An Empirically Driven Time-Dependent Model of the Solar Wind

Jon A. Linker1, Ronald M. Caplan1, Cooper Downs1, Roberto Lionello1, Pete Riley1, Zoran Mikic1, Carl J. Henney2 Charles N. Arge2, Tae Kim3 and Nikolai Pogorelov3

1Predictive Science Inc., San Diego, CA 92121
2Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, NM 87117
3Department of Space Science, University of Alabama, Huntsville, AL35899

E-mail: linkerj@predsci.com, caplanr@predsci.com, cdowns@predsci.com, lionel@predsci.com, pete@predsci.com, mikicz@predsci.com, cjhenney@gmail.com, afrl.rvb.pa@kirtland.af.mil, tkk0023@uah.edu, np0002@uah.edu

Abstract. We describe the development and application of a time-dependent model of the solar wind. The model is empirically driven, starting from magnetic maps created with the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model at a daily cadence. Potential field solutions are used to model the coronal magnetic field, and an empirical specification is used to develop boundary conditions for an MHD model of the solar wind. The time-dependent MHD simulation shows classic features of stream structure in the interplanetary medium that are seen in steady-state models; it also shows time evolutionary features that do not appear in a steady-state approach. The model results compare reasonably well with 1 AU OMNI observations. Data gaps when SOLIS magnetograms were unavailable hinder the model performance. The reasonable comparisons with observations suggest that this modeling approach is suitable for driving long term models of the outer heliosphere. Improvements to the ingestion of magnetograms in flux transport models will be necessary to apply this approach in a time-dependent space weather model.

1. Introduction

The outer atmosphere of the Sun, the solar corona, is a plasma that expands to become the supersonic solar wind, which envelopes the planets and forms the heliosphere. The structure and dynamics of the solar wind are strongly influenced by the solar magnetic field, including the locations of fast and slow solar wind and the position of the heliospheric current sheet (HCS). The magnetized solar wind is also the primary medium by which solar activity is transmitted to the Earth and beyond, in the form of coronal mass ejections (CMEs), which evolve and propagate in the wind, and energetic particles, which are transported along the magnetic field. Realistic models of the solar wind (in the sense of having sufficient fidelity to be compared with observations) are thus important not only for understanding how the large-scale heliosphere arises from coronal structure and dynamics that we observe remotely, but also for the prediction of solar wind impacts on space weather at Earth.

The key observational input to coronal and solar wind models are maps of the global photospheric radial magnetic field ($B_r$). Global solar maps are developed from full-disk
magnetograms of the line-of-sight (LOS) magnetic field (in turn derived from measurements of the Zeeman splitting of spectral lines) and are available from ground and space-based observatories. These observations are presently available only from the Earth view, so the maps are built up over the course of a solar rotation. Often referred to as “synoptic” maps, they are really diachronic maps [1]. These maps serve as an essential boundary condition for coronal models, be they potential field or full magnetohydrodynamic (MHD).

MHD models with a lower boundary at the solar surface can in principle predict both the structure of the solar corona and the solar wind. However, the processes that heat the solar corona and accelerate the solar wind occur on scales far below that of a global model, are far from completely understood, and indeed may not be realizable in single fluid MHD. An active area of research is to develop global MHD solutions that parameterize/model these processes to fully describe the detailed properties of the corona (as observed in EUV and X-ray emission, for example) and also predict the properties of the solar wind [2, 3, 4].

Empirical models have been shown to be able to predict solar wind structure with reasonable success from a magnetic field model based on observed photospheric fields [5, 6, 7, 8]. At the present time, the U.S. National Centers for Environmental Prediction compute potential field source surface (PFSS) [9] and potential field current sheet (PFCS) [10] models for the magnetic field based on photospheric magnetic maps, and then use the Wang-Sheeley-Arge (WSA) model [8] to empirically specify the boundary conditions for the Enlil MHD model [11]. The MHD equations are integrated to steady state. These solar wind solutions are used to predict the arrival of fast solar wind streams and as the background state for “cone model” CME simulations. Models of the ambient corona and solar wind are typically integrated to steady state, in part because of the lack of a description of the time-evolving photospheric magnetic field. However, the processes by which the magnetic flux on the Sun evolves have been studied for many years. Flux transport models [12, 13, 14, 15] incorporate these processes (primarily differential rotation, meridional flow, supergranular diffusion, and random flux emergence) and have been successful in predicting the evolution of photospheric magnetic fields. These models can assimilate magnetograms from available observatories to produce a continuous approximation of the state of the photospheric magnetic field, as a sequence of synchronic maps. The Air Force Data Assimilative Photospheric flux Transport (ADAPT) model [16] is a unique example in that it includes rigorous data assimilation and ensemble modeling techniques [17].

In this paper, we demonstrate a time-dependent, empirically driven MHD model of the solar wind. We describe how sequences of ADAPT maps can be used to create time-dependent boundary conditions for an evolving solar wind model. By construction, our simulation does not include the effects of CMEs, but focuses on modeling the ambient wind through which CMEs propagate. A goal of this work is to develop a time-dependent model of the solar wind for the 5-year period from 9/27/2003 to 9/27/2008, to be used to drive simulations of the outer heliosphere using the MS-FLUKSS code [18]. We show our initial results for the time period 9/27/2003-9/27/2004, and compare them with OMNI observations.

2. Model Description
2.1. Empirically Driven Models
The ambient solar corona (and in turn the solar wind) restructures in response to changes in the photospheric magnetic field. To capture the evolution of the Sun’s magnetic field, we use maps of the photospheric magnetic field derived from the ADAPT model. For the time period of interest, ADAPT was run using daily full disk magnetograms obtained from National Solar Observatory’s Synoptic Optical Long-term Investigations of the Sun (NSO SOLIS) Vector Spectromagnetograph (VSM). The maps were provided on a 180 × 360 uniform latitude and longitude mesh. We smoothed the maps to remove abrupt pixel to pixel variations. Eventually, we would like to compute time-dependent MHD solutions of the solar corona driven by ADAPT.
maps [19], but the calculation of such solutions over years of time would require a large computational investment. In the place of an MHD model for the magnetic field, we first compute a PFSS model from 1 to 2 solar radii \( (R_S) \) for daily ADAPT maps, followed by a PFCS model to compute the field from 2-30\( R_S \). This last step is required to obtain a field where \(|B_r|\) shows little variation in latitude, consistent with observations [20]; such configurations arise naturally in MHD models. The PFSS and PFCS models are computed numerically on nonuniform 101 \( \times \) 181 \( \times \) 361 \( (r, \theta, \phi) \) spherical meshes using a preconditioned conjugate gradient method. We note that during 2004, there were a number of significant data gaps for SOLIS magnetograms, related to testing the VSM and moving it to Kitt Peak. During these time periods, ADAPT continued to produce daily synchronic maps, but there are obviously quality problems as the model will drift away from observations during these time periods. We will return to this issue in section 3.3.

Empirically driven MHD models of the solar wind can circumvent the requirement of a detailed coronal model. Reference [5], using PFSS models, first showed an inverse correlation between coronal flux tube expansion (known as the expansion factor) and solar wind speed. This technique was later implemented using PFSS models based on daily updated observatory maps [6]. Reference [7] developed an empirical technique using polytropic MHD models as the the underlying field model and a mapping based on the distance to the coronal hole boundary (DCHB); this empirical method was then used to form the boundary conditions for solar wind models with an inner radius beyond the Alfven and sonic critical points \( (30R_S) \). Reference [8] augmented the expansion factor technique used in [6] with a factor based on the DCHB; this is the present WSA model. Recently, reference [21] compared the three empirical techniques and showed that the techniques of [8] and [7] produce similar results that are superior to use of the expansion factor alone. The WSA and DCHB models produce similar results because the slow wind produced in the WSA model arises predominantly from the DCHB term. We use the DCHB model to specify the velocity as a 4\( \pi \) steradian map at 30\( R_S \); the density \( n \) is then computed from the empirical observation of roughly constant momentum flux [22], and the temperature \( T \) from thermal pressure balance. The details are described by reference [7]. Figure 1 summarizes our empirically driven model.

2.2. MHD model
The empirical procedure described above provides us with a sequence of boundary maps at 30\( R_S \) of radial magnetic field, density, temperature, and radial velocity, in the rotating frame of the Sun, at a cadence of 1 per day, to drive our heliospheric MHD solutions. The solutions are

![Figure 1. Diagram showing the components of the empirically driven time-dependent model. Sequences of ADAPT maps are supplied at the solar boundary. These are used to calculate sequences of PFSS and PFCS models, that in turn provide the radial magnetic field at the inner boundary of the heliospheric MHD model. The DCHB prescription (see text) is used to provide radial velocity, density, and temperature at the MHD inner boundary.](image-url)
Figure 2. Boundary conditions and results for PFSS models. (a) ADAPT magnetic map for 11/27/2003 at 12:00UT. The approximate location of the assimilation window for new magnetic data is shown as a green oval. (b) The same as (a) but for 12/08/2003 at 12:00UT. (c) Signed coronal hole boundaries (blue for inward magnetic flux, and red for outward) for the PFSS model on 11/27/2003. (d) The same as (c) for 12/08/2003. (e) Synoptic EIT 195 Å image for this time period. (f) Position of the HCS (boundary between blue and red) at 12/08/2003.

computed on a nonuniform $265 \times 181 \times 361$ spherical mesh extending from $30 - 230R_S$ with the Magnetohydrodynamic Algorithm outside a Sphere (MAS) code (Earth is at $\sim 215R_S$ or 1 AU). MAS has been used extensively in models of coronal structure [23, 24, 2, 25], coronal dynamics [26, 27, 28] and coronal mass ejections [29, 30]. MAS solves the time-dependent resistive MHD equations on a nonuniform spherical coordinate grid using a semi-implicit algorithm [31]. The code is massively parallel and scales to thousands of cores. Among its many advantageous properties, the formulation exactly preserves $\nabla \cdot \mathbf{B} = 0$. MAS is the primary MHD model in CORHEL (Corona-Heliosphere), a suite of models [32] for describing the solar corona and inner heliosphere.

Our method for coupling coronal and heliospheric solutions (including the set of equations solved) is described by [30]. Here we make a few brief remarks. As the inner boundary for the calculation is chosen beyond the critical points, all of the MHD values should be specified, subject to the constraint $\nabla \cdot \mathbf{B} = 0$. The heliospheric calculations are performed in the inertial frame, so the supplied boundary values must be transformed from the rotating frame to the inertial frame. In practice this means the boundary values move in the longitudinal direction with the Sun’s rotation rate; this is accomplished by linearly interpolating the values to their new position on the grid at each time step. The boundary values also change in time as the PFSS/PFCS solutions change. As the times steps in the calculation ($\sim 2$ minutes) are much smaller than 1 day, values are interpolated in time between the values specified for each PFSS/PFCS. The
Figure 3. The magnitude of the radial magnetic field at 1 AU from OMNI data (black) and the average global radial magnetic field at 1 AU predicted from PFSS models using ADAPT maps (green). The ADAPT maps were scaled by a factor of 1.5 (see text). ADAPT captures the general trend of the interplanetary magnetic field during this time period, when there was a large-scale decrease in the field as part of the approach to and during the recent unusual solar minimum.

magnetic field is advanced via specification of the tangential (to the boundary) electric field; in practice this is accomplished by a Helmholtz decomposition of the electric field into two potentials. As described by [30], this has the advantage of exactly preserving the supplied $B_r$. At the outer boundary, all the quantities are computed with the help of characteristic equations.

3. Results

3.1. PFSS solutions

Figure 2 shows the PFSS solutions for two time snapshots: 11/27/2003 at 12:00UT (Figures 2(a)&(c)) and 12/08/2003 at 12:00UT (Figures 2(b),(d)&(f)). Figures 2(a)-(b) show the ADAPT maps used as boundary conditions. The maps are scaled from -20 to 20 G to better illustrate the structure in the weaker field regions. Figure 2(c)-(d) shows the signed open/closed regions (proxies for coronal hole boundaries), with blue indicating inward-pointing open field regions ($-B_r$), red indicating outward-pointing open field regions ($+B_r$), and gray indicating closed field regions. It is the structure of the open/closed regions that determines the parameters that drive the heliospheric model. Figure 2(e) shows a SOHO Extreme Ultraviolet Imaging Telescope (EIT) 195Å “synoptic” map [33] for this time period (Carrington rotation 2010; 11/19-12/17/2003). The EIT map is built up over the solar rotation from measurements near disk center, similar to a magnetic synoptic map (available at http://sun.stanford.edu/synop/EIT). The map is filled between 7°-173° co-latitude. The dark regions in emission are observed coronal holes. The open field regions in the model correspond roughly to the EIT map, although the shapes are somewhat different and in general the modeled coronal holes are somewhat larger than those observed; this could in part be due to obscuration of coronal holes by nearby active region loops. Figure 2(f) shows the HCS location predicted by the model at this time.

We can compare the heliospheric open magnetic flux predicted by the model with observations of $B_r$ at 1 AU from OMNI (http://omniweb.gsfc.nasa.gov). We calculate an equivalent field strength at 1 AU by computing the magnitude of the open flux in the model, dividing by the
Figure 4. Time-dependent solar wind simulation results in the heliographic equator. Red indicates the largest values and blue the smallest. The Earth’s location is shown as a white disk in each image. Figures (a)-(c) correspond to 11/27/2003 15:07UT while Figures (d)-(f) are 8 days later at 12/08/2003 15:07UT. Figures (a) and (d) show plasma density, (b) and (e) show plasma temperature. Figures (c) and (f) show the radial velocity and magnetic field lines traced from the outer boundary of the calculation inward. The field lines are traced in 3D, so lines that appear to end actually pass beneath the displayed surface.

surface area at the upper boundary, and scaling to 1 AU using the expected $r^{-2}$ fall off. We have found that coronal models, whether simple (PFSS) or complex (e.g., thermodynamic MHD models), tend to underestimate the interplanetary magnetic field (IMF) when using typical observatory maps [34, 1]; the reasons for this are unresolved. To account for this underestimate, we uniformly multiply the ADAPT values by 1.5. During 2003-2008, the IMF exhibited an unprecedented drop in IMF field strength [35], associated with the approach to the unusual solar minimum of 2008-2009. Figure 3 shows that the model with ADAPT maps captures this trend rather well, particularly in the time period of the simulation presented here (2003-2004).

3.2. Time-dependent Solution

The MHD solution is initialized by taking the first ADAPT map on 9/27/2003, computing PFSS and PFCS models, and empirically prescribing the boundary values at $30R_S$ as described in section 2.1. The initial magnetic field in the heliosphere is a potential field consistent with the supplied $B_r$. We advance the solution for 200 hours of real time assuming the boundaries are not changing (in the rotating frame) to obtain a steady-state solar wind with a Parker spiral magnetic field. We then proceed to compute the time-dependent solution until 9/27/2004, modifying boundary values as described in section 2.2.

We illustrate the behavior of the time-dependent solution in Figure 4, which shows the
solution at 11/27/2003 15:07UT and 12/08/2003 15:07UT in the heliographic plane. The approximate location of the Earth (actually slightly out of this plane) is shown as a white disk. The density ($n$) has been scaled by $r^2$ and the temperature ($T$) by $r$ in the images for easier visualization of the quantities. The figure shows classic features of interplanetary solutions, with corotating fast and slow solar wind streams (Figures 4(c)&(f)). The density $n$ in Figures 4(a)&(d) is enhanced at streamer interface regions; these regions are at the leading edge of the high-speed wind where the interaction between fast and slow wind occurs. Temperature (Figures 4(b)&(e)) is enhanced at the streamer interface and within the fast streams. Superimposed on the radial velocity ($v_r$) in Figures 4(c)&(f) are magnetic field lines traced from $230R_S$ inward. The field lines are traced in three dimensions so lines that appear to end actually pass beneath the velocity surface. Figure 4(f) shows the expected spiral magnetic field lines.

Figure 5. 3D view of the radial velocity at 11/27/2003 15:07UT. Values of velocity are shown on a surface in the heliographic plane, on a semi-transparent sphere at $r = 150R_S$, and on a semi-transparent longitudinal cut plane at the location of the Earth.

The solution also exhibits features that are not found in a steady-state description, particularly in the 11/27/2003 frames. Figures 4(a)-(c) show the formation of a new fast stream (near the top of each figure) that has not yet propagated out to 1 AU. This feature is associated with a restructuring of the magnetic field; note the presence of disconnected field lines (i.e., field lines that do not trace back to the Sun but are connected at both ends to the outer boundary) in the upper and lower parts of Figure 4(c). These disconnections occur at the HCS and appear to come about because, at times, the HCS at the lower boundary can change significantly on the order of a day. If we were using a true time-dependent coronal model to drive the heliospheric solutions, these reconfigurations might be topologically different; closed field lines might expand outward and reconnect with surrounding open field lines in so-called interchange reconnection [36].

Figure 5 shows a three-dimensional view of the $v_r$ at 11/27/2003 15:07UT. The opaque plane cutting through the center of the plot shows $v_r$ in the heliographic plane, the same as in Figure 4(c). Near the north pole of the semi-transparent sphere and in the longitudinal cut plane, high speed wind is seen to dominate; however, there is a mix of slow and fast wind at all latitudes, arising from the complex coronal structure present at this time period.

3.3. Comparison with Observations
To test the simulation results against observations, we collect data from the simulation at the L1 point every 6 hours to form a time series. As the model is only realistic for large scale structures, we compare it with 6 hour running averages of $B_r$, $v_r$, $n$, and $T$ from OMNI, also plotted every 6 hours. The results from the entire year of the simulation are shown in Figures 6-7. Also shown as green boxes are SOLIS data gaps, defined as periods where SOLIS magnetograms were unavailable for three or more days (the box is placed on the third and subsequent days). CMEs
Figure 6. Comparison of the simulation results with OMNI observations for 9/27/2003-9/27/2004. Time is given along the x axis as fractional year. Data are plotted every 6 hours. Time periods when SOLIS magnetograms were unavailable for the ADAPT model for more than 3 days are shown as green boxes at the bottom of each plot. (a) The radial magnetic field ($B_r$) in nT. (b) The radial velocity ($v_r$) in km/s.

have not been removed from the data set, the largest of which are noticeable as velocity spikes in Figure 6(b).

Figure 6(a) shows that the simulation reproduces the overall sector structure and magnitude of the heliospheric magnetic field quite well. The location of fast streams also often show a good correspondence with the observed streams (Figure 6(b)), particularly in 2003 and early 2004. Figure 7(a) shows that the model uniformly predicts much higher densities at the stream interfaces than are observed. This discrepancy appears to arise in the boundary specification, where the momentum flux is assumed to be constant. The lower speed wind in the vicinity
Figure 7. Comparison of the simulation results with OMNI observations for 9/27/2003-9/27/2004, in the same format as Figure 6. (a) The number density \( n \) in cm\(^{-3}\) (b) The temperature \( T \) in Kelvin.

of the HCS makes the density much higher there, indicating that this aspect of the empirical specification can perhaps be improved. The plasma temperature in the fast streams is roughly similar to the observations (Figure 7(b)), but there are temperature spikes in the OMNI data that are not associated with fast speed wind and are not reproduced by the model.

It is perhaps surprising that \( B_r \) shows reasonable correspondence with the OMNI data even during some of the time periods of long SOLIS data gaps, such as 2004.25 to 2004.45 (3/31-6/01/2004), when the VSM was operational for only 7 out of 63 days. However, while the location of the fast streams during this period were not entirely dissimilar from the OMNI data, the model predicted much faster speeds than were measured. During another period of long data gaps (2004.51-2004.61, 7/6-8/10/2004, VSM operational for 12 out of 36 days) the model
Figure 8. Comparison of the simulation results with OMNI observations for 11/17-12/17/2003. Data are plotted every 6 hours. This period had few SOLIS data gaps. (a) The radial magnetic field \( B_r \) in nT. (b) The radial velocity \( v_r \) in km/s. (c) The number density \( n \) in cm\(^{-3}\). (d) The temperature \( T \) in Kelvin.

appears to drift away from reality for all quantities.

For a more detailed comparison, we examine the same quantities in Figures 6-7 for a 30 day period from 11/17-12/17/2003 in Figure 8. This time period had only a few SOLIS data gaps. The magnitude and sign of \( B_r \) from the model correspond well with the observations, as do \( v_r \) and \( T \). As we saw in Figure 7(a), the model predicts densities at the stream interfaces that are much higher than observed. While the solution corresponds quite well with the observations in a global sense, the predicted arrival of the HCS crossings and the fast wind streams can differ from the measurements by as much as a day. The measurements (even with 6 hour averages) also show more structure than is in the model.

4. Summary & Discussion

We have developed a time-dependent model of the solar wind using ADAPT maps as input. For the year of time simulated here (9/27/2003-9/27/2004), the model compares reasonably well with OMNI measurements. It is perhaps surprising that the model performed well in late 2003, because the Sun was very active at that time, with some of the largest CMEs ever recorded (and are not included in the model). Despite this activity, the model comparisons indicate that the large scale heliospheric structure was reproduced during this time period, indicating that this is a valid approach for driving models of the outer heliosphere over long time intervals. Data gaps for SOLIS magnetograms certainly hinder the performance of the model; there are fewer of these in subsequent years. By circumventing the calculation of a full coronal model, the computational requirements for modeling the inner heliosphere are greatly reduced. The one year simulation required about 20 hours of wall clock time on 576 processors.

It is interesting to speculate on the usefulness of this approach for space weather models.
While it does not appear thus far that the results are markedly better than solutions computed for individual Carrington rotations, the time-dependent approach is more efficient than computing sequences of steady-state models with an artificial relaxation time for each solution. A higher time cadence of maps (as is possible now with GONG or HMI) may improve the results and be essential for space weather applications. However there are important data issues to address if this approach is to be used in a more practical or operational setting.

In their present state, ADAPT maps (or those from any flux transport model) differ significantly from the true evolution of the Sun’s photospheric magnetic field. When the model is run in near real time, active regions appear in an unrealistic manner; first one polarity of the active region appears in the assimilation window, followed by the opposite polarity appearing later. Our procedures automatically balance the total positive and negative magnetic flux in every map, but this is done globally on the map. Balancing the flux to compensate for a poorly observed AR, followed by rebalancing when the full region comes into view, can lead to artificial changes to open/closed boundaries and the HCS. This likely drives some artificial evolution in our present model. This problem could be avoided by automatically identifying these instances and delaying the appearance of the active region until the full region is observed, but such procedures have yet to be developed.

A second difficulty is that data are only assimilated on the Earth-facing side of the Sun. Active regions that emerged several days earlier appear in the map only when they rotate into view; this artificially forces the evolution to occur in the narrow assimilation window, which sweeps across the Sun at the rate of the solar rotation. This issue could be mitigated for scientific studies by retrospective analysis to estimate where and when the active regions first emerged and incorporating them in the maps prior to the first Earth-based observation. This could in principle be done most effectively during the STEREO era. However, for space weather applications, this limitation may only be diminished by obtaining magnetograph measurements from a view away from the Sun-Earth line.

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