PRediction Of Geospace Radiation Environment and Solar wind parameterS

Work Package 2
Propagation of the Solar Wind from the Sun to L1

Deliverable 2.2
The coupling of the AWSoM and SWIFT codes

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Contents

Summary

Space weather forecasts require reliable knowledge of the IMF Bz field at L1 and this is required before they are measured there *in situ*. The AWSoM code developed at the University of Michigan will take magnetogram observations and use these to drive MHD simulations, time-accurate, out to around 30 solar radii. These coronal simulations can then be used to drive a fast, spherical geometry inner-heliospheric MHD code (SWIFT) to give predictions at L1. This report covers the decisions made, and tests performed, in coupling the AWSoM code to the SWIFT code to provide an initial test-bed toolchain which can take GONG magnetogram data, pipe into AWSoM and then through SWIFT to predictions at L1. The coupled toolchain is available for all members of the PROGRESS project to use and will be actively improved and optimized over the next six months using historical data from GONG and uncertainty quantification software. Real-time test predictions from the full ASWoM/SWIFT code set are expected to start in five months.

1 Introduction

This report details the work done, and decisions made, in coupling the spherical geometry SWIFT Lagrangian-remap code to the University of Michigan AWSoM code [3]. AWSoM takes GONG data and uses this to drive a coronal simulation out to 20-30 solar radii. At this radius output from AWSoM is used to drive SWIFT which then completes the simulation from 20-30 radii out to L1. The conversion of the *Lare3d* code [1] to the spherical geometry SWIFT code has already been documented in deliverable report D2.1 in December 2015. The full simulation suite, from GONG data to L1, will be documented in D2.3 at the end of the project. WP2 will be coupled to all other work packages providing forecasts of L1 variables for all of the other toolsets. This coupling is the aim of WP7. The final toolchain will forecast space weather using GONG observations of the solar magnetic field coupled to predictive simulations.

2 Overview of D2.2 within WP2 activity

2.1 Reading GONG data and improvements to AWSoM

Within the PROGRESS project we will use standard GONG synoptic magnetogram maps to initiate the solar corona. For the purpose of validation we first simulated the steady state solar wind for Carrington Rotation (CR) 2123 (among other rotations), see Fig. 1. To initialize AWSoM, we first determine the Potential Field Source Surface Model

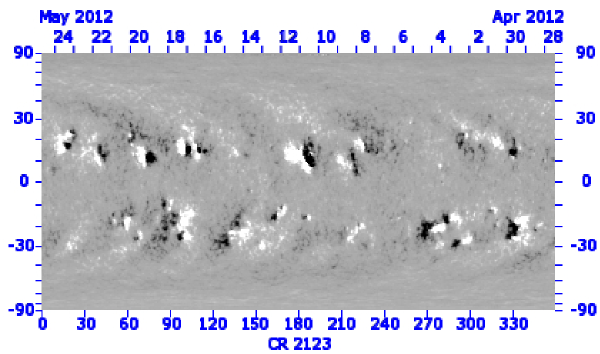

Figure 1: Standard GONG synoptic magnetogram map showing the radial magnetic field component in gray-scale for Carrington Rotation 2123, downloaded from http://gong.nso.edu/data/magmap/. The resolution of the map is 360×180 for the longitude and latitude, respectively

(PFSSM) solution for a given magnetogram. AWSoM has two different PFSSM solvers, one using the spherical harmonics and one using a finite difference scheme. The spherical harmonics method is fast, but suffers from so-called Gibbs phenomenon (or ringing) near active regions resulting in less accurate solutions. The finite difference method does not suffer from the ringing, but is much slower in performance (it uses an implicit solver in 3D). Since our goal is to obtain fast and time accurate solutions at LI and 1AU and the background wind does not much depend on the accuracy of the active regions, we decided to employ the spherical harmonics method using 180 harmonics. This PFSSM magnetic field is used in AWSoM to initialize the magnetic field and to set the radial magnetic field component boundary condition. We split the magnetic field in the initial field $\mathbf{B}_0$ and AWSoM numerically solves for the corrected field $\mathbf{B}_1$. The total magnetic field is $\mathbf{B}_0+\mathbf{B}_1$.

The correction to the PFSSM field is due to the changes in temperature along a field line, and hence pressure, from the AWSoM heating model changing the force balance from the force-free PFSMM configuration.

We made a significant speed improvement to AWSoM in the following way: The original AWSoM has the inner boundary located at the upper chromosphere. To numerically resolve the upper chromosphere, transition region, and lower corona, AWSoM needed a resolution too high for the short runtimes required of a predictive code. To mitigate that we have implemented a 1D version of AWSoM that can solve the lower corona (between 1 and 1.15 solar radius) much faster. Each boundary cell at the inner boundary (now located at 1.15 Rsun) of the 3D AWSoM is connected to a 1D AWSoM solver along the PFSSM magnetic field between 1 and 1.15 solar radius. The equations solved along the field lines connecting the AWSoM lower boundary cells to the photosphere are derived by intergating the full MHD equations along a thread of magnetic flux. This integration is over a magnetic flux tube element of length ds bounded by two closed cross sections of the flux tube and a bundle of magnetic field lines about the considered thread, all of which pass through the contours of these cross sections. The resulting equations are simplified in the low-β approximation. In particularly, the continuity equation for a steady-state flow along the flux tube gives $\rho u/B = constant$, where u is the field aligned velocity, ρ the mass density and B the magnetic field strength. The same procedure gives a time-dependent energy equation and Alfvén wave energy spectrum required to give the set of thread equations. These are then solved for each thread which intersects a boundary point of AWSoM. Hence, the 3D AWSoM no longer needs the extremely small cell sizes of the lower corona, allowing for much larger time-steps. The resulting speed up is by more than a factor of 200 and to the new AWSoM model takes only 60 minutes on 60 Intel x86 processor cores to predict values all the way out to 1 AU.

Figure 2 displays for CR2123 the steady state solar wind speed, proton number density, proton average temperature, and magnetic field magnitude along the Earth orbit for the model (black) and OMNI data (red), which contains the solar wind and IMF conditions at 1AU. Besides the shown quantities AWSoM can also output the electron temperature, Alfvén wave energies, and any velocity and magnetic field component. This shows a good qualitative match to OMNI date for the radial velocity and temperature but less well captures the density and magnetic field strength. AWSoM-R continues to be improved at Michigan and CCMC and these improvements will all become available to the PROGRESS project once verified.

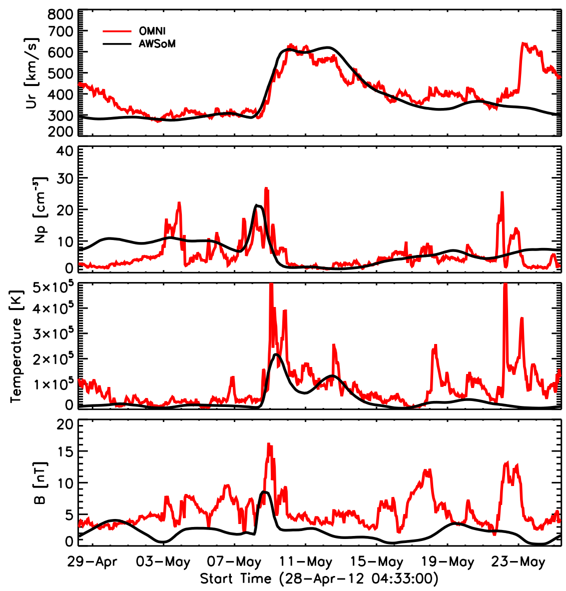

Figure 2: The simulated solar wind properties along the Earth orbit and the OMNI data during CR2123.

2.2 Boundary output from AWSoM data format

For time accurate simulations using AWSoM, we update the PFSSM solution (hence $\mathbf{B}_0$, while maintaining the total magnetic field) within AWSoM every six hours with the latest synoptic GONG magnetogram. In addition, we change the magnetic field boundary conditions to the latest magnetogram. If needed, we can increase the magnetogram update cadence or even interpolate between two consecutive magnetograms. However, except for active regions, the variations at the inner boundary is very slow and six hour cadence is sufficient for most cases. Thus AWSoM can be run using GONG data, a 1D model along PFSSM field lines up to 1.15 solar radii and then the full spherical geometry 3D AWSoM AMR code out to around 20 solar radii. This is the Solar Corona (SC) part of AWSoM. This can be extended to L1 or 1 AU by coupling the spherical AWSoM to a Cartesian version beyond 30 solar radii, this is the Inner Heliosphere (IH) component of AWSoM. The two components are coupled via a buffer grid. SC first interpolates the solar wind conditions (magnetohydrodynamic and Alfvén wave turbulence variables) onto a spherical grid with a grid resolution of $2 \times 180 \times 90$ cells for the radial, longitudinal, and latitudinal direction. The radial extend of the buffer is between 18 and 21.55 solar radius. This buffer is communicated through MPI calls to the IH component. IH interpolates these variables into the ghost cells of the inner boundary of IH. Since the inner boundary of IH is located in the superfast solar wind regime, SC does not need information from IH. This buffer is also written into a buffer file. Instead of this latter coupling to Cartesian AWSoM the PROGRESS project aims to couple to a fast 3D spherical MHD solver (SWIFT) through boundary data exchange as detailed below.

2.3 Loading AWSoM data to drive SWIFT

As explained in the previous section, AWSoM writes a buffer zone of MHD variables which can be read into SWIFT and used as boundary conditions for driving the solar wind at 0.1 AU.

The buffer zone is written into two files, each of which contains the data for a 2D spherical shell at a given radius. The files are written in double precision as a series of Fortran records. They are of a very basic self-describing nature and contains information about the size and shape of the arrays and number of arrays written. There is also a list of names for each array. This information can be used to verify that the data being read is that which was expected. The data is written in the HelioGraphic Inertial Coordinate system (HGI), for which z is the rotation axis of the Sun pointing “North”, the x-axis is the intersection of the ecliptic and solar equatorial planes, which was at 74.367° ecliptic longitude at 12:00 UT 01/01/1900 and the y-axis completes the right handed coordinate system. Each variable in the file is a 2D array with the first dimension corresponding to longitude and the second dimension corresponding to latitude. The longitude angle runs from $0°$ to $360°$, with 0 corresponding to the $y = 0$, x-z plane and the angle increases in an anti-clockwise direction about the positive z-axis. The latitude angle runs from $-90°$ to $90°$ where $-90°$ corresponds with the negative z-axis and $90°$ corresponds with the positive z-axis. All variables are node-centred. The variables written are density, the cartesian components of velocity followed by those of magnetic field, an electron heat flux parameter, forward and backward components of the Alfvén wave energy density, electron pressure and ion pressure.

The SWIFT code uses a slightly different coordinate system, so a certain amount of transformation must be performed on the data when reading the buffer files for use as boundary conditions. SWIFT is written in spherical coordinates following the convention specified by the ISO standard 80000-2. This is a right-handed system (r, θ, ϕ) where ϕ is equivalent to the longitude of the AWSoM output buffer but θ varies from 0 to π where 0 is aligned with the positive z-axis and π with the negative z-axis. In addition, the vector components of velocity and magnetic field are required in spherical directions rather than Cartesian. Finally, the grid staggering used for SWIFT (shown in Figure 3) differs from that supplied by the AWSoM code. A comparison of the density output by AWSoM and the final transformed version used in SWIFT is shown in Figure 4 to verify that the necessary transformations and interpolations are working correctly.

At present, the code has been set up such that the resolution of the buffer written by AWSoM exactly matches that used by SWIFT. In our initial test runs this resolution has been 59 points in the radial direction (from 0.1 to 1 AU), 64 in the θ direction and 128 in the ϕ direction. Future runs will be performed at a higher resolution to match that used for ENLIL predictions. These typically use a similar resolution in θ but 180 points in the ϕ direction and 320 in the radial direction. Matching the SWIFT resolution to that of

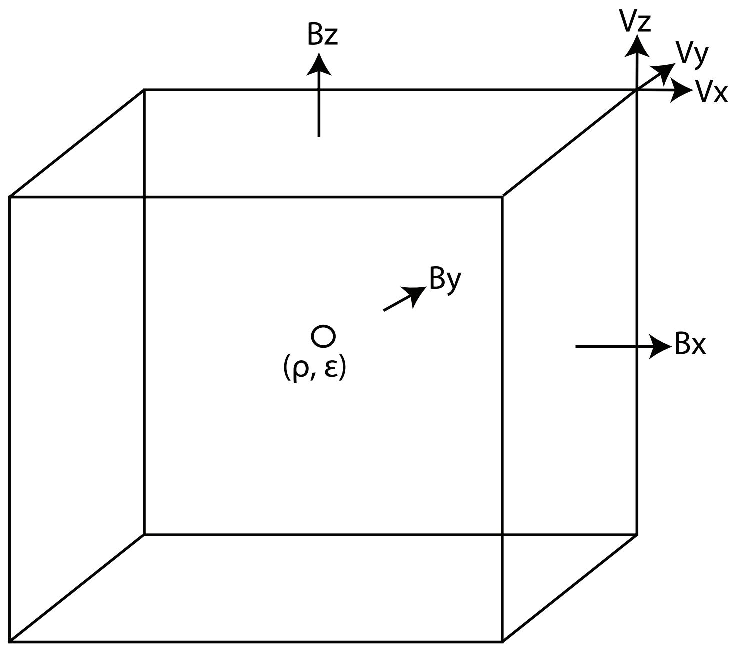

Figure 3: Staggered grid locations for SWIFT variables.

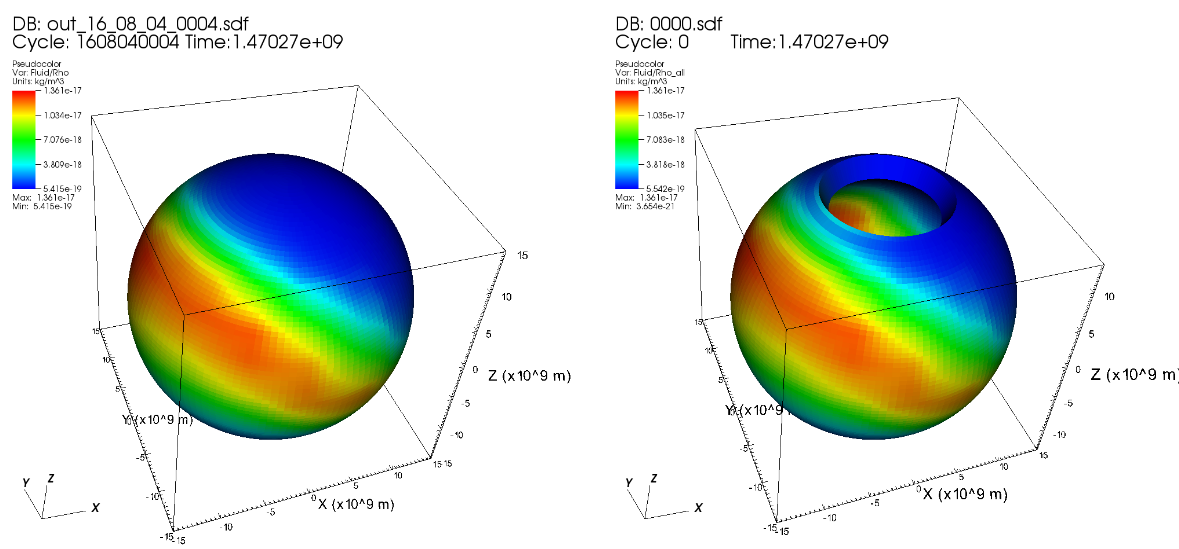

Figure 4: The figure on the left-hand side shows the density written to a buffer file from AWSoM. The right-hand side shows the boundary values used in SWIFT after reading the file, converting coordinates and applying boundary conditions.

the AWSoM output buffer eases the coupling of the two codes since there is a one to one mapping between points.

2.4 Example test output

Once the routines for coupling the AWSoM and SWIFT codes had been written and checked for correctness, a test problem was run using the procedure that we plan to use for the production runs. The procedure for driving the model in a time accurate manner using observational magnetograms is as follows. Hourly updated magnetograms are retrieved from the GONG ftp site (`ftp://gong2.nso.edu/QR/bqs/`). The synoptic magnetogram data is extrapolated to a 3D potential field source surface solution using spherical harmonics. This data is then provided to the AWSoM code which integrates out to a distance of 0.1 AU. During our test runs, this stage of the process took about 30 minutes on a 36 core, 2.1 GHz Intel Xeon machine. The AWSoM code then writes a set of buffer files for use by the SWIFT code. SWIFT reads the buffer and sets boundary values at 0.1 AU based on the contents of this file. It then solves the full MHD equations to evolve a solar wind solution out to 1.1 AU. With the resolution specified above, the timestep for this model is approximately 10 minutes so there are approximately 5 steps taken for each set of magnetogram data. In production runs, the boundary values for these interim steps will be provided by rotating the magnetograms which bracket the time required and then interpolating the data to give an appropriately weighted average. Since the differences between successive magnetograms is relatively small, in our test setup we omit this procedure and merely switch from one magnetogram to the next every 5 steps.

The initial conditions for SWIFT are produced by reading data from the first set of AWSoM buffer files and simply extrapolating the values radially throughout the computational domain. Values for the velocity components and the specific internal energies are merely duplicated in the radial direction. Density and the magnetic field components are reduced by a factor of $(r0/r)^2$, where $r0$ is the radius of the inner boundary. This gives

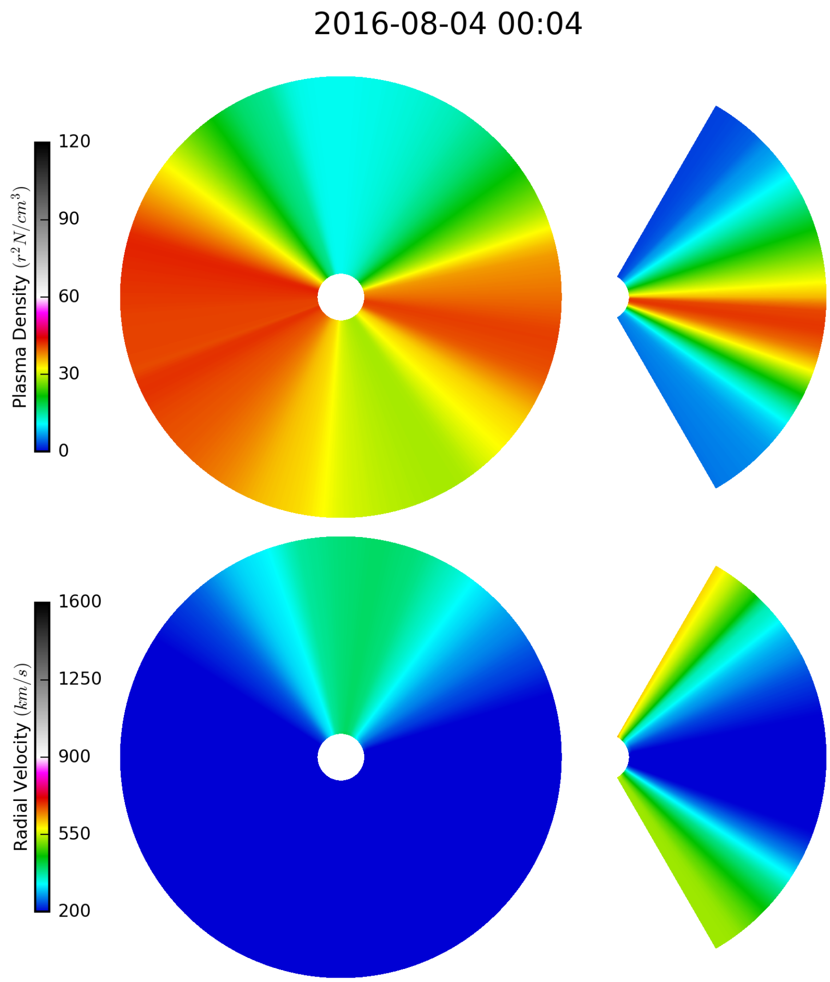

Figure 5: Slices through $\theta = \pi/2$ and $\phi = 0$ for normalised plasma density and radial velocity at the start of the simulation.

conditions such as that shown in Figure 5. A better set of initial conditions might be provided by application of the Parker spiral solar wind model, but since these conditions will be completely flushed out once the simulation has been run for long enough it was decided this was not worth the additional computational costs at startup.

The simulation was driven using hourly updated magnetograms from the 4th of August 2016 until the 23rd of August 2016. Slices through the solar wind solution for the final time of the simulation are presented in Figure 6 along with results from WSA-ENLIL of the same time frame in Figure 7. The left-hand plot is a slice through the ecliptic plane looking down from the solar north pole, with the Sun-Earth line directed horizontally

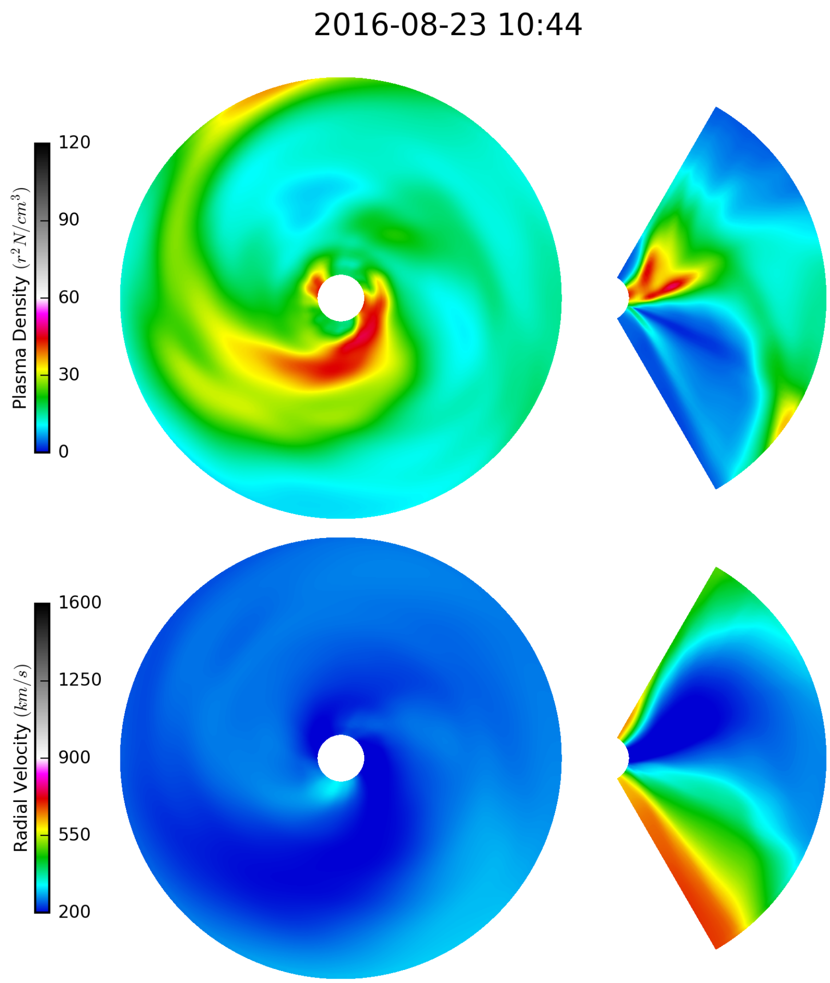

Figure 6: Slices through the meridional slice containing the Earth's location and $\phi = 0$ for normalised plasma density and radial velocity at the end of the simulation.

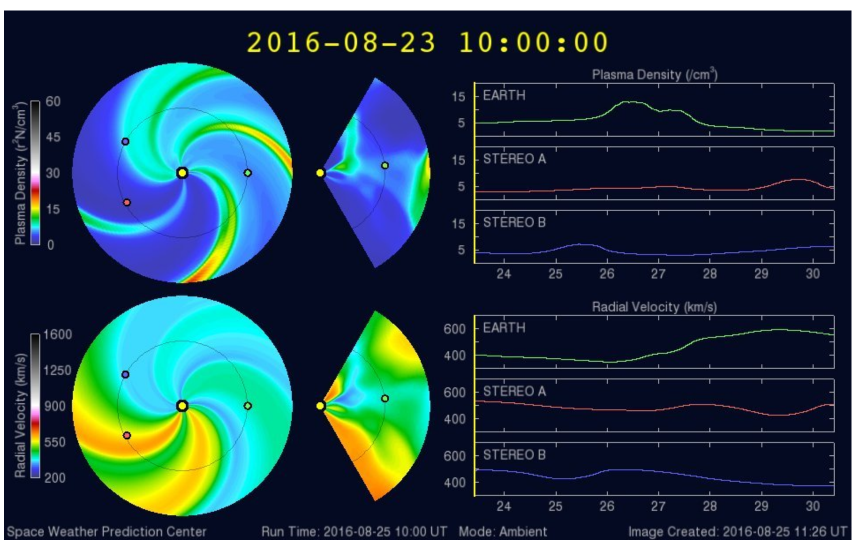

Figure 7: ENLIL results at a time corresponding to the final time in our SWIFT test run.

from left to right. The right-hand plot is a slice through the meridional plane containing the Earth. The WSA-ENLIL plot was obtained from the archives at `https://www.ngdc.noaa.gov/enlil_data/`. It can be seen that whilst some general features of the two models are similar, there are some large differences in the densities and the fine structure of the magnetic field. The density anomalies are due to some known problems with the AWSoM model which are currently being rectified. The fine structure is partly due to a lack of resolution in the ϕ direction from our current simulations. The values used in driving the boundaries lack such fine structure from the outset as can be seen in Figure 8 which compares the values used in the SWIFT simulation compared with those generated by the WSA model used for driving the ENLIL simulation. The WSA-ENLIL boundary driving at 21.5 solar radii is far more highly structured and dynamic than that from AWSoM-R. While both approaches use similar resolution for the potential field solver the specification of density, velocity and temperature in ENLIL uses an emperical best fit model [2] with parameters tuned to match WIND observations at L1. This gives ENLIL boundary a more highly structured driver and to acheive the same variation with the full first-principles approach of AWSoM-R may need an increased resolution or tuning of the Alfvén wave turbulence model, both currently being investigated at Michigan. In the coupled ASWoM/SWIFT model developed by the PROGRESS project the aim is to be fully predictive and use a direct causal chain from GONG data to measurements at L1 and 1 AU. This will not use parameter 'tuning' such as that in WSA-ENLIL. In the PROGRESS model, providing sufficiently high resolution can be used, a truly causal predictive model can be used and so the physical processes which connect the atmospheric layers are all fully included.

After five or six days of running the simulation, all artifacts from the initial conditions are flushed from the system and remaining values are the result of physically meaningful driving boundary values. A time series of values beyond this time as measured at the Earth's position are plotted in Figure 9 along with OMNI data. The same output from

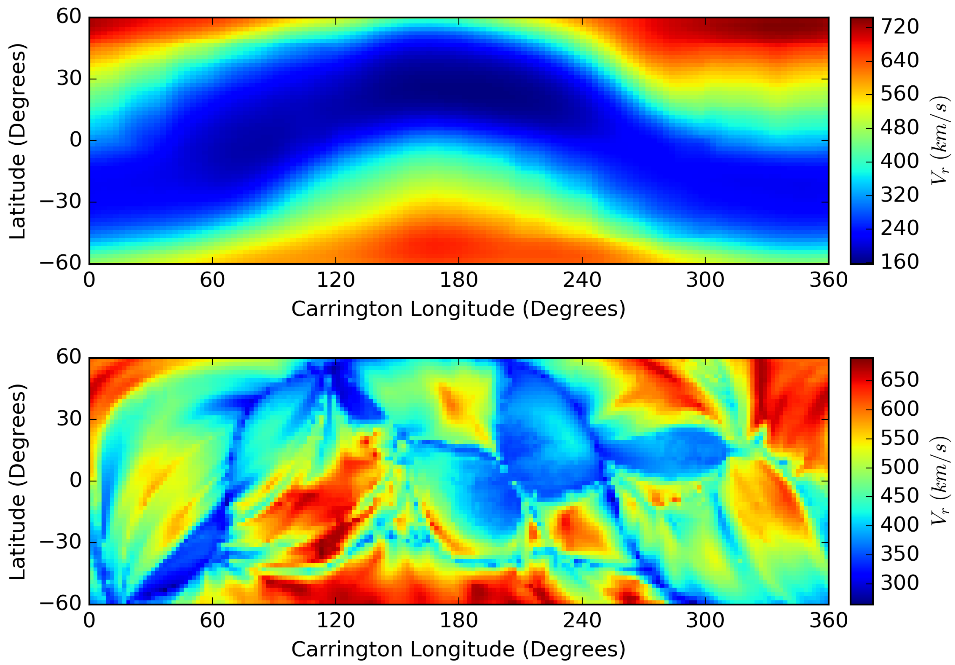

Figure 8: Boundary values for V_r. The plot on top shows the values produced by AWSoM and the one below shows the values used by ENLIL.

WSA-ENLIL is shown in Figure 10

Figure 9 shows that AWSoM/SWIFT is within a factor of roughly 4 for the match to OMNI data but the results in Figure 10 from ENLIL are closer. As has been discussed above this is due to the nature of the WSA-ENLIL empirical fitting of boundary parameters allowing greater details at 21.5 solar radii than possible with the current resolution of coupled AWSoM/SWIFT or possibly the Alfvén wave turbulence model parameterisation in AWSoM. Both options are being investigated in 2017. Note however that the ENLIL simulated output at 1 A.U. no longer contains the fine structure of its boundary driver at 21.5 Rsun as shown in Figure 8.

3 Issues and future development

Several issues have been identified in the AWSoM/SWIFT coupling which may affect the later stages of the project, i.e. running time accurate predictions out to L1 and 1 AU. These are:

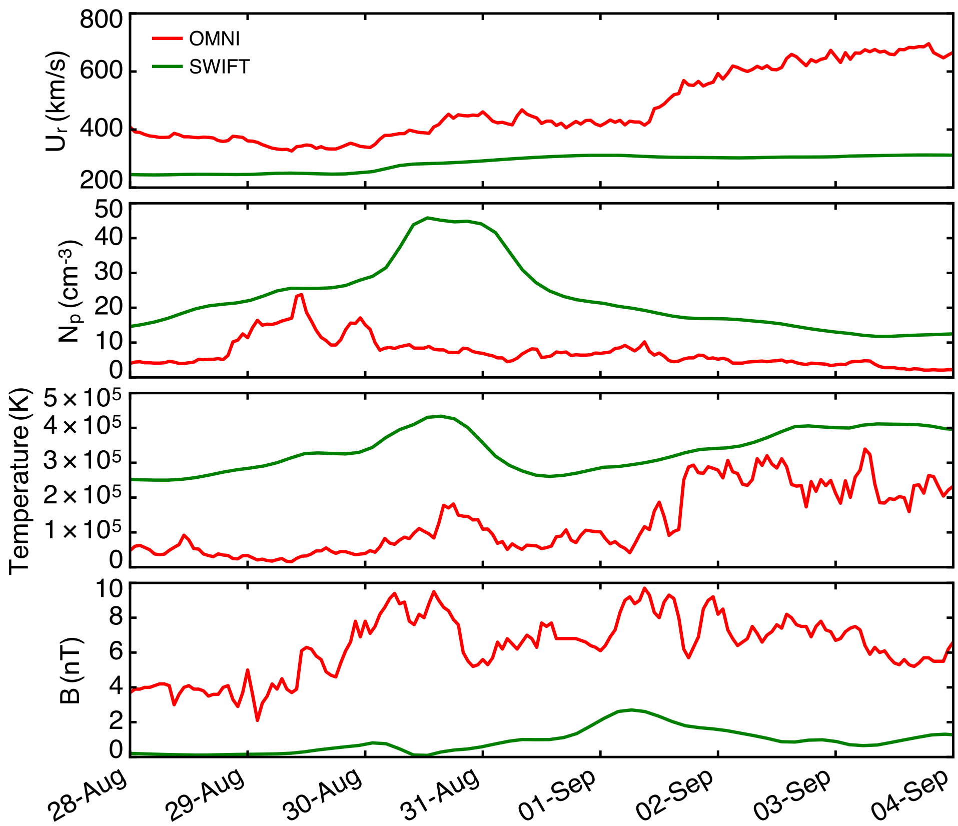

Figure 9: The simulated solar wind properties along the Earth orbit for the SWIFT test run compared to OMNI data.

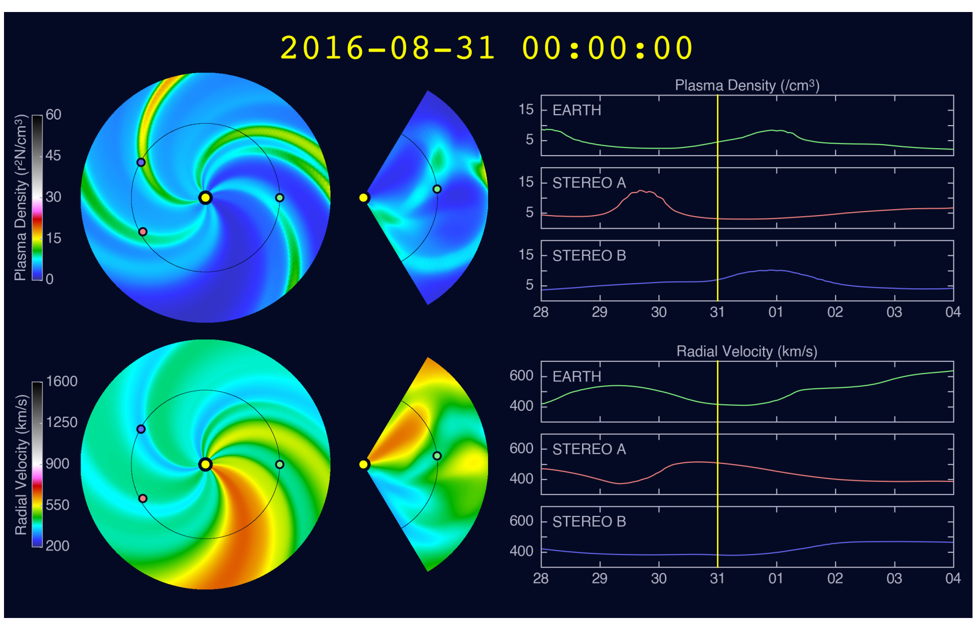

Figure 10: The simulated solar wind properties along the Earth orbit from WSA-ENLIL for the same times as in Figure 9.

- It will be useful to have the option of specifying an arbitrary resolution for SWIFT in which case the values from AWSoM will need to be interpolated onto the SWIFT grid. In any case, a more accurate mapping of the variables will require spatial interpolation onto the correct locations in the SWIFT staggered grid. This is a worthwhile improvement to the current implementation which will be added in the near future.

- As resolution increases, and the SWIFT time-step drops, there may be a need to update the boundary driving more frequently than GONG data updates. This can be achieved by either interpolating between two GONG data sets or applying differential rotation to GONG data and recomputing the AWSoM data at 0.1 AU.

- To maintain a time accurate, predictive capability it may be necessary to pipeline simultaneous runs of AWSoM or SWIFT. AWSoM pipelining may be needed if many instances are needed to be completed to fill boundary driving of SWIFT between GONG updates. SWIFT pipelining may be needed to run multiple copies forward in time, without boundary updates, to predict L1 and 1 AU space weather days into the future.

4 Conclusions

We have completed the coupling of AWSoM and SWIFT so can now run simulations from GONG data out to predictions at 1 AU. On the course resolution used for these tests it takes about 30 minutes on the 36 core workstation at Warwick dedicated to this project. At this resolution, when combined with SWIFT pipelining, we could run predictions out to 1 AU with predictions 2 days into the future. What remains now that the technical challenges of the AWSoM/SWIFT code couplings are complete is to assess what is needed for the time-accurate solution at L1 and 1 AU. This is the subject of PROGRESS task 2.6 which will take until month 27, i.e. April 2017. After this we will be continually running and improving real-time predictions of L1 variables based on AWSoM/SWIFT coupled codes. This data will be available for all other members of the PROGRESS project. The source code for AWSoM/SWIFT is also now available to any project partner who wishes copies. AWSoM is available as part of the SWMF package (http://csem.engin.umich.edu/tools/swmf/downloads.php) and the coupling, input decks and source needed to run SWIFT are maintained on a git repository (https://cfsa-pmw.warwick.ac.uk/SWIFT/SWIFT).

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