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Forecasting space weather with EUHFORIA in the virtual space weather modeling centre

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Abstract

Solar coronal mass ejections (CMEs) are large-scale eruptive events in which large amounts of plasma (up to 10^{13} – 10^{16} g) and magnetic fields are expelled into interplanetary space at very high velocities (typically 450 km/s, but up to 3000 km/s). When sampled *in situ* by a spacecraft in the interplanetary medium, they are termed interplanetary CMEs. They are nowadays considered to be the major drivers of space weather and the associated geomagnetic activity. The detectable space weather effects on Earth appear in a broad spectrum of time and length scales and have various harmful effects for human health and for our technologies on which we are ever more dependent. Severe conditions in space can hinder or damage satellite operations as well as communication and navigation systems and can even cause power grid outages leading to a variety of socio-economic losses. Therefore, the International Space Environment Service has set up a collaborative network of space weather service-providing warning centres around the globe, delivering coordinated operational space weather services for the benefit of the extensive user community. In order to improve the forecasts and predictions, NASA, ESA and other agencies have set-up space weather modelling frameworks. Here, we discuss how such frameworks enable to run and couple different space weather models, and to validate their results by comparing them with those of other similar models and, where possible, to *in situ* data. Examples of such frameworks are the Community Coordinated Modeling Center (CCMC, NASA GSFC), the Space Weather Modeling Framework at the Center for Space Environment Modeling at the University of Michigan, and ESAs novel Virtual Space Weather Modeling Centre that is being developed. The latter one includes space weather models that are geographically distributed and is the focus of this paper.

Keywords: space weather, plasma, forecasting

(Some figures may appear in colour only in the online journal)

1. The use and need for integrated space weather systems

1.1. Motivation

The so-called space weather phenomena cause substantial socio-economic damage on Earth including both direct effects on specific industry sectors, such as electric power, spacecraft and aviation industries, and indirect effects on dependent infrastructures and services, such as positioning and navigation systems, electrical power grids and oil and gas pipelines. Our society becomes ever more dependent on technological infrastructures and satellite services, and the more this trend

continues to grow, the more dramatic the potential impact of space weather events will become. The threat-assessment report by the Lloyd's insurance company [1] concluded that extreme events would cause \$2.6 trillion damage, while more recently Eastwood *et al* [2] estimated that the total economic loss varies between 0.5\$tn and 2.7\$tn based on calculations examining disruption to the global supply chain.

The solar coronal mass ejections (CMEs) are key components of the space weather. These are large-scale solar eruptive events in which large amounts of plasma (up to 10^{13} – 10^{16} g) and magnetic fields are expelled into interplanetary space at velocities up to several thousand kilometres per second. They play the main role in creating disturbed

space weather conditions by driving geomagnetic storms. The space weather effects from CMEs are two-fold. Firstly, CMEs interact directly with the Earth's magnetosphere, driving significant changes in the geomagnetic field and causing strong variations in the ionospheric current systems. Secondly, CME-driven shock waves accelerate protons to extremely high energies that cause radiation storms on Earth. Even a single high-energy charged particle may seriously damage delicate satellite electronics. While for a CME it takes a few days to reach the Earth, solar energetic particles (SEPs) arrive very shortly after eruption at the Sun has occurred. The major geomagnetic storms occur when CMEs are Earthward directed, fast enough to create a shock wave, and carry strong southward oriented magnetic fields. The internal magnetic structure of the CMEs upon their arrival at 1 AU is thus crucial. SEPs and related effects, in turn, are primarily determined by the speed, shape and extent of a CME when it is launched from the Sun, as well as by the properties of the ambient corona the CME surges into. The problem is that our ability to predict the space weather relevant parameters in interplanetary CMEs (ICMEs) well in advance is currently very modest, and even worse for SEP events.

On the theoretical/numerical front, we are increasingly appreciating that the solar interior, atmosphere and heliosphere form a nonlinear coupled system with multiple complex feedback pathways. Interpretation of the observations has moved past the intuitive or elemental model phase, and is demanding for advanced numerical models that reflect the coupled processes in the system. The intricate physics behind the space weather phenomena requires physics-based models. The current empirical and semi-empirical models used for space weather forecasting do not always work satisfactorily, especially when it comes to predicting the 'geo-effectiveness' of CME impacts, i.e. the magnitude and features of the main effects such an impact has at Earth. High performance computing (HPC) is a 'game changing' technology in this field (and in many other fields as well), enabling us to advance and extend our efforts towards (more) reliable physics-based SW predictions and forecasting.

Developing numerical models for the big problems in solar physics, and indeed in heliophysics in general, requires a change in the way in which science is managed, performed, and funded. Small research groups, with unpredictably fluctuating resources and few long-term, fully-supported scientists and (postdoctoral) students have revealed the potential value of these models, but we have now reached a phase that larger, collaborative, coordinated efforts are required. The obvious analogy is the experience of the general circulation model (GCM) to study climate: in the final decade of the past Century, the GCMs grew to be so complex, incorporating so many coupled processes, that research groups had no option but to collaborate on large community-based models to make headway. The foundation of a similar effort applicable to solar and space weather physics is currently being created by, e.g., the ESA Virtual Space Modeling Centre (VSWMC).

However, such physics-based models become complicated themselves and are not always easy to operate. Hence, a simple, preferentially graphical user interface (GUI) is needed

for the easy of use and accessibility of those models, avoiding for instance the installation and optimization of the codes (supporting software, compilation options, etc). Therefore, a standard environment is needed that can serve as a model (and data) repository, and at the same time a facility that enables optimal model simulations, verification, and validation. Moreover, such a standardization also enables coupling (s) of (sub-)models, yielding new, more advanced models.

1.2. VSWMC objective and scope

The goal of the ESA VSWMC-Part 2 project is to further develop VSWMC, building on the Phase 1 prototype VSWMC system and focusing on the interaction with the Space Situational Awareness (SSA) Space Weather (SWE) system. New models and new model couplings have been integrated, including a first demonstration of an end-to-end Sun-to-Earth simulation capability. Moreover, a coupling toolkit is being developed, facilitating the coupling of different models transforming dimensions of I/O quantities, interpolating in space and time, if needed, etc. The front-end GUI is accessible via the SWE Portal and is designed to build simulation set-ups involving one or several models and facilitating parameterized runs with easy specification of I/O parameters. The VSWMC also guarantees easily accessible input and output data and includes several integrated visualization tool modules.

1.3. VSWMC $\neq$ CCMC, nor CSEM/SWMF

Like the already existing and fully operational Community Coordinated Modeling Center (CCMC, <https://ccmc.gsfc.nasa.gov/>) at GSFC (NASA) and the Space Weather Modeling Framework (SWMF) at the Space Environment Modeling (CSEM) at the University of Michigan, the VSWMC provides a repository for models (and data) as well as a facility that enables to execute models and coupled model simulations. However, there are some major differences between the VSWMC and the CCMC and CSEM/SWMF.

First of all, the VSWMC is newly developed and currently contains only a limited amount of models (about 12) and model couplings, while the mature CCMC and SWMF contain many more models. A fundamental difference lies in the architectural design: at CCMC and CSEM the models are installed locally, on the same cluster, while the VSWMC enables a combination of both local and distributed models, so that different models can run on different, remote computer servers or clusters and are coupled over the internet via high level architecture (HLA). Moreover, in the VSWMC, the visualization tools are integrated as models that can be coupled to any other integrated model (when the I/O is compatible, of course), so that a model run can immediately produce the required visual output (if any). Last but not least, the VSWMC is setup for interactive use (unlike the 'runs on demand' procedure that applies to many models in the CCMC and the SWMF). Moreover, via a developer tool the modelers will be able to install/adjust their own model and to couple it to other models in the repository.

Figure 1. Schematic illustration of the VSWMC architecture. Credit: N. Mihalache.

2. VSWMC architecture

2.1. Brief overview of architectural components

Figure 1 illustrates the VSWMC architecture schematically. The VSWMC users interface the VSWMC via a web portal that has been integrated in the SSA SWE system of ESA. The

developer environment contains 4 service components, including a model repository, a simulation repository and the model coupling interfaces (MCIs). The core system also contains a data archive and user management component. Only the runtime system interacts with the HLA (see below) bus to coordinate the simulations. Notice that the visualizations are implemented as federates (HLA terminology, see

below), i.e. like any other model, taking (syntectic) data from the simulations and converting them into figures or movies. The run-time system (RTS) prepares (coupled simulation) models for execution and manages data exchange between models. It is capable of executing parameterized simulation (or federation) runs. As a simulation is interpreted, the different models participating in it are retrieved from the model repository and coupled together automatically via the coupling toolkit.

2.2. High level architecture

The VSWMC uses HLA [3] which is a general purpose software architecture that has been developed to enable distributed computer simulation systems, i.e. with different components of the simulation running on different (remote) computers with different operating systems. Within the HLA framework different computer simulations, or different components of a large simulation, can interact (i.e. interchange data, synchronize actions, etc) regardless of the computing platforms on which they run and regardless of the programming language they are developed in. The interaction between the different components of the simulation is managed by a run-time infrastructure (RTI). In other words, HLA provides a general framework and standard (IEEE Standard 1516–2000) facilitating inter-operability (and reusability) of distributed computer simulation components. It is currently also used in applications in a number of different domains such as, defence, air traffic management, off-shore, railway and car industry, manufacturing, etc.

HLA uses the following terminology:

- A federate is an application that is integrated in the HLA framework and that is thus capable of participating in a simulation. Thus, in the VSWMC all the integrated models and model couplers are federates.
- A federation is the term used for a declaration between federates describing how and what will be simulated, i.e. a set-up of multiple (coupled) simulation entities, connected via the RTI using a common Object Model Template (OMT). Hence, in the VSWMC, each of the demonstration simulations set up in the framework is a federation.
- A Federation Execution then refers to an actual simulation execution, i.e. a run of one of the VSWMC (single or coupled) models in our case.

Hence, one could say that the HLA provides the federation formalism by which federates can be modelled such that the framework can support federation executions, i.e. runs of the coupled models. This is very similar to any other simulation model application.

2.3. Framework node communication

In the current ‘Phase 2’ of the VSWMC a limited number of models have been installed, see figure 2 and are being coupled to each other via HLA. The models cover the low and mid-corona (Xtrapol, EUHFORIA Corona), data nodes

Figure 2. Scheme of the framework node communication in the VSWMC.

(ODI), the solar wind (EUHFORIA Heliosphere, AMRVAC), the Earth magnetosphere (Gumics-4, COOLFluid, iPIC3D), the radiation belts (BAS-RBM) and several effects quantified by indices like the disturbance storm time (Dst) index, the Kp-index (the global geomagnetic storm index) and the stand-off distance of the bow shock, and visualizations. Xtrapol actually runs on a cluster in Paris (France), BAS-RBM on a server in Cambridge (United Kingdom), COOLFluid on a cluster at the Von Karman Institute (St.-Genesius-Rode, Belgium), while the other models run on the Tier 2 HPC cluster (EUHFORIA, iPIC3D, AMRVAC), a virtual server (ODI, Kp, Dst, Stand-off) or the visualization node (visualization 1 and 2) of the KU Leuven (Belgium).

The models are coupled to each other over the internet with HLA via a coupling toolkit that takes care of the interpolations (in space and/or time), dimensional transformations, quantity transformations, etc of the I/O whenever necessary. Clearly, for some couplings, e.g. EUHFORIA-Gumics4, no I/O transformations are necessary as the interpolations are done by the models themselves and in such cases the coupling is very simple, at least when both models are integrated in the framework, i.e. made compatible as far as data formats and passage is concerned. In most cases, however, the coupling toolkit is required to make the I/O of the coupled models compatible and to keep track of the model simulation time, which is a non-trivial problem when different coupled models are running on different clusters in different countries with different operation systems and, in most cases, batch queues.

3. EUHFORIA

3.1. State-of-the-art

The EUHFORIA model (European heliospheric forecasting information asset) simulates the solar wind and the evolution of superimposed CMEs from 0.1 AU to 2.1 AU [4]. The results feature a highly dynamic heliosphere that the model is able to capture in good agreement with *in situ* observations. EUHFORIA is comparable to ENLIL [5], SUSANOO [6], and the Alfvén wave solar model (AWSOM) [7]. These

Figure 3. Snapshot of a flux-rope CME evolution simulation with EUHFORIA, showing 3D magnetic field lines and the radial velocity (colour coded) in the equatorial plane [credit: J. Pomoell].

standard models use an oversimplified cone CME model, ignoring the internal magnetic field of the CMEs [8]. Recently, however, first attempts have been made to include the internal magnetic structure of the CMEs, both in AWSOM and in SUSANOO. In EUHFORIA too we have included spheromac and Gibson-Low (self-similar) flux-rope CMEs (see figure 3). These have been shown to have the potential to fit *in situ* magnetic field data of ICME flux-rope passing at the Lagrangian 1 (L1) point, which is essential for predicting their so-called ‘geo-effectiveness’, i.e. the severeness of the magnetic (sub)storms they will cause at Earth.

3.2. Rationale

The project has both scientific and applications goals. The ambitious science goals include the quantification of the deformation, deflection and erosion of flux ropes evolving in the inner heliosphere, the characterization of the magnetosheaths of CMEs, and the clarification of the role of CME-CME interactions in enhanced SEP production. Clearly, this requires the use of flux-rope CME models capable of simulating the effect of an internal magnetic field on the evolution of the CME in the (also magnetised) solar wind, and the integration of solar energetic particle (SEP) transport and acceleration models in EUHFORIA.

The EUHFORIA project also put forward challenging applications goals, including improved space weather forecasts not only comprising the time of arrival of CMEs but also predicting their geo-effectiveness, which should be feasible provided the flux-rope models can capture the key features of the CME passage at the first Lagrange stability point (L1). Another aim of the project is to provide support for space missions (e.g. Solar Orbiter/ESA) e.g. by predicting the solar wind parameters at the location of the space craft and determining the magnetic connection of the space craft to the photosphere of the Sun.

Figure 4. EUHFORIA is a data-driven model [credit: J. Pomoell].

3.3. Data-driven model

EUHFORIA is a data-driven model (see figure 4). Indeed, the coronal part is based on the semi-empirical Wang-Sheeley-Arge (WSA) model [9] and uses GONG magnetograms (Janus maps) as boundary conditions for the potential field source surface (PFSS) extrapolations¹ of the coronal magnetic field. The WSA model derives the solar wind speed from the resulting 3D coronal field. The MHD wind solution uses this speed as a boundary condition at 0.1 AU and stretches out to 2.1 AU. Also the CME parameters use observational data, namely coronagraph imagery. Indeed, the CME speed, insertion time, longitude, latitude and half width of the CMEs are obtained from 3D reconstruction techniques with the graduated cylindrical shell (GCS) model developed by Thernisien *et al* [10]. In addition, for the flux-rope CME models, the tilt, helicity and the toroidal magnetic flux are determined from magnetic and EUV observations.

3.4. Integration in the VSWMC

EUHFORIA plays a key role in the VSWMC due to the VSWMC ambition to demonstrate an end-to-end Sun-to-Earth simulation capability. As explained above, the model is integrated in the VSWMC and has been coupled to several other models, see figure 2. In particular, the two parts of EUHFORIA (coronal + heliospheric) are of course closely coupled although the heliospheric part is agnostic of the coronal part which only serves to provide the required boundary conditions (MHD quantities) at the inlet boundary at 0.1 AU. As such, any other coronal model capable of providing this input could replace it. On the other end, EUHFORIA Heliosphere provides the MHD parameters of the solar wind with the superposed CMEs at L1, the other planets and any (artificial or real) spacecraft within its computational domain. This enables to couple other models to EUHFORIA, e.g., effects models and magnetospheric models that typically use L1 measurements as an input. The latter measurements can be replaced by the synthetic data from EUHFORIA to establish the coupling. For example, within the VSWMC, EUHFORIA has been coupled to semi-empirical models to predict the Dst index [11], the Kp index

¹ PFSS extrapolations assume a ‘source surface’ (usually at 2.5 solar radii) from where the magnetic field is purely radial, i.e. the latitudinal and longitudinal components vanish.

[12] and the bow shock stand-off distance [13], also during a CME impact, and this 2 to 3 days before it actually occurs. Also couplings to more physics-based Earth magnetosphere models have been implemented, namely Gumics 4 [14] and COOLFluiD [15], and also, but outside the VSWMC framework, for OpenGGMC [16].

4. Conclusion

The VSWMC-2 development is at the end of phase 2 and about a dozen models are installed and are (being) coupled to each other using the HLA framework capabilities. The GUI user interface is being further developed and tested and will contain a facility to actually build a coupled simulation based on the models installed with automatic compatibility checks. On the longer run, it is technically possible that a modeler creates a MCI for his own model, which would enable him/her to actually couple the model to the other models in the system.

In late 2018, the VSWMC will be tested and then integrated in the SSA SWE system. It will then include a first demonstration of an end-to-end simulation capability and have a more extended coupling toolkit, a front-end GUI (accessible via the SWE portal), and an integrated visualization tools. In addition, a first prototype will be installed of a developer environment (DE) to support modelers to create an MCI for their own model.

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