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Nowcasting and forecasting of the magnetopause and bow shock—A status update

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Key Points:

- Recent spacecraft data sets have enabled the advancement of empirical models of the magnetopause and bow shock
- Improved computational modeling capabilities allow for real-time of boundaries
- Metrics and skill scores are beginning to be effectively used to assess boundary forecasting accuracy

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Abstract There has long been interest in knowing the shape and location of the Earth's magnetopause and of the standing fast-mode bow shock upstream of the Earth's magnetosphere. This quest for knowledge spans both the research and operations arenas. Pertinent to the latter, nowcasting and near-term forecasting are important for determining the extent to which the magnetosphere is compressed or expanded due to the influence of the solar wind bulk plasma and fields and the coupling to other magnetosphere-ionosphere processes with possible effects on assets. This article provides an update to a previous article on the same topic published 15 years earlier, with focus on studies that have been conducted, the current status of nowcasting and forecasting of geophysical boundaries, and future endeavors.

1. Introduction

This article presents an update to a previous paper that discussed nowcasting and forecasting of the Earth's magnetopause and bow shock [*Petrinec*, 2001]. This previous work described a chain of events which included the observation of solar wind parameters and magnetic field in real time from a monitor in halo orbit about the Sun-Earth L_1 Lagrange point, the downlink of the data with minimal latency, packaging the observations as text files and availability of such files to the public on a NOAA site, and the use of empirical magnetopause and bow shock models parameterized by the solar wind to estimate the locations and shapes of these boundaries from the present to near future, displayed as time-varying animations on another web site (updated every 5 min). One motivation for this earlier effort was to demonstrate that real-time observations of the solar wind plasma environment could be used for near-term estimates of the size and shape of the magnetosphere and location of the standing fast-mode bow shock. Simple and straightforward, the display of these predicted geophysical boundary locations and shapes had some utility as a crude space weather application. The animations also included a demarcation representing geosynchronous orbit (since this is a common orbit for many kinds of spacecraft), which could provide some advance visual warning if an enhancement of solar wind pressure and/or strongly southward interplanetary magnetic field was likely to compress/erode the magnetosphere inside of this orbit. These Geosynchronous Magnetopause Crossings (GMCs) result in geostationary satellites finding themselves crossing into the magnetosheath [cf. *Opp*, 1968; *Skillman and Sugiura*, 1971; *Russell*, 1976; *Rufenach et al.*, 1989; *McComas et al.*, 1994; *Dmitriev et al.*, 2004, 2005, 2011, 2016; *Suvorova et al.*, 2005]; a generally more turbulent region. Such conditions are often a good indicator of an impending geomagnetic storm [e.g., *Rufenach et al.*, 1989], if one is not already occurring [e.g., *Li et al.*, 2010]. A second motivation of this effort was to provide educational opportunities for the greater public; to dynamically and simply illustrate with a basis in real spacecraft observations how the plasmas of the extended solar atmosphere and the terrestrial space environment interact. The web site and its embedded graphics purposely used common formats in order to accommodate the greatest variety of browsers (and versions) and platforms with minimal intervention on the part of the user (e.g., no need to download plug-ins and applets). Interest from and discussions with teachers and HAM radio operators suggest that this has been a useful endeavor.

Since the time of publication of the *Petrinec* [2001] article, there have been a number of efforts to advance models related to the geophysical boundaries and to further understand the response of real-time solar wind observations on these boundaries. Several of these pursuits are described in the following sections. In the remainder of the paper, the adjective "recent" as it applies to studies and models refers to efforts of the past 15 years (2001–2016).

It is noted here that several agencies within the United States (e.g., the NOAA and NASA federal agencies) are interested in space weather applications and forecasting, including knowledge of the geophysical

Table 1. Past and Present GEM Focus Groups of Direct Relevance to the Magnetopause and Bow Shock

GEM Focus Group	Duration
Foreshock, bowshock, magnetosheath	2004–2009
Dayside magnetopause reconnection	2004–2009
Cusp Physics	2006–2010
The magnetosheath	2010–2014
Transient phenomena at the magnetopause and bow shock and their ground signatures	2012–2016
Magnetic reconnection in the magnetosphere	2013–2017
Geospace systems science	2014–2018
Dayside kinetic processes in global solar wind-magnetosphere interaction	2016–2020
Geospace general circulation model (GGCM) metrics and validation	2005–2010
Metrics and validation	2011–2015
Modeling methods and validation	2016–2020

boundaries (At the time of this writing, the U.S. President has issued an executive order to have the relevant agencies coordinate efforts to prepare the nation for space weather events: https://www.whitehouse.gov/the-press-office/2016/10/13/executive-order-coordinating-efforts-prepare-nation-space-weather-events). In addition, the National Science Foundation (NSF)-sponsored Geospace Environment Modeling (GEM) program has implemented over the years two research areas (RA) with emphasis on the outer magnetosphere and interactions with the solar wind (the earlier Dayside RA, and the current Solar Wind-Magnetosphere Interaction RA), under which several multiyear focus groups have occurred, addressing various aspects of the geophysical boundaries, the most relevant of these are listed in Table 1 (the first eight entries). In addition, there have been GEM focus groups with intent to quantitatively assess the validity and predictive capability of various models (the last three entries in Table 1). Institutes outside the U.S. have also shown interest in space weather and the forecasting of the geophysical boundaries. These will be further discussed in section 3.

2. Boundary Models: Location, Shape, and Dependences

Several recent studies and models of the magnetopause, bow shock, and magnetosheath thickness have been put forth, with relevance to real-time forecasting efforts. Some of these works are briefly described below. Studies performing comparisons of existing parameterized models with observations and/or numerical models are described in section 4.

2.1. Empirical Models

There have been several recent empirical studies of the magnetopause shape and location. *Chao et al.* [2002] derived modified coefficients for the same axially symmetric magnetopause functional form (parameterized by the convected solar wind) as that of *Shue et al.* [1998]. *Šafránková et al.* [2005] used high-latitude magnetopause crossings to provide a modification to an earlier, asymmetric model of the magnetopause [*Boardsen et al.*, 2000]. Another, more recent study that examined in detail the 3-D magnetopause shape (including the indentations of the magnetospheric cusps and the effect of dipole tilt angle) is that of *Lin et al.* [2010]. This empirical model (without cusp indentations) has been incorporated as the outer magnetosphere boundary into the most recent semiempirical magnetospheric magnetic field models [*Tsyganenko*, 2014; *Tsyganenko and Andreeva*, 2015]. *Wang et al.* [2013] used the technique of ingesting a large data set of magnetopause crossings and the implementation of a support vector regression machine to estimate the size and shape of the 3-D asymmetric magnetopause as a function of solar wind conditions and dipole tilt angle, without the use of a priori assumptions as to functional form. Finally, some recent studies have examined the parameter ranges needed for the magnetopause to intersect geosynchronous orbit, along with dawn-dusk asymmetries, using observations [*Dmitriev et al.*, 2004, 2005, 2011, 2016; *Suvorova et al.*, 2005] and long-term predictions on the future increased occurrence of geosynchronous intersections by scaling current empirical models and the decay rate of the Earth's dipole moment [*Zhong et al.*, 2014].

In addition to the magnetopause, *Chao et al.* [2002] modeled the shape and location of the fast-mode bow shock upstream from the Earth's magnetopause using observations and parameterized by the solar wind. Three-dimensional asymmetries of the bow shock due primarily to the solar wind were empirically modeled by *Verigin et al.* [2001], *Merka et al.* [2005b], and *Jeřáb et al.* [2005], while additional parameterization by the Earth's dipole tilt angle was conducted by *Jelínek et al.* [2008]. Several of these studies of 3-D effects on the bow shock have built upon the earlier work of *Peredo et al.* [1995]. The distant tail bow shock shape and location was modeled using ARTEMIS observations at lunar distances by *Liu et al.* [2016], and asymmetries to the distant Mach cone angle were analytically derived by *Verigin et al.* [2003].

Related to modeling the locations and shapes of the geophysical boundaries, there have been several observations-based investigations of the thickness of the magnetosheath and its various dependences [e.g., *Paularena et al.*, 2001; *Němeček et al.*, 2003; *Jelínek et al.*, 2010, 2012; *Dimmock and Nykyri*, 2013].

A few recent studies have also examined how the variations in the solar wind are manifest as changes to the shape and location of the boundaries. For example, *Dmitriev and Suvorova* [2012] examined traveling distortions to the magnetopause shape, while *Suvorova et al.* [2010] empirically examined how the magnetopause location expands outward as the interplanetary magnetic field (IMF) becomes radial. Changes to the shape and motion of the bow shock due to propagating discontinuities in the solar wind were examined empirically by *Meziane et al.* [2014].

2.2. Global Numerical Models

In addition to the empirical models, there have been several studies of the geophysical boundary shapes and locations as determined from global numerical models. The magnetopause location and shape and its dependences on the solar wind have recently been examined using MHD models [e.g., *Lu et al.*, 2013; *García and Hughes*, 2007]. Inward excursions of the magnetopause to geosynchronous orbit during a large coronal mass ejection event were studied using an MHD model by *Lopez et al.* [2007]. The bow shock location, 3-D shape and characteristics, and its dependences on the solar wind parameters and IMF have recently been studied using MHD and other numerical models [e.g., *De Sterck and Poedts*, 2001; *De Sterck et al.*, 2001; *Chapman and Cairns*, 2003, 2004; *Chapman et al.*, 2004; *Hu et al.*, 2010; *Hu et al.*, 2015; *Wang et al.*, 2015a, 2015b]. *Nykyri* [2013] used a global MHD model for studying the impact of magnetosheath plasma properties on the Kelvin-Helmholtz instability (KHI) during Parker-Spiral and ortho-Parker-Spiral IMF orientations and for various upstream solar wind plasma conditions. These results indicate a dawn-favored asymmetry of the KHI in the magnetosheath, which may play a significant role in the acceleration of radiation belt particles.

3. Web Sites and Services With Explicit Real-Time Modeling of the Earth's Magnetopause and Bow Shock

The NOAA National Centers for Environmental Information (NCEI) provides a web site that displays in real time and into the near future the magnetopause location (based on the *Shue et al.* [1998] in the equatorial plane), parameterized by the observed solar wind parameters and IMF by a monitoring spacecraft at L1 [cf. *Redmon et al.*, 2014; *Loto'aniu et al.*, 2011; http://www.ngdc.noaa.gov/stp/mag_pause/]. Geosynchronous orbit and the locations of the GOES satellites are also included in the continuously updated display. A time series of the estimated standoff distance of the magnetopause is run in coordination with the animation of the magnetopause location display. NCEI is developing space weather products using observations from the GOES-R series of spacecraft for transition to and operational use by the NOAA National Weather Service (NWS) Space Weather Prediction Center (SWPC). The first in the GOES-R series of spacecraft launched on 19 November 2016 (now called GOES-16). After the post launch test phase has completed, the NCEI-developed magnetopause location product will take advantage of GOES-R's new Magnetospheric Particle Sensor-Low Energy Range (MPS-LO) to include electron and ion density and temperature moments in the identification of GMCs [*Suvorova et al.*, 2005].

The Community Coordinated Modeling Center (CCMC) at NASA/Goddard Space Flight Center (GSFC) is a multiagency partnership to enable, support, and perform the research and development for next-generation space science and space weather models (as per their mission statement). As part of the efforts of the CCMC, there exists a site with real-time tools. One such tool provides continuous runs of the Space Weather Modeling Framework (SWMF) BATS-R-US global MHD model of the magnetosphere [cf. *Gombosi et al.*, 2004; *Tóth et al.*, 2005], driven by the real-time solar wind data stream. The site http://ccmc.gsfc.nasa.gov/cgi-bin/display/RT_t.cgi?page=mpause provides visual displays of current density contours in the magnetosphere equatorial plane, including the location of the model magnetopause, geosynchronous orbit, along with the locations of the GOES satellites and the COMS satellite (S. Korea). A 24 h history of the magnetopause shape and location displayed as an animation is also included on the site. In addition, a continuously updated time series plot of the estimated standoff distance of the magnetopause and its relation to geosynchronous orbit is also shown.

International real-time space weather display sites have also appeared in recent years. The Space Environment Prediction Center at the Center for Space Science and Applied Research, Chinese Academy of Sciences also provides a real-time web site for dynamically modeling the Earth's magnetopause and bow shock (http://eng.sepc.ac.cn/MBS.php). This site uses the *Lin et al*. [2010] empirical magnetopause model and the *Chao et al*. [2002] model for the bow shock location and shape. This site also includes a time series plot of the estimated magnetopause standoff distance and time intervals during which the geosynchronous orbit intersects the magnetopause shape.

The Korea Meteorological Administration National Meteorological Satellite Center also maintains a real-time space weather site at http://spaceweather.kma.go.kr/en/current.do. Finally, for a time the National Institute of Information and Communications Technology in Tokyo, Japan, provided a real-time service displaying the predicted magnetopause.

4. Metrics and Skill Scores

As empirical and numerical models of the geophysical boundaries are developed and published, efforts are often taken to test the models against new observational data sets. In addition, the models are often compared with observations taken during extreme solar wind conditions to better understand the capabilities and limitations of the models and to provide information as to how modifications, revisions, and/or extrapolations might be made. The tests are typically a straightforward comparison—determining the variation of the particular model from the observed boundary crossings, given the solar wind parameters, IMF, dipole tilt angle conditions, etc. Some recent comparison studies of magnetopause models against observations have been performed by *Šafránková et al*. [2002], *Ober et al*. [2002], *Yang et al*. [2002], *Merka et al*. [2003a], *Lopez et al*. [2007], *Case and Wild* [2013], *Samsonov et al*. [2016], *Dmitriev et al*. [2016], and *Park et al*. [2016]. Some recent comparison studies of bow shock models against observations have been performed by *Fairfield et al*. [2001], *Ober et al*. [2002], *Dmitriev et al*. [2003], *Merka et al*. [2003b, 2005a], and *Meziane et al*. [2014].

As described in Table 1, one of the recent NSF GEM Workshop Focus Groups was called "Metrics and Validation" (cochaired by one of the authors (L.R.)). As part of this effort, a magnetopause crossing challenge was initiated. One method for quantitatively testing the forecasting ability of various models was based on the study of *Yang et al*. [2002], calculating probability of prediction (PoP), probability of detection (PoD), and false alarm rate (FAR), and applied to observations at geosynchronous orbit. A similar test method described during this focus group compared the daily minimum magnetopause standoff distances from the SWMF numerical model and the *Shue et al*. [1998] empirical model (both driven by the OMNI solar wind database) and calculated similar probability scores as that in the *Yang et al*. [2002] study, as well as the Heidke Skill Score (HSS). The results of such comparisons are very preliminary, and much more work is needed. As part of this continuing effort, a new GEM Focus Group called "Modeling Methods and Validation" has been established (cochaired by two of the authors (L.R. and R.J.R.)). Magnetopause location challenge results are in preparation for publication by one of the authors (L.R.). There is also an online metrics analysis tool that can calculate skill scores such as root-mean-square (RMS) error, prediction efficiency (PE), and threshold-based metrics such as PoD, FAR, and HSS, and an improved analysis tool is currently being developed that will go beyond the single-event, single-observatory analysis toward aggregate scores for multiple locations and time periods.

5. Future Work, Additional Capabilities, and Summary

One of the authors (R.J.R.) is working with others at NCEI to develop operational space weather products for transition to NOAA's SWPC using GOES series spacecraft. In particular, they are working on an improved real-time nowcast and forecast magnetopause location and geosynchronous crossing application, fusing together empirical model predictions [*Shue et al*., 1998] and identification of GOES crossings into the magnetosheath based on polarity reversals in the dayside geosynchronous equatorial magnetic field and exceeding thresholds in the ratio of the density and temperature for low-energy electrons and ions [*Suvorova et al*., 2005; *Loto'aniu et al*., 2011].

Table 2. Some Dynamic Modeling Efforts—Present and Future

Current Dynamic Modeling Capability Goals	Future Dynamic Modeling Capability Goals
Three-dimensional bow shock location and shape as a function of solar wind conditions	Foreshock boundaries in 3-D as a function of solar wind conditions
Parameters immediately downstream of the bow shock, including θ_{Bn} (related to wave activity)	Times when the bow shock moves across a specified distance, object (e.g., the Moon), or spacecraft
Three-dimensional magnetopause location (e.g., standoff distance) and shape as a function of solar wind conditions	Macroscopic parameters throughout the magnetosheath as a function of solar wind conditions
Times when magnetopause moves across a specified distance or spacecraft	Wave modes and growth rates throughout the magnetosheath, including KHI at the magnetopause
Magnetic shear angle between magnetosheath and magnetopause, over the entire magnetopause surface	Magnetic reconnection line extent at the magnetopause
Magnetic reconnection line location at the magnetopause	Magnetic reconnection rate as a function of location along the magnetopause

One of the authors (L.R.) is working on collection of magnetopause crossing events of the NASA Magnetospheric Multiscale (MMS) satellite constellation where reconnection was observed. Preliminary results have been obtained using the RECON-X tool applied to global magnetospheric MHD simulations [*Komar et al.*, 2013; *Glocer et al.*, 2016]. The tool determines separatrix boundaries, separating regions of different magnetic topology, as well as the separator line and magnetic null point locations in the dayside. There is good agreement between observations and MHD model results in many cases, but there are also cases with poor results. More work is needed to determine optimal model parameters leading to a reliable specification of the dayside magnetopause location in a wider range of solar wind conditions.

One of the authors {S.M.P.) is working on two additional projects related to the bow shock and magnetopause, using the real-time solar wind data stream. The first of these is related to the nowcasting and forecasting of the changes in the plasma parameters and magnetic field intensity immediately downstream of the Earth's bow shock, using the Rankine-Hugoniot relations [*Petrinec and Russell*, 1997]. As part of this project, the demarcation between the quasi-parallel and quasi-perpendicular regions at the shock surface is included. The quasi-parallel region of the bow shock surface is known to be more turbulent than the quasi-perpendicular region, with the growth of large-scale waves that can lead to shock reformation and increased wave activity in the downstream flow in the magnetosheath. The demarcation along the shock surface of these two regions can be used along with the general magnetosheath flow pattern to determine which regions of the magnetosheath and magnetopause are more heavily influenced by enhanced wave activity generated at or upstream of the bow shock [cf. *Greenstadt*, 1991; *Dimmock et al.*, 2014, 2015; *Nykyri and Dimmock*, 2016].

A second project which is still in its initial stages is the creation of magnetic shear plots across the magnetopause surface using the solar wind real-time data stream as input. It is widely believed that large magnetic shear regions are more conducive to magnetic reconnection than low-shear regions. Observations-based models of the likely location of magnetic reconnection occurrence have been developed and have been used for the planning of missions such as the NASA Magnetospheric Multiscale (MMS) mission [cf. *Fuselier et al.*, 2014]. It is thought that short-term forecasting of the reconnection location at the magnetopause will be of future interest; especially with regard to the extent of the dayside magnetopause reconnection line and the rate at which magnetic reconnection proceeds. A summary of some current and future dynamic modeling goals as related to the bow shock and magnetopause are listed in Table 2.

New sets of spacecraft observations during the past 15 years in coordination with measurements of the solar wind by upstream monitors have enabled the development of more sophisticated empirical models of the Earth's magnetopause and bow shock. In parallel, advancements in computational resources, capabilities, and techniques have allowed for real-time modeling of the global magnetosphere system. These improvements are being exploited to help transition the modeling of geophysical boundaries from the research to the operations arena. As this transition occurs, the use of metrics and skill scores are beginning to be more effectively used to assess the validity of the models to accurately represent these boundaries and to point out where improvements to the models are needed. One of the current challenges of accurate space weather prediction is that upstream conditions such as the IMF orientation are estimated from the propagation of observations from a single upstream monitor; typically located around the Sun-Earth L_1 Lagrange point. As a consequence of large-scale fluctuations of the solar wind, the orientation of the IMF at the Earth's bow shock and magnetosphere can often not be accurately ascertained at any specific moment in time. In addition, the origin of the solar wind cannot currently be solved self-consistently, and most solar wind models utilize the solar rotation (i.e., 27 days) averaged solar surface fields as model input. This further complicates the current capabilities of models and observations to accurately determine the solar wind influence on the geophysical boundaries and to the magnetosphere. Additional remote and in situ sampling of the space environment by space and ground-based observatories, along with continued model development efforts, are expected to improve the overall understanding and predictive capabilities of Sun-Earth interactions.

As society's reliance on technological systems increases, the risk of potential impacts of the space environment and space weather events to space and ground-based assets also increases, and it is anticipated that efforts will continue to be made to model and forecast the space environment such as that representing the interaction regions of the solar wind and magnetosphere.

Acknowledgments
This manuscript describes recent modeling efforts and web site tool development; no observations are explicitly used in this paper. Real-time web sites rely upon observations from solar wind monitors (http://www.swpc.noaa.gov/products/ace-real-time-solar-wind; and http://www.swpc.noaa.gov/products/real-time-solar-wind), while empirical models in the literature are based upon observations from a variety of spacecraft, which are available to the public and stored at CDAWeb. This effort was supported at Lockheed Martin by NSF grant 1303186.

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