-disturbance with the low-frequency Alfvén turbulence. We give a representative description of the simulation results at time \( t = 2.0 \) hours after CME initiation, when the CME-driven shock has reached approximately 15 \( R_s \). The model at this time is shown in Figure 1 where the CME disturbance is shown on the meridional cut plane. The plasma velocity shown in Panel (a) reveals the shock front extending into the fast wind over the pole and protruding into the slow-speed wind at low latitude where the CME propagates. Panels (b) through (d) show the reflection rate, total (sum of forward and counter-propagating) wave energy density, and wave dissipation rate respectively. Inspection reveals the remarkable impact the CME has on the Alfvénic turbulence. We find complex structured enhancements in wave energy, as well as reflection and dissipation.
Figure 1. Wave related quantities are shown in color contours on a meridional cut plane passing through the center of the CME, two hours after initiation. Panel (a) shows the plasma velocity, which clearly illustrates the shock front propagating ahead of the CME and extending into fast wind. Three-dimensional magnetic field lines are shown with the twisted and distorted field of the flux rope clearly evident. The black line is where data is extracted for line plots. Panel (b) shows the magnitude of the wave reflection coefficient, which is greatly enhanced at the shock front and in the CME. The total (forward and counter-propagating) wave energy density and wave dissipation rate are shown in panels (c) and (d) respectively. Levels of wave energy and dissipation are greatly enhanced in the sheath and suppressed in the flux rope.

rates, while also producing regions of depleted wave energy in the ejected flux rope. Panel (b) shows the enhancements in wave reflection are greatest at the shock front at the flanks of the CME and in the flux rope. The logarithmic representation in Panel (c) shows variation in wave energy density that covers 4 orders of magnitude. A broad region of the sheath wrapping around the flux rope contains energy at level of $10^{-5}$ erg/cm$^3$ with the exception of the region connected to the heliospheric current sheet. Panel (d) shows that the dissipation rate with a pattern of enhancement that roughly matches the elevated levels of wave reflection.

To better understand the relationship of the Alfvénic turbulence with the CME disturbance, we provide Figure 2, which shows color contour images of the wave related quantities (Panels (b)-(d) respectively) divided by the pre-eruption ambient values. Panel (a) shows the mass density ratio, which provides a measure of the compression going through the shock. As expected for
Figure 2. The same wave related quantities from Figure 1 are shown divided by the ambient values. Panel (a) shows the plasma mass density, which shows the shock compression that varies between three and four for this strong shock. Panel (b) shows the wave reflection ration, which shows the large increases at the shock and at the heliospheric current sheet. The wave energy and dissipation ratios are shown in panels (c) and (d) respectively. The wave energy in the sheath typically increases by a factor of ten, while peaking at a value of 25 at the nose of the CME. In conjunction wave dissipation rates rates increase in the sheath by roughly a factor of 50, reaching a peak of 140 at the nose of the CME.

For a strong shock, the compression ratio varies between three and four, while a low density cavity is found in the ejected flux rope. The wave reflection ratio shows a large increase at the shock front that varies by factor of 10 to 25, while a region of enhancement cuts through the center of the flux rope, which marks the location of the pre-eruption current sheet. This magnitude of the reflection is mathematically expressed in equations 6 and 7, which is dependent on the gradient in the Alfvén speed. The reflection in this case is occurring where the density increase at the shock resulting in a dramatic decrease in the Alfvén speed over a short distance. The opposite is true at the current sheet, where magnetic field was once nonexistent and is then replaced by the flux rope. The wave energy is typically enhanced in the sheath region by a factor of 8-10, which is consistent with adiabatic compression at the shock. At the nose of the shock, the Alfvén energy increases by a factor of 25, which corresponds a high rate of reflection.
Figure 3. Plots of wave related and plasma thermal quantities from data extracted on the black line shown in Panel (a) of Figure 1. For reference, solid lines show ambient values at time $t = 0$ while dashed lines show CME-perturbed quantities at $t = 2$ hours. The top panel shows forward $E_{w1}$ and counter-propagating $E_{w2}$ wave energy densities in blue and red respectively. On this field line pointing toward the sun, the $E_{w2}$ wave propagates away from the Sun while $E_{w1}$ is directed toward the Sun. The reflection and dissipation rates are plotted in green and black respectively. Note the large increases in wave energy associate with reflection from the moving shock wave. Plotted in the bottom panel are the electron and proton temperatures (perpendicular and parallel) the temperature ratio, $T_{perp}/T_{para}$, and the parallel plasma beta in lines colored black, red, green, blue and purple. Note the inverse relationship between the temperature ratio and plasma beta.
transporting wave energy to the current sheet region that previously had very low energy. Panel (d) shows the greatest increases in wave dissipation occur where both energy and reflection are simultaneously increased. Due to the quadratic dependence on wave energy, the dissipation rate increases by roughly a factor of 50 over most of the sheath and reaches a peak value of 140 at the nose of the CME.

Next we evaluate the line plots of the wave quantities in the top panel of Figure 3. These values are extracted along a straight line, shown in Figure 1, that extends from the center of the Sun and passing through the CME. Here, the forward and counter-propagating wave energies are plotted with blue and red lines respectively, where direction is with regard to a field line pointing toward the Sun. Green and black lines show the reflection rate and energy dissipation rate respectively. In all four cases, solid and dashed lines show values at time $t = 0$ and $t = 2$ hours respectively. At time $t = 2$ hours, the wave reflection peaks at the shock with a value that is 42.7 times greater than the ambient value. This strong reflection is most clearly seen in the wave energy reflected back toward the Sun, $E_{w1}$, which increased by a factor of 68.5 over the ambient value. In comparison, $E_{w2}$ increases by only a factor of 13.6 here. Reflection does not create wave energy but only converts one form to another. In this example gain in $E_{w2}$ comes from a large compression, while the much large increase in $E_{w1}$ is attributed to reflection converting $E_{w2}$ to $E_{w1}$. The waves interact to dissipate energy at a rate 111 times above the ambient value.

We next discuss the heating and cooling of the plasma and the temperature anisotropy. For this purpose, we provide color contour images of thermodynamic quantities in Figure 4, which are shown on the same time and meridional slice as the previous Figures. Here, the electron temperature, shown in Panel (a), is elevated at the shock from roughly 0.7 MK to 1.2 MK, with a significant precursor of hot electrons extending ahead of the shock. The proton parallel, perpendicular temperatures, and their ratio, $T_{\text{per}}/T_{\text{par}}$, are shown in Panels (b) through (d) respectively. To complement this Figure, the bottom panel of Figure 3 provides line plots of the electron temperature, and proton perpendicular and parallel temperatures, their ratio, $T_{\text{per}}/T_{\text{par}}$ and the parallel plasma $\beta$. Examining the line plots we find that prior to the shock, the parallel temperature is 0.4 MK, which then rises to 9.7 MK as the density increases by a factor of 3.6 at the shock. In contrast, the perpendicular temperature rises nearly twice as much from 0.5 MK to 19.8 MK. These elevated temperatures are greatest at the nose of the CME where the shock passes through the slow wind with the highest Mach number. In the flux rope, we find a complex mix of hot plasma caused by Joule heating at magnetic current sheets surrounded by cold plasma cooled by adiabatic expansion. The electrons receive no heating from either shock or magnetic dissipation, and thus form a large cool cavity at a temperature near 0.27 MK.

In reality, the dissipative heating at shock and current sheets is distributed to both parallel and perpendicular temperatures by a host of complex plasma instabilities. For our model, the MHD simulation is designed to account for the effects of the fire hose, mirror mode, and cyclotron plasma instabilities. These instabilities are invoked to limit the temperature anisotropy in accordance with their respective thresholds for onset, which are prescribed analytically. The thresholds for these instabilities are determined by the parallel and perpendicular plasma $\beta$s, which vary strongly over the range of the CME-disturbed solar wind. Examining the bottom panel of Figure 3, we find in the sheath, high temperatures and mass density produce parallel $\beta$ that ranges from roughly 10 to 60. In contrast, the plasma beta in the flux rope is much lower, ranging from roughly 0.5 to 0.01. The affects of plasma instabilities can be seen in the inverse relationship between $T_{\text{per}}/T_{\text{par}}$ and the parallel $\beta$, which is indicative of the thresholds for the cyclotron and mirror mode instabilities, which limits $T_{\text{per}}/T_{\text{par}}$ to a value approaching 7 in the lowest $\beta$ portions of the flux rope.
Figure 4. Plasma temperatures are shown in color contours at two hours after CME initiation on the same cut plane shown in Figures 1 and 2. Panel (a) shows the electron temperature, which exhibits only mild elevation behind the shock with a hot precursor formed by heat conduction. Parallel and perpendicular temperatures are shown in panels (b) and (c) which show high degrees of shock heating, while Panel (d) shows the temperature ratio $T_{\text{perp}}/T_{\text{para}}$.

4. Conclusions

We simulate the propagation of a CME with the AWSoM coronal model to provide an understanding of the driven interaction between Alfvén wave turbulence, kinetic instabilities and temperature anisotropies in the environment close to the Sun. In the impacted solar corona, turbulence, temperatures, and dissipative heating increases by orders of magnitude providing conditions suitable for a host of kinetic instabilities. Significant enhancements of wave turbulence are found primarily in the CME sheath region while a significant depression in wave energy forms in the magnetic flux rope that at its lowest is at 1% of the level of the background level. In passing through the strong fast-mode shock, the total turbulent energy increases by factors ranging from 10 to 25 while wave energy reflected by the shock toward the Sun reaches a factor of nearly 100. Over most of the sheath, wave dissipation rates increase by a factor of 50 while peaking at 140 times the ambient value at the nose of the CME.

In spite of these large increases, wave heating is relatively insignificant on the time-scale of encountered by a fast CME close to the Sun. The conspicuous signs of heating we find here are
driven by dissipative heating at the shock and at current sheets as well as adiabatic compressional heating, and adiabatic expansion being the only source of cooling. At the shock, we find very strong anisotropic proton heating with proton perpendicular and parallel temperatures reaching 20 MK and 10 MK respectively. The temperature ratio (perpendicular/parallel) remains at a value of roughly two over a broad range of the sheath region. Localized temperature peaks occur in the flux rope rope where the temperature ratio is much higher reaching values approaching 7.

The AWSoM is designed such that proton heating from dissipative processes, either turbulence, shocks or current sheets preferentially goes to the proton perpendicular thermal energy. This ansatz alone would produce enormous temperature anisotropies that would incite kinetic instabilities whose primary effect is to redistribute energy to the parallel thermal reservoir of the protons. It is known that elevated perpendicular temperatures will drives mirror-mode and cyclotron instabilities, which has been made manifest at CME-driven shocks by the presence of increased temperature anisotropy and mirror mode waves [13]. Our MHD model can not describe the development of such instabilities, but where temperature ratios exceed the stability threshold, temperatures can relax back to the marginal stable state with the time scale of the relaxation set by the corresponding growth rates of the fire hose mirror mode and cyclotron instabilities. The end result is that the temperature ratio scales inversely with the parallel plasma beta, which is consistent with solar wind observations [8, 19] and ACE observation of CME sheaths with elevated perpendicular proton temperature enhancements capable of driving the mirror mode instability [13].

Understanding this complex interaction between the CME-affected plasma and turbulence is essential to the acceleration of solar energetic particles that are scattered by turbulent structures, which strongly affects their transport and energization from multiple shock crossings. Such work is also essential to understanding the impact of the CMEs on the distribution and dissipation of Alfvén waves, which is particularly timely as we anticipate predicting observations of Alfvén wave turbulence to be made by Solar Orbiter and Solar Probe Plus. Our future will also involve more physics of turbulent dissipation including the effects of the inertial range and stochastic heating.

4.1. Acknowledgments
W. Manchester was supported by NASA grant NNX16AL12G and NSF grants AGS1322543 and AGS1408789. B. van der Holst was supported by NASA grant NNX16AL12G, NSF grant AGS1459862 and the European Union’s Horizon 2020 research and innovation program under grant agreement No. 637302 PROGRESS. The authors wish to acknowledge high-performance computing support provided with the Yellowstone Supercomputer operated by NCAR’s Computational and Information Systems Laboratory, and the Pleiades supercomputer operated by NASA’s Advanced Supercomputing Division. Our work utilizes synoptic magnetogram data obtained by the Global Oscillation Network Group (GONG) Program, managed by the National Solar Observatory.
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