Natural Resources Canada　Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7620

Space Weather Modelling for Operational Applications: Approach and Activities

L. Nikolic and L. Trichtchenko

2015

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7620

Space Weather Modelling for Operational Applications: Approach and Activities

L. Nikolic and L. Trichtchenko

2015

doi:10.4095/295980

Recommended citation
Nikolic L. and Trichtchenko, L., 2015. Space Weather Modelling for Operational Applications: Approach and Activities; Geological Survey of Canada, Open File 7620, 29 p. doi:10.4095/295980

Table of Contents

1 Introduction

The term Space Weather (SW) has become frequently used in the scientific community in the last 1-2 decades. The first reference to the subject which is “counterpart to meteorology on the Earth” was at the end of the 1950’s [1]. Although the name of this scientific field appears new, the scientific roots of SW research go back to the first systematic studies of sunspots in the early 17th century, to the discovery of large magnetic needle fluctuations by George Graham in 1724, and to the observation of solar flares by Richard Carrington in 1859. Reports on correlation between disruptions of telegraphic services and occurrence of aurorae in 19th century, were the first evidence that SW phenomena can impact technology. However, it took more than 100 years to establish a solid connection between solar phenomena and their effects on Earth. Important missing links in the Sun-Earth chain were closed by Eugene Parker's solar wind theory in the 1950's [2] and discovery of Coronal Mass Ejections (CME) in 1971 [3].

Today, the term "Space Weather" refers to variable conditions in our space environment that can adversely affect human activities and technologies. The source of this variability is our Sun, although to some extent other cosmic phenomena, such as galactic cosmic rays can impact the near-Earth environment. Our growing dependence on technological assets in recent decades has been accompanied by increasing vulnerability to SW phenomena that can disrupt their safe operation. Collapse of the Hydro-Quebec power grid in 1989, and failures of the Canadian Anik-E satellites in 1994 are some examples of events that spurred research interest in Sun-to-Earth physical processes [4], [5]. The fact that solar activity can have an impact on modern society has prompted research and operational efforts to understand and forecast SW [6], [7], [8]. There is a growing interest in SW services from a wide range of stakeholders including: government agencies, power-grid companies, aviation, pipeline operators and global navigation satellite system (GNSS) users. Due to its close proximity to the north magnetic pole, Canada is particularly vulnerable to SW. The Canadian Space Weather Forecast Centre (CSWFC) of Natural Resources Canada (NRCan) in Ottawa conducts research on SW and its effects on critical infrastructure [9]. The center provides SW forecasts and is a Regional Warning Centre (RWC) of the International Space Environment Service (ISES). Furthermore the center contributes to the World Meteorological Organization (WMO).

Great progress in the SW field has come since the 1990’s when, in addition to ground based observations and measurements, a number of satellites have been launched improving monitoring and understanding of Sun's activity and phenomena in the Earth's environment. Satellites such as Solar and Heliospeheric Observatory (SOHO) [10], Solar Dynamics Observatory (SDO) [11] Advanced Composition Explorer (ACE) [12] and STEREO [13] provide valuable data to SW research and operational communities. Unfortunately, the most reliable observations, from the L1 point, allow only ~1h advanced warning of approaching solar disturbances. To achieve a more advanced forecast, SW operations heavily depend on the development of numerical models. In particular, a breakthrough in SW forecasting depends on the development of suitable large scale simulations. Despite the fact that physics based simulations, such as magnetohydrodynamics (MHD), have been used in academic research since the early 1980s, the implementation of these codes into SW operations poses a challenge, ranging from computational constraints to the lack of observational data that can be used to deduce code-relevant input parameters. Furthermore, most of the scientific codes developed and used in research were not designed with operational functionality in mind. It is a general consensus in the SW community that more efforts should be made to improve modelling capabilities, physics of the models, and in particular, to transfer simulation codes into operations [14], [15], [16], [17]. The Canadian Space Weather Forecast Centre recognizes these needs and is trying to enhance its forecast capabilities using advanced numerical approaches.

The research efforts in the SW field are very dynamic and it is very difficult to give a systematic and comprehensive scientific review of all activities. Therefore, the main aim of this paper is to help to understand the general approach and key activities. In particular, we discuss the background, trends and challenges of SW modelling efforts from an operational point of view. In order to get insight into the domain of interest and drivers of SW, in Section 2 we describe the Sun-Earth system, and in Section 3 we discuss the solar disturbances and their forecast. Section 4 is devoted to the discussion of physics based numerical modelling. In Section 5 we briefly address the transition of scientific codes to operations, and in Section 6 we give a short overview of international and Canadian SW forecast activities. A summary is given in Section 7.

2 The Sun - Earth system

The Sun-Earth system covers a distance of more than 150×10^6 km with a variety of phenomena that exhibit different characteristic time and space scales. In order to describe it, we will consider three global domains: the Sun - which is the main source of disturbances that drive SW processes, interplanetary space (inner heliosphere) - the region between the Sun and Earth where solar disturbances travel and evolve, and the Earth with its space environment [18], [19] (see Figure 2.1).

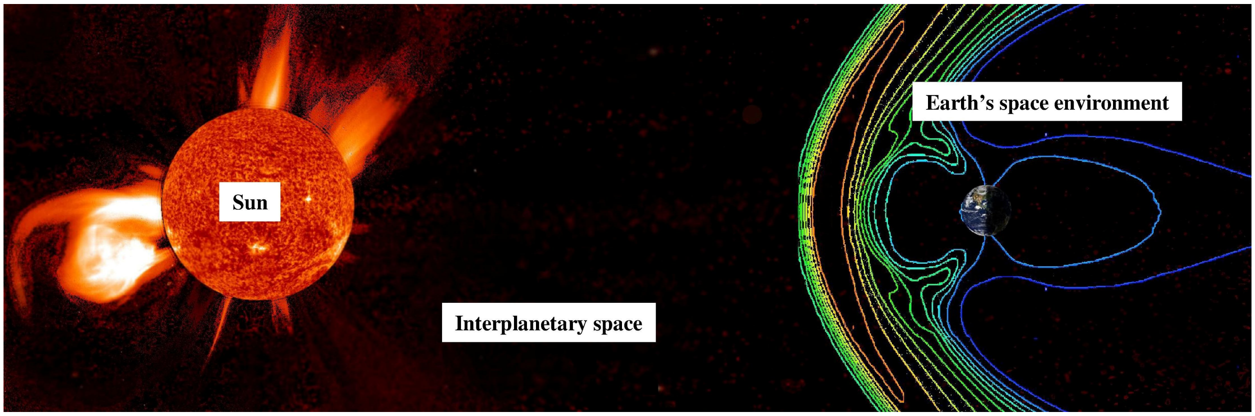

Figure 2.1. The Sun, interplanetary space and Earth's space environment. The Sun is the main driver of the SW phenomena. Solar disturbances travel through interplanetary space on different time scales. It takes from 8 minutes to a couple of days for the disturbances to reach the Earth. A constant stream of solar particles, called the solar wind, distorts Earth's magnetic field. On the day-side of the Earth, magnetic field lines are compressed while on the night-side the field lines are stretched into a long tail-like configuration.

2.1 Sun

The Sun is the central body of our solar system and the main driver of SW phenomena. It is more than 100 times larger in the diameter and ~330×10^3 times heavier than the Earth. The total mass of the Sun consists primarily of ionized light elements – hydrogen (~71%) and helium (~27%). The gravitational force associated with this enormous mass is strong enough to compress the Sun's material to high densities and temperatures igniting thermonuclear reactions. In the Sun's core (see Figure 2.2) where the density and temperature reach ~1.622×10^5 kg/m^3 and ~15×10^6 K, respectively, the Sun burns hydrogen into helium in a nuclear fusion process. The energy created in the core is carried outward by solar neutrinos and gamma rays which are by-products of the fusion. While neutrinos can easily escape from the Sun, gamma rays can propagate only a short distance through dense layer that lies between ~0.2 and 0.7 Sun's radii (R_S). In this region, called radiation zone, high energy gamma photons are scattered, absorbed and re-emitted, gradually shifting towards lower frequency. The radiation zone is surrounded by a cooler lower density plasma layer that favors energy transport by convection. The photons that reach this outer layer of the Sun, called the convection zone, are absorbed and carried toward the surface by convection flows. Since the plasma circulates in turbulent cells with hotter gas rising and cooler gas sinking, the visible part of this layer (photosphere) exhibits a granular structure.

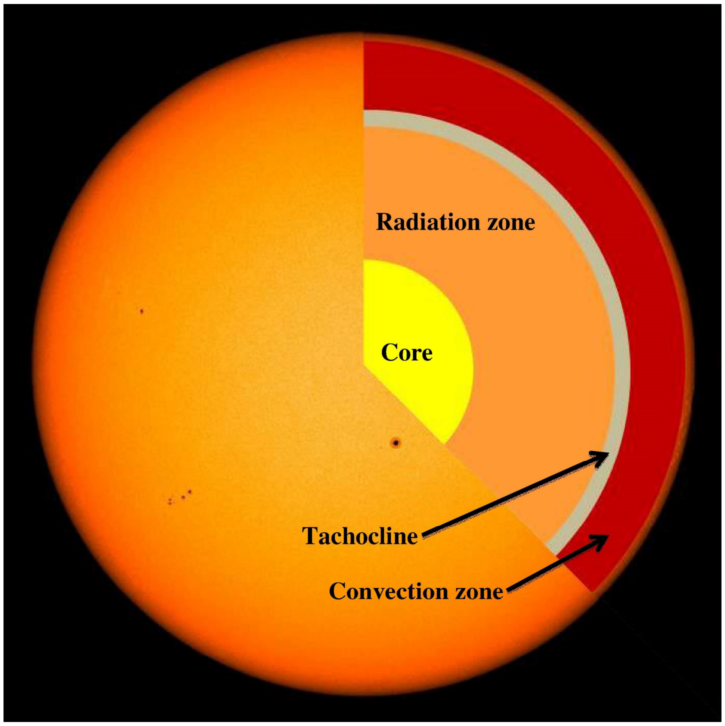

Figure 2.2. Standard model of the Sun's interior. In the Sun's core high density and temperatures provide conditions for nuclear fusion reactions. The energy created in the core is transported by radiative diffusion through the relatively dense radiation zone that lies between ~0.2 and 0.7 R_S. In the outer, lower density and cooler layer called the convection zone, the energy is transported through convection. The Sun's very strong magnetic field is generated in the tachocline which represents very thin transitional layer between radiation and convection zones.

While radiation zone rotates uniformly, the rotation period of material in the convection zone is latitudinally dependent; around 26 days near the equator and 37 days near the poles. In the thin layer between radiation and convection zone, called the tachocline, the solar dynamo effect generates very strong magnetic fields (~10^5 G) that protrude through the convection zone to the solar surface. Regions of strong magnetic field can inhibit convection of the heat, and these regions appear as sunspots on the solar surface in visible light. The magnetic field can reach ~2000–4000 G inside the sunspot. The sunspot activity follows an approximately 11-year cycle, but their number varies from cycle to cycle. Moreover, at the beginning of the solar cycle the sunspots appear at high latitudes and as the cycle progresses they drift toward the solar equator.

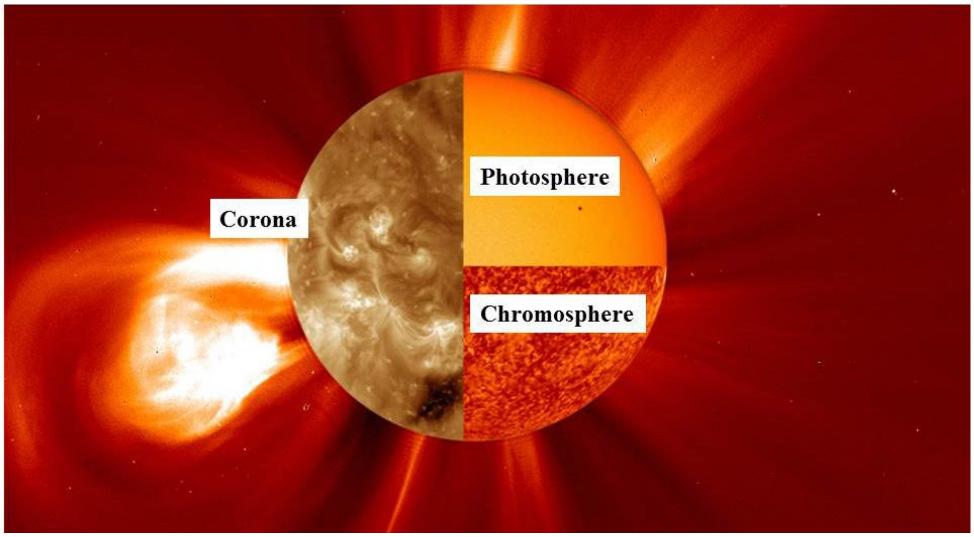

Figure 2.3. A composite image of the Sun's atmosphere. Observations of the Sun in different wavelengths reveal a layered structure of its atmosphere. The visible, less than 500 km thick region of the convection zone is called the photosphere. This relatively cool layer is surrounded by the very thin chromosphere. The solar corona is the largest layer of the Sun's atmosphere. It extends several million kilometers outward from the Sun and can be seen by the naked eye only during a solar eclipse.

The solar atmosphere also exhibits a layered structure (see Figure 2.3). Surrounding the photosphere, which is the less than 500 km thick visible solar surface layer, are the chromosphere and solar corona. Moving outward from the center of the Sun, temperature steadily decreases ranging from ~6600 K in the innermost part of the photosphere to ~4400 K in its outermost part. However, surprisingly, in the chromosphere the temperature of the gas starts to rise reaching ~30×10^3 K at the top of this ~2000 km thick layer.

The solar corona is the largest layer of the Sun's atmosphere. It extends several million kilometers outward from the Sun and can be seen by the naked eye only during a solar eclipse. Due to its high temperature, which can reach over 10^6 K, the solar corona emits radiation, particularly at shorter wavelengths in the EUV and soft X-ray spectrum. While the other layers of the Sun have a spherical shape due to the Sun's gravity, the shape and dynamics of the solar corona is strongly influenced by the magnetic field. Coronal loops and coronal holes are the basic coronal structures. Coronal loops are dense structures of plasma that follow closed magnetic field lines. The closed magnetic field ropes that connect regions of opposite magnetic polarity in complex sunspot groups are often precursors of solar flares and coronal mass ejections (CME). Solar flares represent a sudden release of magnetic energy across the entire electromagnetic (EM) spectrum. This is often coupled with acceleration of protons and electrons (Solar Energetic Particle (SEP) event) to energies more than 1MeV. CMEs, often associated with solar flares, are ejections of large quantities of hot coronal plasma ($\sim 10^{12}$ kg). Earth-directed CMEs can cause the most violent geomagnetic storms.

Due to the high temperature of the corona, particles can acquire enough kinetic energy to escape the Sun's gravity. This constant stream of charged particles, called the solar wind, flows radially from the Sun and consists mainly of protons and electrons. Solar wind parameters such as speed and density are strongly dependent on the Sun's activity. For example, coronal holes which are formed by open magnetic field lines are known to be sources of fast (up to ~800 km/s), low density ($\sim 3\ \mathrm{cm}^{-3}$) solar wind streams. Due to the high conductivity of the solar wind, the solar magnetic field is frozen into the plasma and is dragged into the interplanetary space by the radial outflow.

2.2 Sun-Earth interplanetary space

This domain is a part of the inner heliosphere and represents the largest region in the Sun-to-Earth system. From a modelling point of view it is convenient to define beginning of this region beyond the solar wind sonic and Alfvén points - typically between 18–30 R_S from the Sun. While the magnetic field plays a dominant role in the corona dynamics, the interplanetary magnetic field is frozen-in to the radially expanding solar wind flow. Coupled with the Sun`s rotation, this gives rise to a spiral and waved magnetic field line configuration when viewed from above or below the equatorial plane.

Interplanetary space plays an important role as it is in this region that solar disturbances evolve and interact. Here, for example, fast and slow solar wind streams interact forming co-rotating interaction regions. Furthermore, a fast CME propagating in the ambient (background) solar wind can drive an interplanetary shock wave. In addition to the ambient solar wind flows and transient disturbances, the Sun-Earth interplanetary space can contain significant population of energetic particles - from 10's keV to 100's MeV. These particles are closely related to solar flares, CMEs or to the interaction of fast and slow solar wind streams [20].

2.3 Earth and its space environment

Earth's space environment represents the region where the Earth's magnetic field is a dominant component over the solar Interplanetary Magnetic Field (IMF).

The dipolar magnetic field of the Earth is reshaped due to the interaction with the solar wind. The supersonic solar wind plasma carrying IMF is mostly deflected by the Earth's magnetic field. The solar wind pressure compresses the field on the day-side and stretches it well beyond 200 Earth radii ($1R_E = 6371$ km) into the magnetotail on the night-side of the Earth (see Figure 2.1). This region of the space environment is called the magnetosphere and contains plasma which consists mostly of electrons and protons of solar wind origin. The inner cavity in the magnetosphere, which is dominated by dipole component of the magnetic field, is called inner magnetosphere (< 8 R_E).

The transition region between fully ionized magnetospheric plasma and the upper atmosphere, from ~60–80 km to more than 500 km altitude, is called the ionosphere. It is dominated by a significant amount of ions and electrons produced through the ionization of the neutral atmosphere by the solar radiation in the ultraviolet (UV) and extreme ultraviolet (EUV) range, and collisions with energetic particles. The ionosphere is broken into three distinct layers called the D, E, and F regions. Since ionization depends on the amount of radiation received from the Sun, the ionosphere exhibits daily and seasonal variations in its physical properties. For example, typical peak electron density in the F region ranges from $\sim 10^4$ to 10^6 cm^{-3}. At high attitudes the ionosphere merges into the torus shaped plasmasphere which is a cold ($T_e \sim 10^3 – 10^4$ K) relatively dense ($n_e \sim 10 – 10^3$ cm^{-3}) plasma component of the inner magnetosphere. The plasmasphere extends to about 3 to 5 R_E and contains plasma of ionospheric origin that co-rotates with the Earth. Trapped energetic electrons and protons which bounce between the northern and southern hemispheres in the inner magnetosphere represent inner ($L \sim 1.5–2$ R_E) and outer ($L \sim 4–6$ R_E) Van Allen radiation belts. At the same time these energetic particles drift azimuthally. It is believed that the particles that form the belts are of solar wind and cosmic ray origin.

3 Violent solar disturbances and their forecast

Despite huge progress in solar-terrestrial science, there are still many unanswered questions concerning the solar disturbances and their effects on Earth and its space environment. Solar flares, solar energetic particles (SEP), high-speed solar wind streams (HSS) from coronal holes and CMEs represent the main SW research topics (see Figure 3.1). All these solar disturbances have roots in complex dynamics of the solar magnetic field and their occurrence is closely related to the 11-year cycle of solar activity. During solar cycle progression magnetic properties of sunspot groups, called active regions, dictate the emergence and behavior of solar outputs. While the magnetic field of the corona is difficult to measure, photospheric magnetic field measurements are done regularly using observations of spectral line splitting (Zeeman effect). As an example, in Figure 3.2 we show a full-surface map of the photospheric magnetic field measured by the Global Oscillation Network Group (GONG). The longitude 0° corresponds to the central meridian on April 10, 2013 (5:04 UT), and the symbols in the map denote sub-Earth and STEREO A and B satellite locations. The red and blue colours represent regions where magnetic field lines point away and toward the Sun's surface.

Forecasting SW is not an easy task. For example, in-situ measurements of solar wind parameters at the L1 point ($\sim 1.5 \times 10^6$ km from the Earth), where the ACE satellite is located, allow only ~1 h advanced warning of geomagnetic storms due to CMEs and HSS. To achieve a longer lead time, SW forecasting ultimately must include observations of violent solar disturbances at their source. While the SW research is often based on assumptions of initial conditions and considers isolated phenomena, the forecasting has to extract information from real-time observations and to take into account complex interplay between solar disturbances and preexisting conditions in the Sun-Earth system. Furthermore, forecasting should follow the SW event chain from the beginning to the end. This includes identification of the event start, its progression and possible impacts. One of the most challenging issues is forecasting the emergence of solar disturbances. Magnetic signatures of active regions such as size, location, complexity and magnetic field intensity (see Figure 3.2), for example, can be used as an indication of possible eruptions.

Observations of conditions and changes in the Sun's atmosphere (EUV and X images, coronagraph images, etc.), represent the most important tools used to identify the birth of solar disturbances. In Figures 3.3–3.6, we show satellite observations of coronal holes which are sources of HSS (Figure 3.3), solar flares (Figure 3.4), CMEs (Figure 3.5) and, as an example, SEP interference with a satellite instrument (Figure 3.6). The nature of solar disturbances reveals a SW forecast challenge. Namely, the disturbances have different propagation times from their initiation to the observations of their effects on Earth. It takes ~8 min for EM radiation (solar flares) to reach the Earth, 10's of minutes for energetic particles, 1–4 days for CMEs, and 2–4 days for HSS (Table 3.1). In practice this means that we cannot base the flare forecast on solar observations of the event start since this does not provide any lead time. For solar flares and SEP, which not only can be generated during a solar flare event but due to shock formation in the interplanetary space as well, forecasting is mainly based on probabilistic models and is far from satisfactory. In the case of recurrent solar phenomena (coronal holes and HSS) and for CMEs, advanced forecast of their arrivals based on solar observations is possible and shows promising results. However, forecasting arrivals of disturbances is just one of the SW forecast components. How a SW event will unfold when a solar disturbance reach the complex Earth environment is a further question. In a recent overview of the US Space Weather Prediction Centre's short (less than 1 day) and long term (1–3 days) forecast capabilities for solar flares, SEP and geomagnetic storms are rated from less than satisfactory to poor [21].

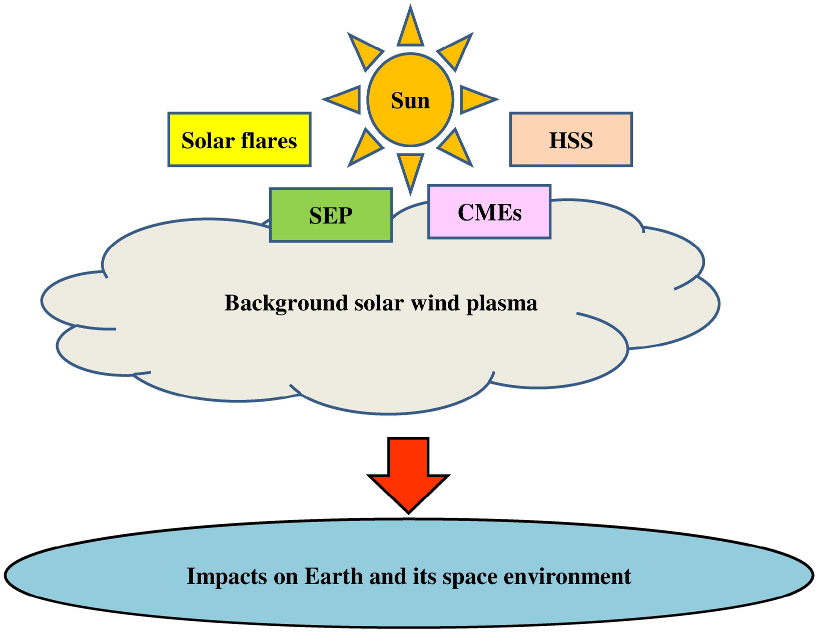

Figure 3.1. Solar outputs of interest in SW. Solar flares represent burst of radiation across the EM spectrum, CMEs are large ejections of coronal plasma into interplanetary space HSS are fast streams of plasma that are associated with coronal holes. SEP are often associated with solar flares and with shocks driven by CMEs. These solar outputs propagate through the constant stream of charged particles called (background) solar wind and can impact Earth and its space environment.

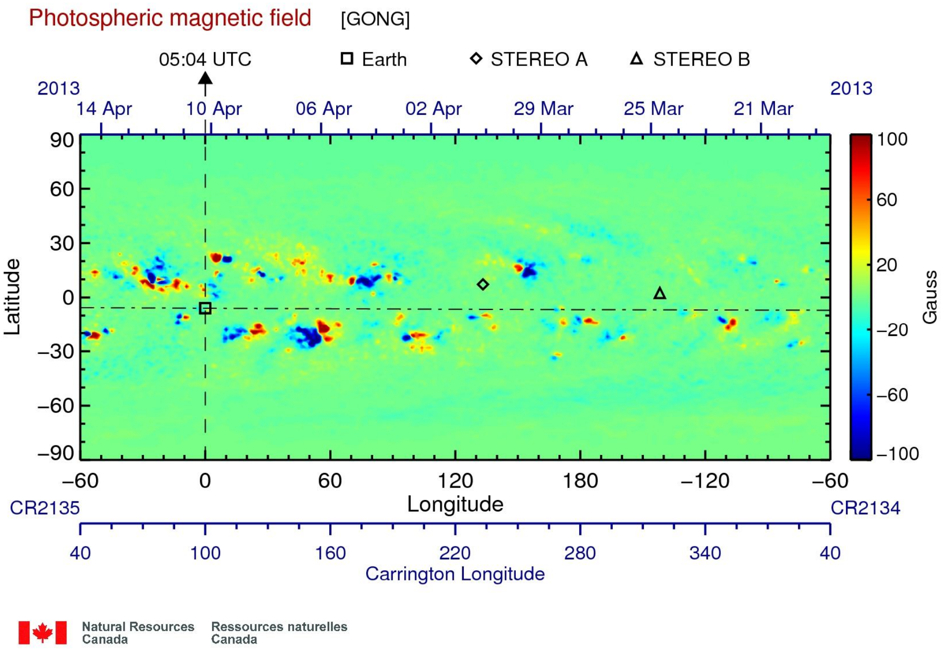

Figure 3.2. Processed GONG magnetogram. The image shows a full-surface map of photospheric magnetic field with the sub-Earth and STEREO A and B satellite locations on April 10, 2013 (5:04 UT). The red and blue colours represent regions where magnetic field lines point away and toward the Sun's surface. The magnetic field scale is saturated at ±100 Gauss.

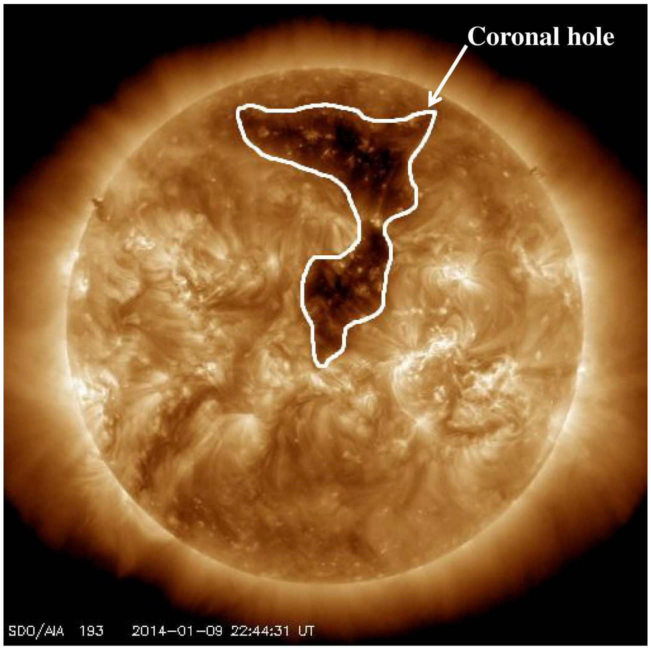

Figure 3.3. SDO satellite AIA 193 image of the Sun on January 14, 2014 (22:44 UT). The dark region seen on the solar disk represents a coronal hole which is the source of HSS.

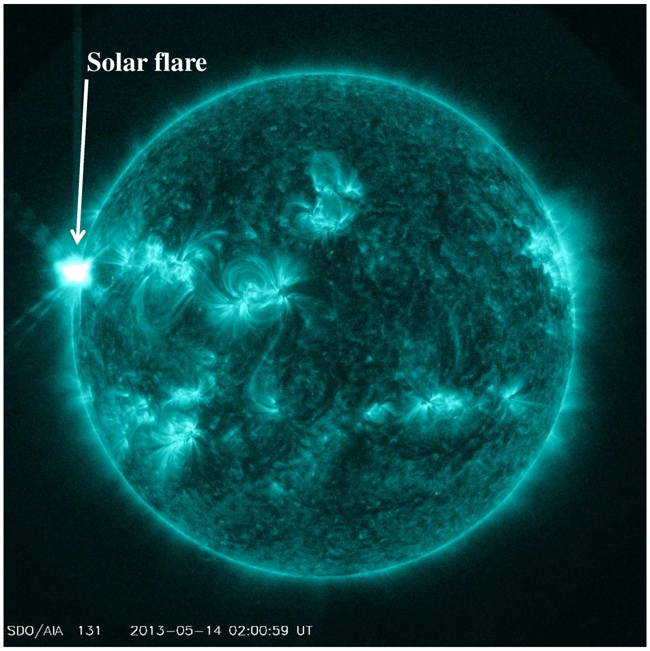

Figure 3.4. SDO satellite AIA 131 image of the solar disc on May 14, 2013 (2:01 UT). The bright flash observed in the left edge of the solar disk represents a solar flare.

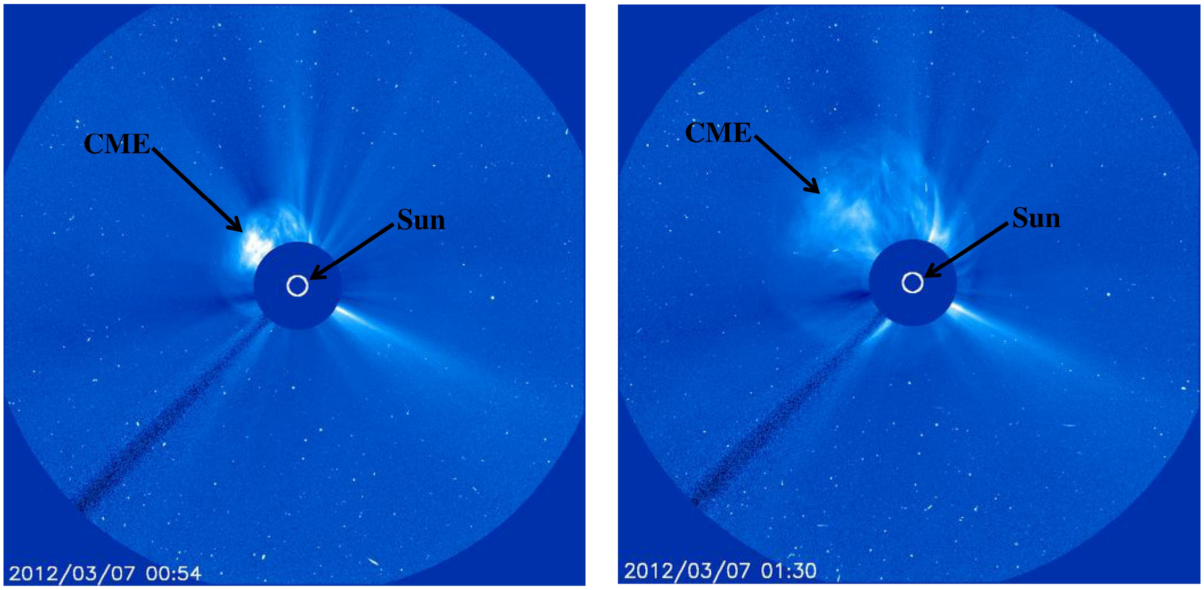

Figure 3.5. Solar corona observed by the LASCO C3 instrument on board of the SOHO satellite on March 7, 2012 at 00:54 UT (left) and 1:30 UT (right). The bright cloud seen in the images shows a CME.

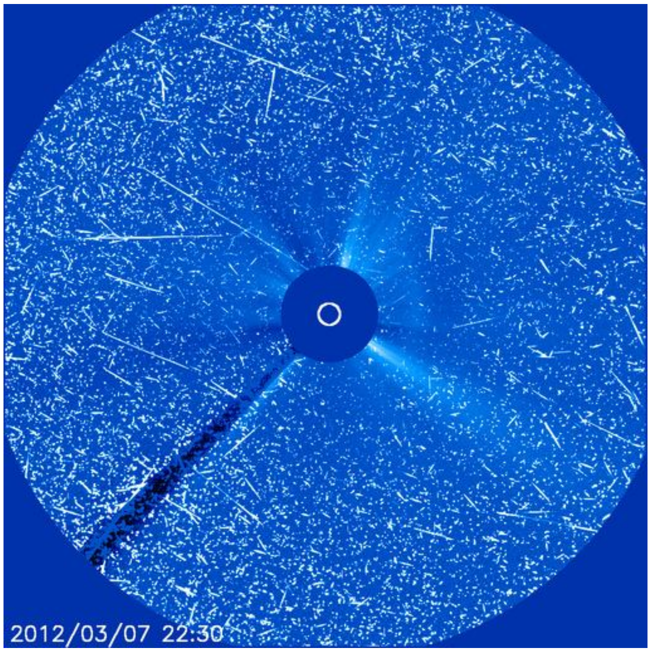

Figure 3.6. The white static in this image shows SEP interference with the LASCO C3 instrument observed on March 7, 2012 (22:30 UT). This SEP event is associated with eruption of an X5-class flare and the CME shown in Figure 3.5.

Solar disturbances	**Arrival time**
Solar flares	~ 8 minutes
Solar energetic particles (SEP)	10’s of minutes
Coronal mass ejection (CME)	1 – 4 days
High speed solar wind streams (HSS)	2 – 4 days

Table 3.1. Solar disturbances and their arrival time on Earth.

SW research shares a similar path of development as terrestrial weather science. To achieve a comparable level of forecast capabilities, SW must overcome two important challenges. One is the lack of observational data and the second is the development of reliable forecast models. Very little of the Sun-Earth system can be directly sampled and many SW processes cannot be well understood by observations at a point or in a plane. Current space- and ground-based observations and measurements only partially cover SW data needs and observational infrastructure needs further development. The second key component to the success of SW forecasting are models which extract useful information from observations and process the data to produce forecasts and nowcasts (see Figure 3.7).

SW forecasting still heavily depends on empirical and semi-empirical models which utilize a set of algorithms to translate observations into event forecast. These algorithms are based on rules derived from correlations and casual relations between properties of physical phenomena and their effects (empirical approach), and simplified physical models (semi-empirical approach).

Typically, empirical and semi-empirical models are simple, fast and easy to use in operations. However, frequent inaccuracy and the absence of a clear physical picture of processes go against these models. Although fully physics based numerical models are the goal of SW modelling efforts, the (semi)empirical models play an important role since they can be used for the assessment of physics based models or as components that provide initial parameters and/or missing physics. In the next section we will discuss physics based numerical modeling.

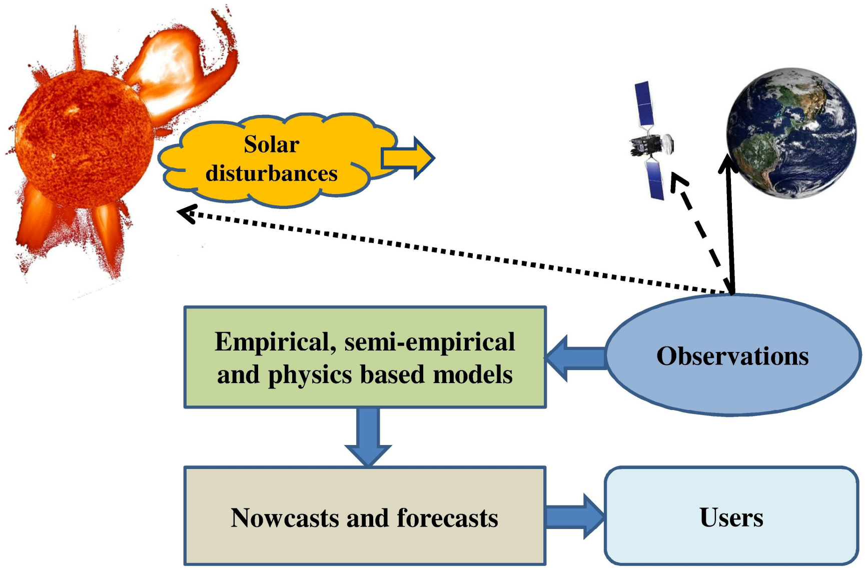

Figure 3.7. A scheme of the workflow in SW operations. Data from space- and ground-based observations of the Sun and its corona, in-situ satellite measurements of particle and field properties and observations of ground effects are used by empirical, semi-empirical and physics based models to produce SW nowcasts and forecasts.

4 Physics based numerical modelling

An accurate physical description of the generation of the solar wind and solar disturbances (see Figure 3.1), their evolution through the interplanetary space and interaction with the Earth's environment should be based on plasma physics theory. This is understandable since all these processes involve charged particles and fields. However, characteristic space and time scales and interplay between phenomena pose a challenge to the implementation of single plasma physics based approach. Research efforts over the past few decades have mainly focused on individual phenomena and domains of the Sun-Earth system; frequently using different choices of approximations, assumptions and simplified theoretical models. For example, much of our understanding of behaviour of charged particles in the Earth's magnetosphere is based on the particle orbit approach which follows the motion of a charged particle in given external electric and magnetic fields. Although this approach is field-plasma non consistent, it is applicable in the case of very low density plasmas. An important second example, taking into account its wide use to describe the global coronal magnetic field, is so-called potential field source surface (PFSS) model [22], [23]. This model assumes that the solar magnetic field controls the structure of the lower corona and neglects the plasma currents on the basis that the magnetic field energy density is greater that plasma energy density in this region.

The aforementioned examples illustrate just some of the approaches and approximations used to investigate the processes in the Sun-Earth system. The choice of appropriate approximations and thus governing equations to describe phenomena is often influenced by the dominant physical conditions and equations solvability. While in many cases simplified models can capture main physical characteristics and show a reasonable agreement with observed phenomena, there are ongoing research efforts to improve the models and their applicability in a wide range of possible physical conditions. This directly leads to more complex models. Therefore, the efforts to more accurately describe SW processes heavily depend on the progress in the numerical plasma modelling which has emerged as an important research tool. By using advanced numerical models it is possible now to develop and run sophisticated physics based numerical models which incorporate the most important processes and interconnect different domains of the Sun-Earth system (see Figure 4.1). As an example, although the interplanetary space represents the largest domain in the Sun-Earth system it is possible to simulate interaction between slow and fast solar wind and propagation of CMEs in the background solar wind using a self-consistent field-plasma description. However, using more advanced numerical models at the same time frequently requires inclusion of physical parameters and processes which are difficult to deduce. Although generation of the Sun's magnetic field and formation of active regions have roots in internal non-equilibrium dynamics of the Sun, it would be a difficult, if not impossible task, to base initial conditions for a Sun-to-Earth numerical model on this dynamics. Therefore, photospheric and coronal observations play a crucial role in providing information from which physical parameters can be quantified and used in the models. For example, based on observed Sun's synoptic magnetograms (see Figure 3.2) PFSS or more self-consistent field-plasma models can be used to derive the coronal magnetic field without a need to consider the internal dynamics of the Sun. Further, information about CMEs, such as their lift-off speed and direction can be extracted from SOHO (Figure 3.5) and STEREO A and B satellite coronal images. However, many parameters necessary to drive physics–based numerical models cannot be easily extracted from current solar observations and many important physical processes (e.g. solar wind heating, generation of CMEs, etc.) are not yet well understood. Empirical and semi-empirical models frequently play a large role in filling this gap. They can be used, for example, in the solar corona to bridge complex coronal physics and to provide initial conditions to an interplanetary physics based model.

Although the interplanetary space represents the largest part of the Sun-Earth system, the solar wind flow and evolution of HSS and CMEs can be modeled by a single physics based model in this simulation domain. However, to accurately describe processes in the solar corona and near-Earth environment, more different models have to be included, such as solar wind and CME models in the solar corona domain, and magnetosphere, ionosphere and thermosphere models in the near-Earth domain [18], [24]. Furthermore, the flow of information between models and their coupling is not always one-directional (Figure 4.1). The physical processes described by different models can be interconnected. This is particularly true in the near-Earth domain. More information on a variety of models used to describe physical processes in the Sun-Earth system can be found in [15], [18], [20], [24].

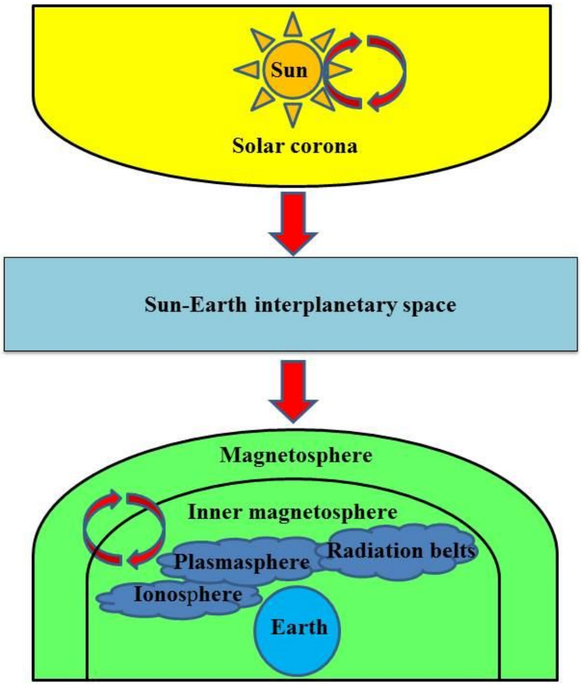

Figure 4.1. A schematic breakdown of the Sun-Earth system into modelling regions. The red arrows represent the information flow between the models indicated. While the energy flows in the region around the Sun (distances less than ~25R_s) and in the region encompassed by the magnetosphere are complex, it can be assumed that the flow of information is one-directional from the solar corona toward the Earth.

4.1 Computer simulations

Computer plasma simulations represent an advanced research tool which is used in investigations of SW processes. Based on fundamental self-consistent plasma equations, these simulations are able to capture detailed physics and describe processes such as propagation of CMEs and HSS, shock formation, interaction of solar wind with Earth's magnetosphere, etc. In this subsection we provide an insight into MHD, kinetic and hybrid simulations [25], [26], [27], [28]. Although all these approaches are used in the scientific community, from the point of view of their computational requirements only MHD simulations currently offer a viable path to simulate the coupled Sun-Earth system.

- **Magneto-hydrodynamics (MHD)**

MHD simulations are based on fluid description where macroscopic variables such as density, speed and temperature are used to describe plasma state. While this method does not include all physics, in particular wave-particle effects, the approach is well established in the numerical plasma modelling. 3D MHD simulation codes have been in use since the early 1980's and they represent the main simulation tool in today's solar-terrestrial research.

In the MHD approach, the plasma is considered as a conducting fluid which represents all plasma species. MHD plasma description is adequate in many cases where characteristic space and time scales of considered phenomena are larger than the ion cyclotron radius and longer than the ion cyclotron period, respectively. The governing equations can be written in different forms that lead to different methods to numerically solve the equations. Furthermore, the physical terms included into the equations depend on considered physical situation. For example, resistive MHD equations used to describe solar corona [29] can be expressed as:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}, \tag{4.1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4.2}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\, \mathbf{j}, \tag{4.3}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \mathbf{v}) = 0, \tag{4.4}$$

$$\rho\left(\frac{\partial\, \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla\, \mathbf{v}\right) = \mathbf{j} \times \mathbf{B} - \nabla p + \rho \mathbf{g} + \nabla \cdot \left(\nu \rho \nabla \mathbf{v}\right), \tag{4.5}$$

$$\frac{\partial p}{\partial t} = -\left(\mathbf{v} \cdot \nabla\right) p - \gamma\, p \nabla \cdot \mathbf{v}, \tag{4.6}$$

where **B** is the magnetic field, μ_0 is the magnetic permeability of vacuum, **j** is the electric current density, **E** is the electric field, **v** is the plasma velocity, η is the resistivity, ρ is the plasma density, **g** is the gravitational acceleration, ν is the kinematic viscosity, and γ is the specific heat ratio.

- **Kinetic simulations**

This approach is based on particle distribution functions $f(\mathbf{x}, \mathbf{v}, t)$ and represents the most powerful physical technique to describe plasma. The governing set of equations for simulations of collisionless plasma consists of Vlasov equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{q}{m}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0, \tag{4.7}$$

coupled with Maxwell equations for the fields

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}, \tag{4.8}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{4.9}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad 4.10$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}, \quad 4.11$$

where q, m, c and ε_0 represent particle charge, mass, speed of light and dielectric permeability of vacuum, respectively. While simulation codes that utilize the kinetic approach based on equations 4.7 - 4.11 have been developed; to simulate evolution of a system in six-dimensional phase space would require enormous computing capabilities. Therefore, this approach is used mainly in the simulations of plasma problems with 2-3 phase dimensions. More common approach to simulate plasma systems based on kinetic theory is so-called particle-in-cell (PIC) simulations. In the PIC simulations plasma is represented with superparticles that represent a large number of physical particles, and equation of motion of the superparticles

$$m\frac{\partial \mathbf{v}}{\partial t} = q\mathbf{E} + \mathbf{j} \times \mathbf{B}, \quad 4.12$$

is solved together with Maxwell equations 4.8 - 4.11. Although these simulations are not the mainstream in the large scale space plasma modelling due to computational constrains, the 3D PIC codes have been in use since the late 1980’s (Tristan code, [25]). They have demonstrated reasonable representation of the main features of the global magnetosphere such as the bow shock, magnetopause, cusps, magnetotail region, etc. Moreover, they can reproduce magnetic field reconnection and particle injection due to the interplanetary magnetic field changes.

- **Hybrid simulations**

Hybrid simulations are used in space plasma physics as a bridge between macro and micro time and space scales. They are a combination of MHD and kinetic approaches. In traditional hybrid simulations, the ion dynamics is described using the PIC technique while electrons are treated by fluid approximation. This method works well in the regions where characteristic space and time scales of phenomena are comparable to ion cyclotron characteristic scales. In terms of computational requirements this approach offers significant advantage over full PIC simulations.

A novel approach to the macro-micro scale problem is MHD simulations with on-demand kinetic simulations. MHD simulations with kinetic aspects at the present time can, for example, include small-scale kinetic algorithms in global MHD simulations to provide anomalous resistivity and microscopic effects. Furthermore, the kinetic algorithm can also be used to trace particles (not self-consistently) using electromagnetic fields obtained by MHD simulations. The full macro-micro (fluid-kinetic) coupling poses a challenge, since it is difficult to transfer physical quantities at the boundaries between MHD and kinetic components. Recently, a coupled MHD-PIC interlocked simulation code has been developed and used to simulate aurora dynamics [30], [31].

4.1 Numerical techniques

Physics based numerical modelling of the Sun-to-Earth system is based not only on the choice of governing equations of physical processes but on the implementation of advanced numerical techniques as well. The advanced models require high performance computing and an efficient implementation of numerical algorithms, parallelization and optimization. The choice of boundary conditions, the choice of numerical grids, time stepping and coupling methods are some of the questions and issues which one faces during code development. Since the outputs of the simulations are usually very large amounts of data, no less attention should be paid to the data post-processing.

Numerical models of the Sun-Earth system, such as MHD simulations, should include different physical models and different strategies to handle both low and high plasma beta accurately, handle both small and large Alfven and Mach numbers (CME shock fronts, magnetospheric fronts), include advantages of higher order numerical techniques, etc. Stability and accuracy are a general request of numerical schemes. As a general rule, more accurate numerical schemes are more time consuming per computational cycle. Choice of computational mesh and time steeping methods are two important factors that can define the quality of simulations. One can opt to use, for example, a uniform Cartesian grid, stretched Cartesian grid, structured adaptive mesh, unstructured grid, Ying-Yang mesh, etc. There is no perfect solution to the choice of numerical grids. For example, while a uniform Cartesian grid is easy to parallelize and provides the lowest programming and computational overhead, this type of grid is not best adjusted to real simulation geometry. Traditionally, most of the standard simulation codes utilize a fixed numerical mesh. However, new simulation code developments utilize more Adaptive Mesh Refinement (AMR) technique [32]. This technique offers the capability of creation and destruction of computational cells depending on the required conditions for resolution and accuracy.

Time marching schemes in simulation codes are usually based on so-called explicit time stepping where new time values of physical quantities are calculated from previous times only. In order to be stable, an explicit scheme must satisfy Courant-Friedrichs-Lewy (CFL) constraints. In other words, an explicit time step is limited by the largest k- mode or highest frequency that enters the system. The implication of the CFL condition is the following: in order to improve space resolution one has to decrease computational cell size, which at the same time means that the time step must be decreased to preserve computational stability. This ultimately increases the total computational time. This can be avoided by using a more complex approach – implicit time stepping, where the solution of the new quantities involves knowledge of these quantities at the new time, thus forming a potentially very large system of coupled nonlinear equations. Implicit time stepping is more computationally costly per computational cycle than the explicit technique. The real advantage of an implicit scheme is that it can stay stable for large time steps. Because of their complexity and concerns about their reliability, implicit schemes are not widely used in the space simulation community. Modern simulation codes, however, offer the choice between explicit and implicit schemes, also allowing their mixing [32]. Since in the Sun-Earth system different simulation domains have different space-resolution and time-step requirements, one can use an asynchronous method for parallel time-marching [33]. This method, for example, uses different local time steps in the corona and in the Sun-Earth interplanetary space according to the local CFL conditions.

5 Transition of scientific codes to operations

Over the last 10-15 years more than $1 billion has been allocated for development of numerical models in the US alone, resulting in a broad range of models for different Sun-to-Earth modelling domains [35]. However, only a fraction of these models have been put into operations. Some examples are: Wang-Sheeley-Arge (WSA) solar wind model [36], Hakamada-Akasofu-Fry (HAF) model for forecasting of interplanetary shock arrivals at Earth [37], High Accuracy Satellite Drag Model (HASDM) [38], Relativistic Electron Forecast Model (REFM) [39], Storm-time Ionospheric Correction Model (STORM) [40], etc. Moreover, it should be noted that a majority of the SW operational models are still (semi)empirical. Some exceptions to this include a real time global magnetosphere MHD code which uses real-time ACE satellite solar wind data [41], and a large scale heliospheric MHD code which is coupled with WSA and CMA initiation models (ENLIL with a CME cone model) [42]. The first model has been developed for the National Institute of Information and Communications Technology (NICT, Japan) to forecast magnetospheric responses to solar wind disturbances, and the second for the National Oceanic and Atmospheric Administration (NOAA, US) SW operations to forecast solar wind disturbances and CME arrivals.

The development of sophisticated numerical models is one of the focal points of the SW research community. Although many of these models have demonstrated reasonable SW forecast capabilities, the driving force behind this development is most often to obtain a scientific understanding of SW phenomena rather than to meet SW user oriented operational needs. It was acknowledged in the 2006 Report of the Assessment Committee for the National Space Weather Program (US) that “there is an absence of suitable connection[s] for ‘research-to-operations’ knowledge transfer and for the transition of research to operations in general” [16]. To bridge the gap between research and operations, a stronger collaboration should be established. This could greatly help the development and advances in both fields. The purely scientific codes exhibit serious operational deficiencies in many aspects. One of the most obvious differences between academic and operational models is that in research, assumptions of input parameters are often made, including the parameters which are not observationally available. Operational models however, rely on available data (Figure 5.1). During the course of operations, shortcomings of a model may surface such as failures due to unforeseen events, sensitivity to particular conditions, model biases, etc. The feedback on the model behavior should be communicated to the research community. This information can be used for further model improvements.

There are many requirements that SW models should fulfil in order to be used in operations [34], [42]. This includes:

- **Outputs of models should meet user needs.** The users of SW products are not necessarily experts in this field. While academic codes tend to produce results which help scientific understanding, operational outputs should provide easily understandable information that could guide the user’s actions. Moreover, the interpretation of the outputs should be adjusted to fit different user groups. For example, the levels of geomagnetic activity may have different meaning for aeromagnetic surveys than the electric power industry.

- **Model accuracy.** The models should have a reasonable agreement between outputs and actual observations. The metric, a quantitative criterion to measure the accuracy, should be developed and used in the process of model evaluations. If a model has a satisfying forecast score it can be considered as a candidate for transfer to operations. Verification and validation of the SW models should be an ongoing process in operations.

- **Reliability of models and supporting systems.** A SW model and the infrastructure that supports its operation should be reliable. This includes data acquisition and quality control, processing, dissemination, software, hardware, etc. To minimize failures a high degree of automatization with error handling is needed.

- **Timeliness of outputs.** SW numerical models should provide forecast and nowcast, including dissemination to users, as early as possible. To achieve this, automatization and near real-time processing is required.

- **IT requirements.** Modern scientific simulation codes often depend on large computing resources, and require specialized IT environment and knowledge to run. This cannot be always met in an operational setting. The code portability, impact on IT security, licensing issues, support and anticipated IT changes, should be considered in an operational evaluation of numerical codes.

- **Documentation.** As a rule, academic numerical codes suffer from the lack of documentation. Description of code inputs and outputs, concepts, limits, instructions how to operate the code, evaluation results etc., should accompany the code transfer to operations. A clear Concept of Operations (CONOPS) has to be developed which will encompass all characteristics and requirements. Furthermore, the code performance in operations and issues should be documented as well.

These are some of the requirements for the research-to-operations transitioning. The dialogue between scientists and operators is an integral part of the process, so that specific requirements and issues can be identified and clarified. This includes: resources needed for the model transition, commitments to support the model operation, necessary training for the operators, etc.

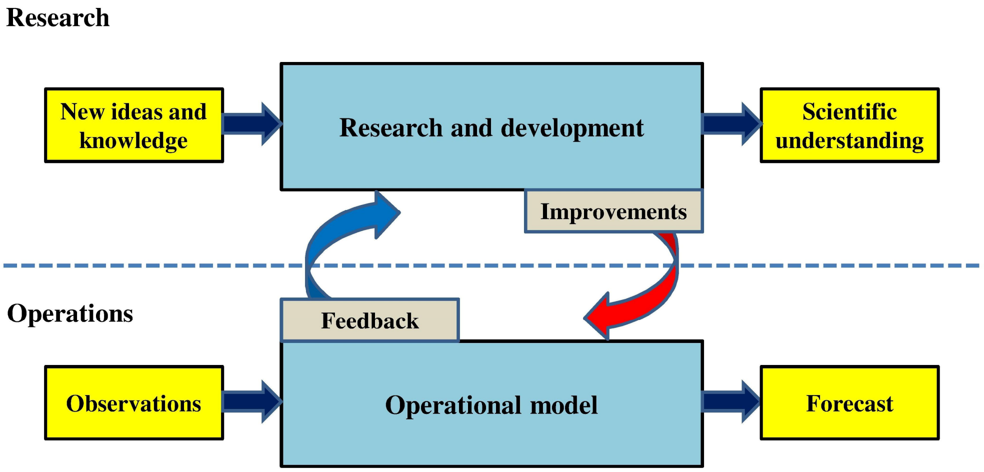

Figure 5.1. Connection between research and operations.

6 Overview of Space Weather modelling activities

SW research is a hot topic in the scientific community and a number of countries have activities in this field [43]. However, only a few countries have articulated programs that put significant effort into the development of SW numerical models, in particular operational models. In the US, much effort has been devoted to the development of SW modelling tools through various substantially founded research projects [44]. In order to enable collaboration and support the SW research and development activities a multy-agency partnership – the Community Coordinated Modelling Centre (CCMC) has been established [45]. The CCMC hosts a variety of SW models supplied by research groups and provides access to the models. This initiative is designed as a step toward the validation and inclusion of models into SW operations. Two US government organizations provide SW operational services and rely on numerical models; the Space Weather Prediction Centre (SWPC, NOAA), and the United States Air Force (USAF) Space Weather Squadron. The centres serve civilian and the Department of Defence customers, respectively. Although forecasting capabilities are mostly based on observations and (semi)empirical models, the Centre for Space Environment Modelling (CESM), University of Michigan [46] and the Centre for Integrated Space Weather Modelling (CISM) [47], have developed advanced multi domain simulations to model the Sun-to-Earth environment. Recently, the first large scale interplanetary MHD simulation code coupled with a semi-empirical WSA code has been transferred to SWPC operations [42], [48].

Japan, along with the US, has been a leader in numerical simulations, including MHD and PIC. Japanese investment in computational technology and availability of resources to the research community have resulted in significant advances in simulation techniques. The National Institute of Information and Communication Technology (NICT) operates Japanese SW forecast centre. The centre has developed an operational 3D MHD code for real time global magnetosphere simulations [49], [50]. NICT has achieved the world's first real-time replication of how the Earth's magnetosphere changes, using the ACE satellite solar wind observations. The NICT is putting efforts to further develop numerical models, such as magnetosphere-ionosphere and troposphere-ionosphere models. Furthermore, the Japanese government is extensively funding simulation research activities with an aim to improve understanding and predictability of solar eruptions and their impact on the Earth [51], [52].

The European scientific community has much expertise in solar-terrestrial research. However, the major effort has been put on observational projects while SW modelling activities were not stimulated enough. While the need for modelling tools has been recognized a long time ago [14], the development of numerical models was incoherent. This was greatly due to different objectives and relevancy of SW effects in EU countries. In recent years the SW awareness and interest in SW forecasting are growing in the European community. Several initiatives have been launched in order to accelerate the SW field development, coordinative and foster collaboration and assess potential for the development of observational and modelling techniques [53], [53], [55], [56], [57].

The US, Japan and European Union are the main driving force in solar-terrestrial science. They are the main contributors to the ground and space based SW observational capabilities, and significantly support research and development activities. The funding of the research projects in other countries is on a much smaller scale. However, recently China and South Korea are increasing efforts to establish themselves in the SW field, including numerical modelling [58], [59], [60].

Figure 6.1. Canadian Space Weather Forecast Center, Canadian Hazards Information Service, Natural Resources Canada, Ottawa.

The Canadian solar-terrestrial community is relatively small. The solar physics research is mainly undertaken by the University of Montreal (UofM) research group [61]. The UofM solar physics group is focused primary on simulations of the Sun's internal dynamics. Large scale MHD codes are used to investigate convective dynamo magnetic field generation and internal plasma flows. Other Canadian universities, such as the University of Calgary [62], University of Alberta [63], University of Saskatchewan [64], and University of New Brunswick [65], have research activities in the SW field. However most of these activities are focused on near-Earth observational and theoretical SW aspects. Simulation efforts are carried out mainly by the University of Alberta [63]. These efforts include MHD simulations of global magnetosphere and PIC simulations of plasma effects such as satellite charging.

Canadian SW operational activities are undertaken by the CSWFC (Figure 6.1), Canadian Hazards Information Service (NRCan). The center provides SW forecast, information and data related to SW (see Figure 6.2). Furthermore, the centre is a Regional Warning Centre of the International Space Environment Service (Figure 6.3) and contributes to the World Meteorological Organization. In order to enhance SW forecasting capabilities and modernize operational services, the research activities in the CSWFC include numerical modelling. In particular, one of the goals is to improve forecast of HSS and Earth directed CMEs. These solar disturbances impact geomagnetic activity (Figure 6.2) to which Canada is susceptible. An accurate forecast of HSS and CME arrivals ultimately involves modelling of the Sun-Earth system. Current modelling capabilities of the center include a semi-empirical WSA-like code [36] used to forecast solar wind speed (quiescent wind and HSS) at the Earth (see figure 6.4). In order to enhance accuracy of the forecast, further development of the code is underway. The code uses the PFSS and Schatten current sheet model to derive the coronal magnetic field using solar magnetograms.

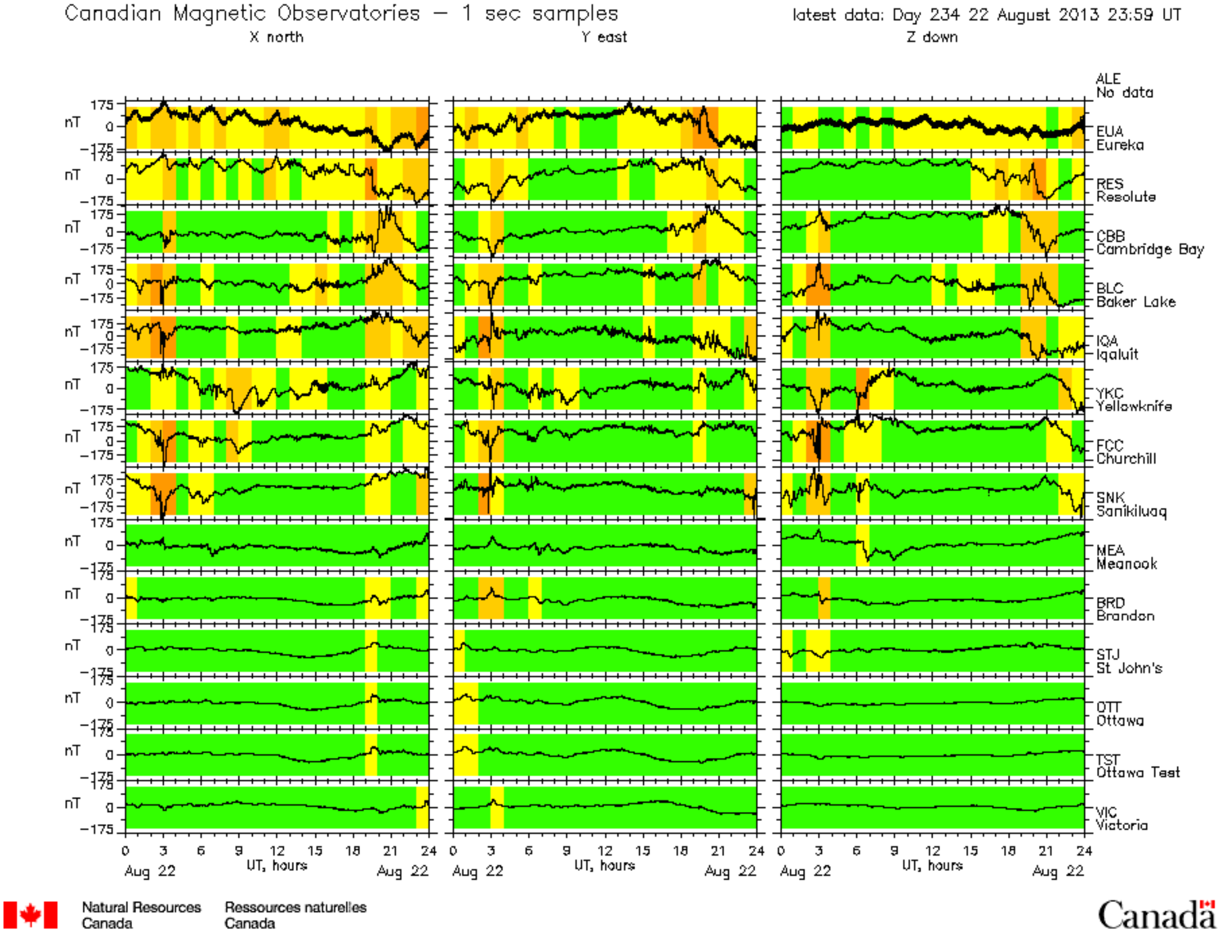

Figure 6.2. This graph shows the data from the Natural Resources Canada's magnetometers for August 22, 2013. For each station, the X (north), Y (east) and Z (vertical down) components of the magnetic field are shown. Stations are displayed starting with the most northerly at the top progressing down the page in decreasing latitude. The colour in the graph represents level of geomagnetic activity form quiet (green) to stormy (red).

Although the goal of the CSWFC is to simulate the Sun-Earth system using fully physics based models, the recent comparison between MHD and PFSS based solar corona models endorse PFSS at this stage of scientific understanding and development [67]. Therefore, the development of a semi-empirical solar wind code, which covers the solar corona and interplanetary space, was stimulated by the PFSS model simplicity and acceptable accuracy. The modelling efforts that are currently underway is to couple PFSS based corona model with a newly developed 3D MHD interplanetary code which utilize AMR technique. The PFSS based solar wind model will provide initial conditions (at ~25Rs) to the interplanetary MHD simulations. Later, a CME model will be added to this numerical framework.

Figure 6.3. The Canadian Space Weather Forecast Centre in Ottawa is operated by Natural Resources Canada. It is a Regional Warning Centre of the International Space Environment Service. The map shows locations of Regional Warning Centres (as of 2014).

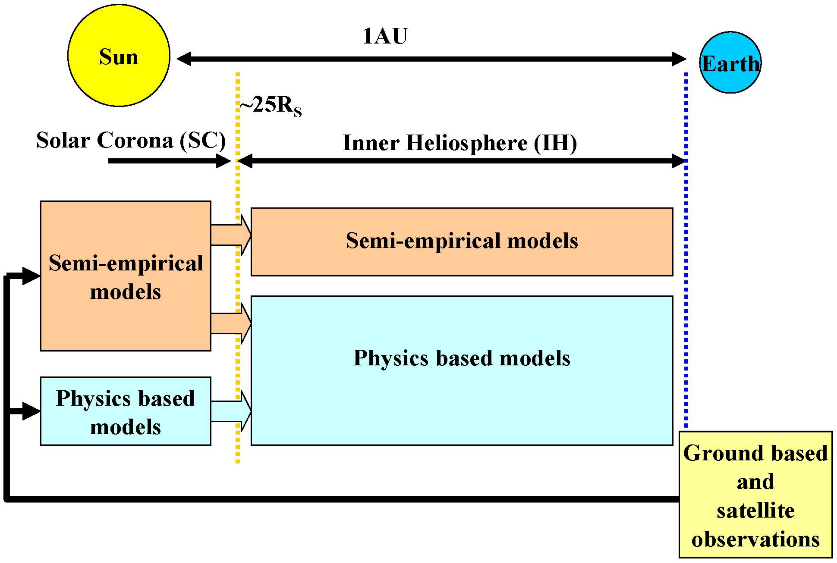

Figure 6.4. CSWFC modelling approaches to the coupled Sun – interplanetary space system. Current capabilities of the center include a semi-empirical solar wind code to forecast solar wind speed (quiescent wind and HSS) at the Earth. Although the goal is to simulate the Sun-Earth system using fully physics based models, the current CSWFC modelling efforts are focused on a numerical framework which includes a semi-empirical coronal model and physics based, MHD, interplanetary code.

7 Summary

The growing dependence of modern society on technological assets has been accompanied by increasing vulnerability to SW phenomena that can disrupt their safe operation. This fact has motivated research and operational efforts to understand and forecast SW phenomena. Due to its close proximity to the north magnetic pole, Canada is particularly vulnerable to SW effects.

The source of violent solar disturbances that drive SW effects is our Sun. Solar flares, CMEs, HSS and SEP represent the main disturbances which can affect Earth and its environment. To forecast SW is not an easy task. Much of the physics of solar disturbances is not yet well understood. Furthermore, the disturbances exhibit different propagation times from their initiation at the Sun to their arrival at the Earth. In order to understand SW phenomena and their effects, a broad range of observational and forecast tools have been developed over the last couple of decades. Although the first SW forecast models were purely empirical, the research efforts are shifting now toward semi-empirical and physics based models. Significant efforts have been put into the development of large scale MHD, PIC and hybrid simulation codes most notably in the US and Japan. Unfortunately, very often, no articulated approach has been given to SW. Recently, in order to provide better insight into modelling capabilities and foster collaboration, several portals were launched to collect information about models which can be used in the SW field.

It is a consensus in the SW scientific community that the field needs more physics based numerical models. Although it has been demonstrated that many academic models have relatively satisfying forecasting capabilities, not much work has been done in the transitioning of these models to operations. The main reason is the lack of focused collaboration between the scientific and operational community. Most of the scientific codes developed in the academic community were not designed with operational functionality in mind. Therefore, many SW operational models currently in use are still empirically based, and just recently large scale physics based codes are finding their way into operation.

The CSWFC recognize the need for advanced SW numerical models and is developing operational numerical models to forecast changes in solar wind parameters. Currently, our modular numerical simulation framework for the propagation of solar disturbances through interplanetary space, encompasses coronal magnetic field and solar wind speed components. These can provide initial parameters for an interplanetary 3D MHD simulation code. The coronal magnetic field and solar wind speed modules can also operate in a stand-alone semi-empirical configuration providing useful information to SW forecasters; including prediction of changes in the solar wind speed due to HSS from coronal holes.

Acknowledgment

Authors would like to thank Dr Robyn Fiori for the review of this paper and valuable suggestions.

References

[1] Kane R. P., The idea of space weather - A historical perspective, Adv. Space Res. **37**, 1261 (2006).

[2] Parker E. N., Suprathermal particle generation in the solar corona, Astrophys. J. **128**, 677 (1958).

[3] Tousey R., The solar corona, Space research XIII, eds. Rycroft M. J. and Runcorn S. K. (Akademie-Verlag, Berlin, 1973), p713.

[4] Space weather – Physics and effects, eds. Bothemer V. and Daglis I. A. (Praxis Publishing 2007).

[5] Space storms and space weather hazards, ed. Daglis I. A., Proceedings of the NATO Advanced Study Institute (19-29 June 2000, Hersonissos, Crete, Greece), (Kluwer Academic Publishers 2001).

[6] http://www.nrcan.gc.ca/hazards/natural-hazards

[7] http://www.sdr.gov

[8] http://www.parliament.uk/documents/post/postpn361-space-weather.pdf

[9] http://www.spaceweather.ca

[10] http://sohowww.nascom.nasa.gov

[11] http://sdo.gsfc.nasa.gov

[12] http://www.swpc.noaa.gov/ace , http://www.srl.caltech.edu/ACE/

[13] http://stereo.gsfc.nasa.gov

[14] Koskinen H. and Pulkkinen T., State of the art space weather modelling and proposed ESA strategy, SPEE-WP310-TN (1998).

[15] National Space Weather Program Implementation Plan, FCM-P31-2000, US (2000). http://www.ofcm.gov/nswp-ip/pdf/nswpip.pdf

[16] Report of the Assessment Committee for the National Space Weather Program, FCM-R24-2006, US (2006). http://www.ofcm.gov/r24/fcm-r24.htm

[17] National Space Weather Program Strategic Plan, FCM-P30-2010, US (2010). http://www.ofcm.gov/nswp-sp/fcm-p30.htm

[18] Wiltberger M. and Baker D., End-to-end modeling of the solar terrestrial system, Space Science Reviews **124**, 217 (2006).

[19] Moldwin M., An introduction to space weather (Cambridge University Press 2008).

[20] Aschwanden M. J. *et al.*, Theoretical modeling for the STEREO mission, Space Sci. Rev. **136**, 565 (2008).

[21] Severe Space Weather Events, Committee on the Societal and Economic Impacts of Severe Space Weather Events, The National Academic press, 2008.

[22] Altschuler M. D. and Newkirk G., Sol. Phys. **9**, 131 (1969).

[23] Altschuler M. D. *et al.*, Sol. Phys. **51**, 345 (1977).

[24] Toth G. *et al.*, Space Weather Modeling Framework: A new tool for the space science community, J. Geophys. Res. **110**, A011126 (2005).

[25] Computer simulation of space plasmas, eds. Matsumoto H. and Sato T. (TERRAPUB, Tokyo, 1985).

[26] Computer Space Plasma Physics: Simulation Techniques and Software, eds. Matsumoto H. and Omura Y., (TERRAPUB, Tokyo, 1993).

[27] Space Plasma Simulation, eds. Buchner J., Dum C. T. and Scholer M., (Springer 2003).

[28] Advanced Methods for Space Simulations, eds. Usui H. and Omura Y. (TERRAPUB, Tokyo, 2007).
[29] Mikic Z. *et al.*, Magnetohydrodynamic modeling of the global solar corona, Phys. Plasmas **6**, 2217 (1999).
[30] Sato T., Hasegawa H. and Ohno N., Macro–micro interlocked simulation algorithm: an exemplification for aurora arc evolution, Computational Science & Discovery **2**, 015007 (2009).
[31] Sato T., Macro–micro interlocked simulator, J. Phys. Conf. Ser. **16**, 310 (2005).
[32] Toth G. *et al.*, Adaptive numerical algorithms in space weather modeling, Computational Physics **231**, 870 (2011).
[33] Shen F., Feng X. S. and Song W. B., An asynchronous and parallel time-marching method: Application to three-dimensional MHD simulation of solar wind. Sci China Ser E-Tech Sci, 2009, 52(10): 2895—2902, doi: 10.1007/s11431-009-0291-1
[34] Wehrenpfennig A., Jakowski N. and Wicket J., A dynamically configurable system for operational processing of space weather data, Phys. Chem. Earth C **26**, 601 (2001).
[35] Tobiska, W. K, Operational space weather entering a new era, Space Weather **7**, S10003 (2009).
[36] Arge C. N. and Pizzo V. J., Improvement in the prediction of solar wind conditions using near-real time solar magnetic field updates, Journal of Geophys. Res. **105**, 465 (2000).
[37] Fry C. D. *et al.*, Improvements to the HAF solar wind model for space weather predictions, Journal of Geophysical Research **106**, 985 (2001).
[38] Storz M. F. *et al.*, High accuracy satellite drag model, Advances in Space Research **36**, 2497 (2004).
[39] Relativistic Electron Forecast Model. http://www.swpc.noaa.gov/refm/doc/REFMDoc.html
[40] Araujo-Pradere E. A., Fuller-Rowell T. J. and Codrescu M. V., STORM: An empirical storm-time ionospheric correction model, Radio Science **37**, 2620 (2002).
[41] Shimazu H. *et al.*, Real-time global MHD simulation of the solar wind interaction with the earth's magnetosphere, Advances in Space Research **42**, 1504 (2008).
[42] Araujo-Pradere E. A., Transitioning space weather models into operations: the basic building blocks, Space Weather **7**, S10006 (2009).
[43] International Space Environment Service (ISES). http://www.ises-spaceweather.org
[44] Space Weather Architecture Transition Plan, Office of the Assistant Secretary of Defense for Command, Control, Communications, and Intelligence (2000). http://www.ofcm.gov/Tplan/swatp.html
[45] Concept of Operations for the Community Coordinated Modeling Center (2002). http://ccmc.gsfc.nasa.gov/CONOPS_final.pdf
[46] Center for Space Environment modeling (CSEM). http://csem.engin.umich.edu
[47] Center for Integrated Space Weather Modeling (CISM). http://www.bu.edu/cism/index.html
[48] Pizzo V. *et al.*, Wang-Sheeley-Arge–Enlil Cone Model Transitions to Operations, Space Weather **9**, S03004 (2011).
[49] Watari S., Space weather center in Japan, Advances in Space Research **42**, 1445 (2008).
[50] National Institute of Information and Communications Technology (NICT) http://www.nict.go.jp/en/
[51] Solar-Terrestrial Environment Laboratory (STEL). http://www.stelab.nagoya-u.ac.jp
[52] Joint Project for Space Weather Modeling (JSWM). http://www.jamstec.go.jp/ifree/space_Earth/jswm/en/

[53] Benefits of a European Space Weather Programme, European Space Agency, ESWPS-DER-TN-0001 (2000).

[54] Developing the scientific basis for monitoring, modelling and predicting Space Weather, COST 724 final report (2007). http://www.cost.eu/domains_actions/essem/Actions/724

[55] COST ES0803. http://www.costes0803.noa.gr

[56] Space Weather Europe. http://www.spaceweather.eu

[57] European Space Agency. http://www.esa.int/esaMI/SSA/SEMOH74SNIG_0.html

[58] State Key Laboratory of Space Weather. http://www.spaceweather.ac.cn/english

[59] Solar Activity Prediction Centre. http://rwcc.bao.ac.cn/index.jsp

[60] Korean Space Weather Centre. http://www.spaceweather.go.kr

[61] Solar Physics Research Group, University of Montreal. http://www.astro.umontreal.ca/groupe/fiche_frame_en.php?id=4

[62] University of Calgary. Physics and Astronomy. http://phas.ucalgary.ca/contact-us/directory

[63] Space Physics, University of Alberta. http://uofa.ualberta.ca/physics/research/space-physics

[64] University of Saskatchewan. Department of Physics and Engineering Physics. http://artsandscience.usask.ca/physics/research/

[65] University of New Brunswick. Atmospheric and Space Physics. http://www.unb.ca/fredericton/science/depts/physics/research/index.html

[66] Norquist D. C. and Meeks W. C., A comparative verification of forecasts from two operational solar wind models, Space Weather **8**, S12005 (2010).

[67] Riley P., Linker J. A., Mikic Z., Lionello R., Ledvina S. A. and Luhmann J. G., A comparison between global magnetohydrodynamic and potential field source surface model results, The Astrophysical Journal 653, 1510 (2006).

[68] De Sterck H., Numerical modelling of MHD space plasmas, DASP - CAP Congress 2010, Toronto, Canada.