Physics of the Space Weather Modeling Framework

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Contents

1 Introduction

The Sun-Earth system is a complex natural system of many different, interconnecting elements. The solar wind transfers significant mass, momentum and energy to the magnetosphere, ionosphere, and upper atmosphere, and dramatically affects the physical processes in each of these physical domains. The ability to simulate and eventually predict space-weather phenomena is important for many applications, for instance, the success of spacecraft missions and the reliability of satellite communication equipment. In extreme cases, the magnetic storms may have significant effects on the power grids used by millions of households.

The various domains of the Sun-Earth system can be simulated with stand-alone models if simplifying assumptions are made about the interaction of a particular domain with the rest of the system. Sometimes the effects of the other domains can be taken into account by the use of satellite and ground based measurements. In other cases, statistical and/or phenomenological models can be used. For the prediction of space-weather events, however, one must use first-principles-based physics models for all of the involved domains and these models must execute and be coupled in an efficient manner, so that the simulation can run faster than real-time.

2 Physics Domains and Their Couplings

The current version of the SWMF includes nine physics domains ranging from the surface of the Sun to the surface of a planet (usually the Earth). The nine physics domains are the following:

- Solar Corona (SC),
- Eruptive Event Generator (EE),
- Inner Heliosphere (IH),
- Solar Energetic Particles (SP),
- Global Magnetosphere (GM),
- Inner Magnetosphere (IM),
- Radiation Belt (RB),
- Ionosphere Electrodynamics (IE),
- Upper Atmosphere (UA).

Each physics domain corresponds to a component of the framework. Each component can have multiple versions. A *component version* is based on a particular *physics model*, which is implemented by a particular *physics module*.

Below we briefly describe all nine physics domains, the typical coordinate systems, the equations to be solved, the boundary conditions, and the couplings with the other domains. A component is responsible for solving the dynamical equations in its domain, and it is also responsible for receiving and providing information as needed. The most computationally challenging couplings are described in more detail, since these present additional tasks to be accomplished by the components.

2.1 Solar Corona – SC

The Solar Corona domain extends from the low corona at $\approx 1\,\mathrm{R_S}$ (solar radius) to approximately $24\,\mathrm{R_S}$. The physics of this domain is well approximated with the equations of magnetohydrodynamics, however, additional source terms are required to take into account the heating and acceleration of the solar wind [*Groth et al.*(2000), *Usmanov et al.*(2000)]. Alternative models mimic the coronal heating by incorporating a variable adiabatic index [*Wu et al.*(1999)], or solve for one extra equation that describes the energy interchange between the solar wind plasma and the large-scale MHD turbulence [*Roussev et al.*(2003b)]. The SC component can be in an inertial (e.g. HGI – Heliographic Inertial) frame or in a rotating (e.g. HGR – Heliographic Rotating) frame. In a rotating frame the inertial forces must be included.

The inner boundary of the SC component is driven by the density, pressure, velocity and magnetic field defined just above the photosphere. The magnetic field may be obtained from synoptic magnetograms, or a simple dipole (possibly with a few higher order terms) may be assumed. The boundary conditions for the temperature and mass density at the Sun may vary with longitude and latitude to achieve the most realistic solar wind near the Sun and at 1AU. The velocity components at the inner boundary should maintain line-tying of the magnetic field. The flow at the outer boundary is usually superfast (faster than the fast magnetosonic speed of the plasma), so no information is propagating inward. Sometimes, however, when a coronal mass ejection (CME) passes the boundary, the solar wind speed may become subfast for short periods of time. During such periods, the SC component needs to receive the outer boundary condition from the Inner Heliosphere.

The Solar Corona provides the plasma variables at the inner boundary of the Inner Heliosphere. The inner boundary of the IH component does not have to coincide with the outer boundary of the Solar Corona, i.e. the two domains are allowed to overlap. Such an overlap is actually numerically advantageous when the flow becomes subfast for a short time. The overlap can reduce reflections or other numerical artifacts at the inner boundary of IH. The Solar Corona also provides information to the Solar Energetic Particle domain: the geometry of one or multiple field lines and the plasma parameters along each field line are provided to the SP component.

2.2 Eruptive Event Generator – EE

The EE domain is embedded in the Solar Corona, and it is restricted to the region of the eruptive event, which is typically in the form of a coronal mass ejection (CME). To date, we lack good understanding of the actual physical processes by which a CME is initiated, and it is still an active field of research. One group of models [*Forbes and Isenberg*(1991), *Gibson and Low*(1998), *Roussev et al.*(2003a)] assume that a magnetic flux rope exists prior to the eruption. Flux ropes may suddenly lose mechanical equilibrium and erupt due to: foot-point motions [*Wu et al.*(2000)]; injection of magnetic helicity [*Chen and Garren*(1993)]; or draining of heavy prominence material [*Low*(2001)]. Another group of models [*Antiochos et al.*(1999), *Manchester*(2003), *Roussev et al.*(2004)] relies on the existence of sheared magnetic arcades, which become unstable and erupt once some critical state is reached. Here a flux rope is formed by reconnection between the opposite polarity feet of the arcade during the eruption process.

The EE component can be represented as a boundary condition for the SC component, or it can be a (non-linear) perturbation of the SC solution. In short, the EE component interacts with the SC component only. Due to the multitude of possibilities, the EE component is integrated into the SC component in the current implementation of the SWMF. Multiple EE versions are possible, but all the EE versions belong to one SC version only.

2.3 Inner Heliosphere – IH

The IH domain extends from around 20 solar radii all the way to the planet. It does not have to cover a spherical region, it may be rectangular and asymmetric with respect to the center of the Sun. The physics of this domain is well approximated with the equations of ideal MHD. The IH component is usually in an inertial (e.g. HGI) frame.

The inner boundary conditions of the IH component are obtained from the SC component or measurements. The flow at the outer boundary of the IH component is always superfast (the interaction with the interstellar medium is outside of the IH). The Inner Heliosphere provides the same information to the SP component as the Solar Corona. The IH component also provides the outer boundaries for the SC component when the flow at the outer boundary of SC is not superfast. Finally the Inner Heliosphere provides the upstream boundary conditions for the Global Magnetosphere. The IH and GM domains overlap: the upstream boundary of GM is typically at about $30\,R_E$ (Earth radii) from the Earth towards the Sun, which is inside the IH domain.

2.4 Solar Energetic Particles – SP

The SP domain consists of one or more one dimensional field lines, which are assumed to advect with the plasma. The physics of this domain is responsible for the acceleration of the solar energetic particles along the field lines. There are various mathematical models that approximate this physical system. They include the effects of acceleration and spatial diffusion, and can be averaged [*Sokolov et al.*(2004)] or non-averaged [*Kóta and Jokipii*(1999), *Kóta et al.*(2005)] with respect to pitch angle.

The geometry of the field line and the plasma parameters along the field line are obtained from the SC and IH components. The boundary conditions can be zero particle flux at the ends of the field line(s). The SP component does not currently provide information to other components.

2.5 Global Magnetosphere – GM

The GM domain contains the bow shock, magnetopause and magnetotail of the planet. The GM domain typically extends to about $30\,R_E$ on the day side, hundreds of R_E on the night side, and 50 to $100\,R_E$ in the directions orthogonal to the Sun-Earth line. The physics of this domain is well approximated with the resistive MHD equations except near the planet, where it overlaps with the Inner Magnetosphere. The GM component typically uses Geocentric Solar Magnetic (GSM), Geocentric Solar Ecliptic (GSE) or possibly Solar Magnetic (SM) coordinate system.

The upstream boundary conditions are obtained from the IH component or from satellite measurements. At the other outer boundaries one can usually assume zero gradient for the plasma variables since these boundaries are far enough from the planet to have no significant effect on the dynamics near the planet. The inner boundary of the Global Magnetosphere is at some distance from the center of the planet, usually at 1 to 3 planet radii. The inner boundary conditions are partially determined by the Ionosphere Electrodynamics, which provides the electric potential at the inner boundary of the GM. The potential is used to calculate the electric field and the corresponding plasma velocities, which are used as the inner boundary condition for the GM. The GM component also receives pressure and possibly density corrections from the Inner Magnetosphere along the closed magnetic field lines (field lines connected to the planet at both ends). These are used to 'nudge' the MHD solution towards the more accurate inner magnetosphere values [*De Zeeuw et al.*(2004)].

The GM component provides the field aligned currents to the IE component. These currents are mapped from the GM down to the ionosphere along the magnetic field lines. The Global Magnetosphere provides the Inner Magnetosphere with the field line volume, average density and pressure along closed field lines. Depending on the needs of the IM component, the GM could also provide the geometry of the closed field lines and the distribution of plasma parameters along field lines.

2.6 Inner Magnetosphere – IM

The IM domain consists of the closed field line region around the planet. This component solves equations describing the motion of keV-energy ions and electrons. Kinetic effects are important for these particles, and several types of theoretical models have been developed to describe them. At least five different groups have developed codes that calculate the distribution function of the ring current ions and associated electrons given an inputted electric and magnetic field distribution (see review by [*Ebihara and Ejiri*(2002)]. The Rice Convection Model (RCM) (e.g., [*Wolf et al.*(1982), *Toffoletto et al.*(2003)] computes field-aligned currents and ionospheric potentials self-consistently, but still requires an inputted magnetic field and assumes that the particles have an isotropic pitch-angle distribution (consistent with MHD). Models developed by [*Fok et al.*(2001)], [*Liemohn et al.*(2004)] and [*Ridley and Liemohn*(2002)] compute full pitch-angle distributions as well as field-aligned currents and ionospheric equipotentials. A different approach uses test-particle

Monte Carlo models [*Chen et al.*(2003), *Ebihara et al.*(2004)]. The IM component typically uses Solar Magnetic (SM) coordinates.

The Inner Magnetosphere obtains the geometrical and plasma information about the closed field lines from the Global Magnetosphere. It also obtains the electric potential solution from the Ionosphere Electrodynamics. The IM component provides the density and pressure corrections along the closed field lines to the GM component. The IM may also provide field aligned currents along the closed magnetic field lines to the IE component (but this is not done in the current implementation of the SWMF).

2.7 Radiation Belt – RB

The RB spatial domain is coincident with that of the Inner Magnetosphere component. This component solves equations for the relativistic electron distribution near the Earth, which are responsible for some of the most detrimental space-weather effects. Gradient and curvature drift dominate the motion of these particles around the Earth, and the kinetic equation is sometimes drift-shell averaged as well as gyration and bounce averaged. Diffusion is the primary transport mechanism left in the equation. The physics of this domain can be solved with the same two techniques mentioned for the Inner Magnetosphere, that is, numerical discretization of the kinetic equation [*Beutier and Boscher*(1995), *Shprits and Thorne*(2004)] or test particle tracking [*Elkington et al.*(1999)]. The RB component typically uses Solar Magnetic (SM) coordinates, or simply equatorial plane radial distance.

The Radiation Belt receives similar information from the Global Magnetosphere as does the Inner Magnetosphere. The RB component does not provide information to the other components.

2.8 Ionosphere Electrodynamics – IE

The IE domain is a two dimensional height-integrated spherical surface at a nominal ionospheric altitude (at around 110 km for the Earth). There are several mathematical models that can describe this domain: empirical models such as the [*Weimer*(1996)] electric potential maps, and the [*Fuller-Rowell and Evans*(1987)] particle precipitation and auroral conductance maps; the assimilative mapping of ionospheric electrodynamics [*Richmond and Kamide*(1988)]; and the height averaged electric potential solver, which uses the field-aligned currents to calculate particle precipitation and conductances [*Ridley et al.*(2004), *Ridley and Liemohn*(2002)]. In the current version of the SWMF, the IE component is a potential solver, but there is nothing in the design that would exclude the incorporation of other types of IE models. Usually the IE component uses the Solar Magnetic (SM) coordinates.

The Ionosphere Electrodynamics obtains the field aligned currents from the Global Magnetosphere and Upper Atmosphere, which is used to generate an auroral precipitation pattern. The UA component also provides IE with the Hall and Pedersen conductivities. In case the UA component is not used, the auroral pattern and the solar illumination are used to generate Hall and Pedersen conductances. This is done through the use of the [*Robinson et al.*(1987)] and [*Moen and Brekke*(1993)] formulation, which takes the average and total electron energy flux and converts them to Hall and Pedersen conductances based on a simple formula. The IE component provides the electric potential to the GM, IM and UA components. In addition, it provides the particle precipitation to the UA component.

2.9 Upper Atmosphere – UA

The UA domain includes the thermosphere and the ionosphere and it extends from around 90 km to about 600 km altitude for the Earth. The physics of the Upper Atmosphere is rather complicated. It can be approximated with the equations of multi-species hydrodynamics including viscosity, thermal conduction, chemical reactions, ion-neutral friction, coupling of the ions to the electric field, source terms due to solar radiation, etc. In such a complex system there are many possible choices even at the level of the mathematical model. For example, one can approximate the system with the assumption of hydrostatic equilibrium

[*Richmond et al.*(1992)] or use a compressible hydrodynamic description [*Ridley et al.*(2005)]. The UA component is typically in a planet-centric rotating frame, i.e. the Geocentric (GEO) coordinate system for the Earth.

The lower and upper boundaries of the UA domain are approximated with physically motivated boundary conditions. The Upper Atmosphere obtains the electric potential along the magnetic field lines and the particle precipitation from the Ionosphere Electrodynamics. The gradient of the potential provides the electric field, which is used to drive the ion motion, while the auroral precipitation is used to calculate ionization rates. The UA component provides field aligned currents and the Hall and Pedersen conductivities to the IE component. The conductivities are calculated from the electron density and integrated along field lines.

2.10 Coupling the Inner Magnetosphere to the Global Magnetosphere

The IM to GM coupling is the most challenging computationally. The GM component needs to know where each of its 3D grid points are mapped onto the IM grid along the closed magnetic field lines in order to apply the pressure and density corrections. This means that field lines must be traced from possibly millions of grid points. In addition, the magnetic field information is typically distributed over many processors of the GM component. Since the GM grid structure and the magnetic field is inherently known by the GM component, it is the responsibility of the GM component to find the mapping of its 3D grid along the closed field lines. For our implementation of the GM component, we have developed a highly parallel method, which can accomplish this task in a few seconds [*Tóth et al.*(2005c)].

2.11 Coupling the Global Magnetosphere to the Inner Magnetosphere

The GM to IM coupling is also challenging computationally. The IM needs the magnetic field line flux tube volumes and the average density and pressure in the flux tubes connected to its 2D spherical grid points. This requires the integration along many (thousands of) magnetic field lines in GM. Field line integration is an inherently serial procedure. A further complication is that the domain decomposition of the GM component may distribute each field line over several processors. We have developed an efficient parallel algorithm [*Tóth et al.*(2005c)], which can trace and integrate along the field lines in a fraction of a second of CPU time. The framework provides a library, which takes care of the information exchange and the collection of data among the processors of GM, but the GM component is responsible for the tracing and integration along field lines within the subdomain corresponding to one GM processor.

2.12 Coupling the Solar Corona and the Inner Heliosphere to the Solar Energetic Particles

The SP component needs the geometry of one or more magnetic field lines, and it also needs the plasma parameters along these lines. This is not a computationally intensive procedure due to the small number of field lines. On the other hand it is an algorithmically non-trivial problem, especially when the SP component uses a Lagrangian grid. In our implementation of the SWMF, the field line is traced through the SC and IH components by the core of the framework, and the components only need to provide the plasma variables for the moving grid points when requested.

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