

Space Weather

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US Air Force Academy Student Space Weather Experiment on Orbit at the International Space Station



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Advances in Space Weather Ensemble Forecasting

At many space weather-related meetings I hear that space weather (SW) forecasting is several decades behind terrestrial weather forecasting. Some attribute the lag to the dearth of space environment observations. Occasionally, the relative youth of our science and the corresponding lack of sophistication in forecasting methodologies are mentioned. Ours will always be the “younger science.” Nonetheless, our community is making significant progress in the latter category, especially with respect to “ensemble forecasting.”

Ensemble forecasting is a numerical method that uses multiple predictions from slightly different initial conditions (or different forecast models) to generate a broad sample of the possible future states of an atmosphere or other dynamical system (see <http://www.metoffice.gov.uk/research/areas/data-assimilation-and-ensembles/ensemble-forecasting/explanation>). The instances of different conditions or different models are called “members.” In the forecast cycle each member starts with a current state of the system based on a combination of observations and a background model, followed by calculation of the system evolution over time. Output from the members is then combined and analyzed for trends and outliers. For SW purposes the dynamical system may be the solar atmosphere, the interplanetary space in which solar disturbances propagate, Earth’s magnetosphere, and/ or Earth’s space atmosphere interaction region.

Ensemble forecasting has a multi-decadal history in meteorology and oceanography. Hurricane-track prediction and tsunami-arrival prediction are ensemble applications in these communities. As noted in *Schunk et al.* [2014], during the last 15 years SW researchers and practitioners have embraced ensemble methods to improve space weather forecast accuracy and provide estimates of forecast uncertainty. There has been

a noticeable up-tic in ensemble-research manuscript submissions to the Journal during the last 5 years, with at least 15 published articles in that time frame. Over one third of these have published in the last 2 years. Below are summaries of ensemble forecasting efforts published in *Space Weather* since the beginning of 2014. Note that in research mode an ensemble forecast may be a reanalysis of an historical event.

Murray et al. [2015] used ensemble methods to assess neutral density forecasts by perturbing a thermospheric physics-based model and a semiempirical model, with smoothed random temperature fluctuations during three 60 day intervals in solar cycles 23 and 24. They found that while the semiempirical model produced the best results during solar minimum, the physical model was more accurate during storm conditions.

Owens et al. [2014] studied methods to improve multiday forecasts of solar-wind-driven magnetospheric activity. Using an ensemble approach, they superposed statistically determined, small-scale solar wind fluctuations on forecasted large-scale variations, in a method called “downscaling.” The ensemble results from the simple downscaling scheme improved the magnetospheric forecast and supported an assessment of forecast uncertainty.

Cash et al. [2015] used the Wang-Sheeley-Arge (WSA)-Enlil operational model to investigate the sensitivity of an extreme coronal mass ejection (CME) to model input parameters. Using an ensemble approach, they varied: the initial CME speed, angular width, and direction, as well as the ambient solar wind background, in an ensemble approach to study the effect on the predicted arrival time of the CME at the STEREO A spacecraft. They found that the ambient solar wind background can significantly influence the CME arrival time and that improvements to the operational version

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On the cover: A prototype Integrated Miniaturized Electrostatic Analyzer (iMESA), capable of measuring plasma density and temperature and estimating spacecraft charging parameters, is exposed to the space environment surrounding the International Space Station from November 2009 through May 2011. The iMESA development is supported by the US Air Force Space Test Program. Photo courtesy of NASA. See also *McHarg et al.* [DOI: 10.1002/2015SW001284], pp. 12–15.

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Coronal mass ejection (CME) forecasting calls for different tactics than employed for terrestrial weather or hurricane forecasting. This article lays out the theoretical underpinnings for the application of the WSA-Enlil modeling system to ensemble forecasting of CMEs in an operational environment.

Recent U.S. Policy Developments Addressing the Effects of Geomagnetically Induced Currents

Introduction

Changes in the dynamics and composition of solar wind (a component of space weather) interacting with Earth's magnetic field can lead to geomagnetic disturbances (GMDs). GMDs occur regularly and can induce electric currents in long conductors that form the backbone of infrastructure systems such as the electrical power grid, gas and oil pipelines, and railways. Geomagnetically induced currents (GICs) can disrupt and potentially damage these systems, which are critical to the economic and social well-being of many nations.

The 1859 Carrington event was one of the most severe space weather events on record [Hapgood, 2011]. Some researchers believe that if a Carrington-level event occurred today, it could result in catastrophic effects to the electrical power grid (widespread and long-term power outages) and other infrastructure [Lloyd's, 2013]. The potential magnitude of the effects is primarily due to the prevalence of the interconnected grid and society's growing dependence on electronic technology. A GMD event in March 1989 triggered the collapse of the Canadian Hydro-Quebec electric power grid, affecting millions of customers [National Research Council, 2008]. The 1989 event, while smaller in magnitude than the Carrington event, was a clear demonstration of the vulnerabilities to GICs.

Shifts in Industry

The March 1989 GMD event elevated space weather as a hazard to modern technology and helped drive research into understanding the vulnerabilities and effects of GICs on technology systems. For industry, it was a call to action. The North American Electric Reliability Corporation (NERC) and Oak Ridge National Laboratory reported that GICs led to damage in some extra high-voltage transformers and other grid components in Canada and in the United States [North American Electric Reliability Corporation (NERC), 1990; Oak Ridge National Laboratory, 1991]. The GIC-driven power outage resulted in Hydro-Quebec investing more than \$1.2 billion (CAD) on monitoring and mitigation technologies between 1989 and 2002 [Government of Canada, Office of Critical Infrastructure Protection and Emergency Preparedness, 2002]. Several U.S. companies also invested in mitigation strategies, and regulatory agencies and organizations took notice. In June 1990, the U.S. Nuclear Regulatory Commission issued an information notice regarding the failure of U.S. electrical power equipment due to GICs [Nuclear Regulatory Commission, 1990], and the NERC followed suit in July 1990 by issuing a position statement urging the National Oceanic and Atmospheric Administration (NOAA) to improve its forecasting of GMDs [NERC, 1990].

In the years since the 1989 event, the economic and social well-being of the United States and other nations has become significantly more dependent on electronic technology. In many cases, these new technologies rely on the stable supply of electrical

power. Interest in GICs extends beyond the electric power industry and governments. Large insurance and reinsurance companies have taken note and are aware of the potential effects of severe space weather and GICs. Lloyd's, a global insurance market, issued a 2010 report that outlines the varied impacts of space weather on different industries, highlights possible mitigation efforts, and identifies business opportunities [Lloyd's, 2010]. A follow-up report by Lloyd's [2013] estimates that a Carrington-level space weather event could cause between \$0.6 and \$2.6 trillion in damages in North America alone, presuming between 20 and 40 million individuals lose power for a duration of 16 days to 2 years. A workshop report from the National Research Council reports a similar estimate of "\$1 trillion to \$2 trillion during the first year...with recovery times of 4 to 10 years" [National Research Council, 2008]. Research into the effects of less severe space weather events on the electrical power grid is also taking place; a recent statistical analysis conducted by Schrijver *et al.* [2014] indicates a connection between elevated geomagnetic activity and an increase in insurance claims.

Members of the research community, industry, and advocacy groups have identified GICs as a hazard to the electrical power grid and have sought to develop approaches to prepare for it. For example, see Boteler [1991]; Kappenman [2004], Forbes and Cyr [2008], JASON [2011], Electric Infrastructure Security Council [2014], and NERC [2012]. This work, in part, has led to a number of recent actions by government policy makers.

Policy Actions

In 2001, Congress established the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) as part of the National Defense Authorization Act for Fiscal Year 2001 (P.L. 106–398). The commission was primarily charged with assessing the nature of a high-altitude EMP attack and the Nation's level of preparedness for such an event. Space weather was not identified by Congress in the commission's scope of work, but was identified and included in the assessment, at the discretion of the commission, due to some similarities between GMD (a natural form of EMP) and EMP from nuclear detonation. The similarities between GMD and nuclear-driven EMP were brought to the attention of Congress during a 2003 hearing in the U.S. House of Representatives [U.S. Government Printing Office, 2003]. The Commission to Assess the Threat to the United States from EMP released its final report in 2008. Subsequently, in each Congress since 2009 (111th through 114th), the U.S. House of Representatives introduced or passed EMP-related legislation, most of which explicitly identified space weather-driven EMP (i.e., GMD).

In the NASA Authorization Act of 2010, Congress recognizes that "space weather events pose a significant threat to modern technological systems" and that "the effects of severe space weather events on the electric power grid...could have significant

societal, economic, national security, and health impacts” (42 U.S.C. section 18388). This act also mandates the Director of the White House Office of Science and Technology Policy (OSTP) to “improve the Nation’s ability to prepare, avoid, mitigate, respond to, and recover from the potentially devastating impacts of space weather events.”

The framework to prepare the United States for space weather was established by Presidential Policy Directive (PPD) 8, which guides the Nation, from the Federal Government down to individual citizens, on how to “prevent, protect against, mitigate the effects of, respond to, and recover from those threats that pose the greatest risk to the security of the Nation” [PPD-8, 2011]. In 2011, the Department of Homeland Security (DHS) released the Strategic National Risk Assessment (SNRA), which was developed to support the implementation of PPD-8. The SNRA identifies space weather as one of the risks that pose the greatest threat to the Nation’s homeland security, and it categorizes space weather as a natural risk alongside other hazards such as tsunamis, volcanic eruptions, wildfires, and hurricanes [PPD-8, 2011].

PPD-21 [2013] identifies strategic imperatives to drive the Federal approach to strengthening infrastructure security and resilience. It identifies energy infrastructure (which includes the electrical power grid) as vital due to the enabling function it provides across all infrastructure sectors. It also instructs the Federal Government to engage with industry and international partners to strengthen the security and resilience of domestic and international infrastructures on which the United States depends.

In line with PPD-21, the Federal Energy Regulatory Commission (FERC) issued Order No. 779 in 2013, which directed NERC to develop a two-stage reliability standard to address the effects of GMDs on the reliable operation of the bulk-power system (as defined by the Federal Power Act (16 U.S.C. section 824o)) [Federal Energy Regulatory Commission, 2013]. The first stage, adopted by FERC in June 2014, requires the implementation of operating plans and procedures by grid owners and operators to mitigate effects of GMD (18 CFR Part 40). The second stage, currently under consideration by FERC, will require grid owners and operators to assess the potential effects of established benchmark GMD events on the bulk-power system. The reliability standard “should require owners and operators to develop and implement a plan to protect against instability, uncontrolled separation, or cascading failures of the bulk-power system” as a result of a benchmarked event. Actions required by the second stage standard cannot be limited to operational procedures or enhanced training and can include engineering solutions.

In addition to these efforts by the U.S. Federal Government, several significant activities are taking place worldwide, including internationally coordinated efforts within organizations such as the North Atlantic Treaty Organization, the World Meteorological Organization, and the United Nations.

Recent Developments in U.S. Space Weather Policy

From 1995 to 2014, the National Space Weather Program (NSWP) served as the primary Federal interagency initiative to coordinate improvements to space weather services. The initiative was headed by the Office of the Federal Coordinator for Meteorology, an interdepartmental office established by the Department

of Commerce. In 2010, the NSWP released a strategic plan that sought to “promote space weather advances...[and enhance] society’s awareness of the potential impacts of space weather” [National Space Weather Program, 2010]. In 2014, the White House built upon the NSWP interagency initiative, expanding the scope and changing the perspective to focus on coordinating national preparedness for space weather events. The resulting interagency Space Weather Operations and Research Mitigation Task Force, convened by OSTP and co-chaired by DHS and NOAA, is developing the *National Space Weather Strategy* and an accompanying *National Space Weather Action Plan*. The draft strategy, released for public comment in April 2015, presents a framework for enhancing preparedness to space weather events, with a focus on the electrical power grid. The draft identifies six high-level goals: (1) establish benchmarks for space weather events, (2) enhance response and recovery capabilities, (3) improve protection and mitigation efforts, (4) improve assessment, modeling, and prediction of impacts on critical infrastructure, (5) improve space weather services through advancing understanding and forecasting, and (6) increase international cooperation [National Science and Technology Council, 2015]. Together, these goals will help secure critical technology-based infrastructures vital to national security and the economy against the negative impacts of space weather events.

On 9 July 2015, the White House Directors of Office of Management and Budget, and OSTP released the Fiscal Year 2017 Science and Technology Budget Priorities, which identifies space weather observations, research, and development as “essential to address the growing societal needs for accurate and timely space weather information.” The memorandum further specifies that U.S. Federal agencies should “prioritize investments in space weather science and preparedness according to the [forthcoming] 2015 *National Space Weather Strategy* and [National Space Weather] *Action Plan*” [M-15-16, 2015].

In total, these policies represent an increased awareness and interest of decision makers and government leaders to space weather events and the effects of space weather on infrastructure critical to national and homeland security, the economy, and social well-being. This increased interest may transform the future of the space weather enterprise by augmenting research and development activities that enhance observations, understanding, event predictions, and approaches to protection, mitigation, response, and recovery.

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Geomagnetically Induced Currents Modeling and Forecasting

Background

Significant progress has been made in understanding the physics, modeling, forecasting, applications, engineering, and regulatory dimensions of geomagnetically induced currents (GIC) over the past decades. This collection demonstrates the evolution of the field over these decades. In this brief commentary I provide some personal observations about modeling and forecasting dimension of the field.

Physics-based modeling and forecasting is the ultimate test for our understanding of any natural phenomenon. In the GIC context, the test is a very challenging one. GIC can be viewed as the end link of the space weather chain from the solar atmosphere down to the upper mantle of the Earth; the GIC signal measured, for example, at high-voltage power transformer neutrals carries information

about all the physical processes along the chain. This is analogous to stock markets where the value of individual indices such as National Association of Securities Dealers Automated Quotations (NASDAQ) is an aggregate of processes operating at multiple different temporal and “spatial” scales resulting in an incredibly complex signal at the end. We see similar complexity in the GIC signal. This complexity poses very interesting challenges for our understanding of the physics of GIC and modeling of the phenomenon.

From the societal standpoint, accurate modeling of the GIC phenomenon is needed for both hazards assessments and execution of active mitigation procedures. More specifically, robust modeling of the geoelectric field is required for any rigorous GIC impacts analyses that involve detailed quantification of possible deleterious effects on systems such as oil pipelines, power

transmission, and railway systems. One of the common questions asked by the end-users is “how bad can it get?” Given the complexity of the system, physics-based modeling of the GIC phenomenon is required for probing such questions. If the key physical processes responsible for GIC are captured accurately and the fundamental physics of the system do not change under extreme driving, it is feasible to use physics-based models to explore theoretical extremes. However, one needs to be careful in evaluating the applicability of individual modeling approaches to address the extremes. It is possible that fundamental approximations associated with, for example, single-fluid magnetohydrodynamic (MHD) simulations become significant limitations under extreme driving conditions. The analyses of extremes are the fundamental piece in our quest to explore the “how bad can it get?” questions. In the absence of extended, several-hundreds-of-years-long observational records, modeling of extremes will most likely play an increasingly important role in studies of GIC.

In addition to studies of extremes, modeling can be used to elevate the situational awareness on a continuous basis. Advance information or forecasts about pending events are the key for active natural hazards mitigation procedures. In the GIC context, a variety of actions can be carried out if reliable information about the incoming event is available. In the high-voltage electric power transmission context, actions range from postponing maintenance of critical lines to deployment of reserve power for making the system more stable while weathering the storm [e.g., *Molinski, 2002*]. However, the selection of an appropriate response requires actionable information (i.e., reliable information presented in a form understandable by, and useful to, operations teams). Mitigation actions can be costly for the operator and appropriate action is not possible without good understanding of the quality of information provided. Developing detailed understanding of the end-user needs (see *Pulkkinen et al. [2015b]* for a recent interagency effort to develop this kind of understanding) and making forecasted GIC information actionable are some of the primary challenges for the space weather modeling and forecasting community.

Finally, for inherently interdisciplinary topics such as GIC, a multidisciplinary approach is required for addressing the problem. One of the greatest advancements in the GIC field over the past years has been the establishment of a common language between the space weather science and power engineering communities. In the U.S., much of the recent multidisciplinary communications has been facilitated through the North American Reliability Corporation's Geomagnetic Disturbances Task Force. Space weather scientists now know what engineers need for impact assessments and engineers know what to ask from the scientists. In most cases, the geoelectric field that drives GIC has been established as the physical interface between the science and power engineering communities. The task for space weather scientists is to characterize the spatiotemporal evolution of the geoelectric field in the past, present, and future and do so as accurately as possible.

Past and Present

Our understanding of the basic physical principles behind GIC builds on our understanding of the space plasma and terrestrial electromagnetic induction processes. While the GIC problem has its own set of specific challenges, progress in these fields

often has direct implications also for progress in understanding GIC. We now know that the dynamic electric currents occupying the solar wind-magnetosphere-ionosphere domains cause geomagnetic variations and the dynamic conditions are controlled by the interaction between the Earth's magnetosphere and interplanetary structures and transients such as coronal mass ejections. Geomagnetic variations generate a surface geoelectric field via the electromagnetic induction process. The geoelectric field in turn drives GIC, which is the fundamental reason why the geoelectric field serves as the key interface between the scientific and engineering communities [e.g., *Bernabeu, 2012*].

Advances in GIC modeling reflect the advances in space plasma and electromagnetic induction modeling. Basic electromagnetic induction modeling tools such as the extensively applied plane wave method have been used successfully in GIC studies for decades. It is generally understood that if the local total (external and internal) geomagnetic field variations and effective local one-dimensional (1-D) ground conductivity are known, in many situations one can model the corresponding geoelectric field using the plane wave method with sufficient accuracy. Also, empirical methods for predicting geomagnetic field variations from driving solar wind conditions have been developed and are available for GIC research purposes [e.g., *Weigel et al., 2003; Wintoft, 2005; Weimer, 2013*]. However, there has been a recent breakthrough in how we can apply modern physics-based space plasma simulations in GIC research [e.g., *Zhang et al., 2012; Ngwira et al., 2014*]. These advances have allowed development of novel forecasting techniques and exploration of theoretical extremes of GIC. The relative maturity of the empirical and physics-based modeling capacity is demonstrated in community-wide validation efforts and in transitioning of one of the major global magnetospheric MHD models to operations at NOAA Space Weather Prediction Center (SWPC). One of the primary uses of the new modeling capacity at NOAA SWPC is to provide advanced forecasting services for the power grid industry.

Once spatiotemporal evolution of the geoelectric field has been specified, it is quite straightforward to compute GIC flow if direct current (DC) characteristics of the system are known [*Lehtinen and Pirjola, 1985; Boteler and Pirjola, 2014*]. What has been critically important for quantifying the impact on the power grids is the development of new engineering models. The engineering models allow quantitative considerations such as power grid voltage stability, harmonics, and transformer heating due to known GIC distribution. These analysis tools are now also available commercially, allowing comprehensive hazards analyses on any high-voltage power transmission system of interest. Such hazards analyses are the core element of the standards being developed in the U.S. in response to the Federal Energy Regulatory Commission's Order no. 779 [*United States of America Federal Energy Regulatory Commission, 2013*].

Future Challenges

While significant progress has been made in modeling and forecasting GIC, a number of interesting challenges lie ahead. The classic 1-D electromagnetic induction modeling that has been used successfully for decades in GIC research has its limitations. The true local geology is generally not 1-D. Severe 2-D or 3-D electromagnetic effects can be experienced in areas of

sharp lateral gradients in ground conductivity, such as at ocean-land boundaries. Consequently, one of the next steps in geoelectric field and GIC modeling is to evaluate the situations where the 1-D modeling fails and consider the usage of 3-D modeling in the corresponding conditions. Toward this end, the electromagnetic induction community has developed 3-D models that in principle are ready for use also in GIC research. However, work is needed to build the bridges that allow execution of 3-D induction models with the data from modern space physics analyses such as global magnetospheric MHD model output. Similar advancements are needed in mapping of the detailed 3-D ground conductivity structures across the regions of interest. These mapping efforts are underway. For example, the EarthScope project targets the derivation of the 3-D ground structures across the contiguous U.S. (<http://www.earthscope.org>). Completion of this effort is highly desirable for the next generation U.S. GIC research efforts.

The “holy grail” of space weather predictions, namely, modeling of interplanetary magnetic field (IMF) evolution at Earth in association with coronal mass ejections, pertains also to GIC. The IMF specification would allow geomagnetic storm strength predictions with a 1–3 day lead time. However, in the GIC context it is not sufficient to capture only the overall average features of the IMF. Since turbulent IMF features are known to be one of the major drivers of GIC [Huttunen *et al.*, 2008], it is necessary to capture also the smaller scale interplanetary structures responsible for GIC. This requirement poses another significant challenge for the space weather modeling community and may require use of techniques such as statistical downscaling (familiar from applications in the terrestrial weather community) to represent IMF fluctuations [Owens *et al.*, 2014].

Another example of future challenges pertains to recent discovery of the role small spatial-scale (~100km) ionospheric features play in generating extreme geoelectric fields [Pulkkinen *et al.*, 2015a; Ngwira *et al.*, 2015]. While small spatial-scale ionospheric features appear to play a significant role in driving extreme geoelectric fields, it is not yet clear what solar wind-magnetosphere-ionosphere processes are responsible for these features. It also is not clear if current global MHD models are capable of producing such features and it is possible that more advanced modeling techniques incorporating kinetic plasma processes may be needed. From the GIC impacts standpoint, the question about scales is important as different geoelectric field spatial scales have different implications for performance of the bulk power system. For example, spatially localized extreme geoelectric field features are thought to pose smaller risk than larger-scale enhancements for the stability and health of the bulk power transmission system.

Major progress has been made in understanding GIC over the past decades, and the field is mature enough to allow quantification of the physical processes and impacts in guiding the mitigation of the hazard. However, we need to keep pushing forward. GIC are one of the ultimate tests of our capacity to understand and model the entire space weather chain; the real quantifiable impacts of the phenomenon pose a societally relevant challenge for physicists, engineers, and policy makers. Multidisciplinary physics-based investigations with well-defined interfaces between disciplines need to continue to further our modeling and forecasting

of GIC. The societal relevance of GIC has drawn a growing number of talented researchers to work on the problem, and the future of the field looks very bright. I look forward to reading about this new GIC research from American Geophysical Union Space Weather Journal and other international publications.

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Biography

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Meeting Report

Annual Forum Raises Awareness Across the Space Weather Enterprise

Reducing our nation's vulnerability to space weather is now a national priority. This was the message conveyed when experts from government agencies, the private sector, and academia gathered for the 2015 Space Weather Enterprise Forum (SWEF) held 20 and 21 October 2015 in Washington, DC.

The SWEF has been held almost yearly since 2007 and began as a method for government agencies and academia to educate and inform a broad range of space weather users, policy makers, and decision makers on the importance of space weather preparedness. This year's forum marked a turning point when those same users and policy and decisionmakers took the podium to highlight their efforts over the past year to formulate a national policy and provide support for that policy in the form of agency funding.

Keynote speaker Senator Gary Peters opened the forum by presenting the perspective from Congress. The Senator spoke of a recent visit to NASA's Goddard Space Flight Center where he gained a better understanding of the devastating consequences of a severe space weather event and the urgency of the work that agencies undertake to mitigate this potential hazard. Noting that a "strong national defense includes a defense of our planet from natural hazards," the Senator stressed that more work is needed from science and industry to inform all stakeholders of the nature of "this difficult and extremely important problem."

Two days of panel discussions provided the audience of 200+ an overview of space weather and its effects and the many ways those effects complicate everyday activities on Earth. A highlight of the forum was the announcement of the 29 October release of the National Space Weather Strategy and National Space Weather Action Plan by the interagency Space Weather Operations, Research, and Mitigation task force. Several task force members, or their representatives, spoke of the strategic goals and the specific implementation activities within their agencies. Chartered by the Executive Office of the President's National Science and Technology Council, the Strategy is intended to be an "all-community" plan that engages all involved—the agencies, industries, academia, and the public—toward greater preparedness. Bill Murtagh, Assistant Director for Space Weather in the Office of Science and

Technology Policy, expressed the administration's urgency by noting "Space weather happens every day. An extreme event, however, can change our country and can change our world."

In another sign of the forum's progress, an industry group served as a Session Coordinator for the first time with Dr. Devrie Intriligator representing the American Commercial Space Weather Association (ACSWA). Formed in 2010, ACSWA serves as a collective voice for the commercial space weather industry. Dr. Intriligator highlighted the growing capabilities of the industry and emphasized the "need for true partnering between government and the commercial sector to make progress on this national call to action."

The forum closed with progress reports from the member agencies. The representatives expressed their support for the national strategy and discussed potential challenges. All echoed the keynote message for increased communication to our stakeholders and, more importantly, to the public as to how they may better prepare.

Senator Bill Nelson and the Office of the Federal Coordinator for Meteorology (<http://www.ofcm.gov>) through its National Space Weather Program (<http://www.nswp.gov>) sponsor the annual Space Weather Enterprise Forums. The nine member agencies of the National Space Weather Program Council rotate hosting duties. This year's host was Dr. William Leith from the United States Geological Survey with assistance from Mr. Michael Bonadonna of Office of the Federal Coordinator for Meteorology. More information can be found at <http://www.nswp.gov/swef/2015/>.

Biography

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Citation: Giles, B. L. (2015), Annual Forum Raises Awareness Across the Space Weather Enterprise, *Space Weather*, 13, 826–826, doi:10.1002/2015SW001338.

White House Releases National Space Weather Strategy and Action Plan

On 29 October 2015, the White House released the *National Space Weather Strategy* (Strategy) and the *National Space Weather Action Plan* (Action Plan) [*National Science and Technology Council*, 2015a, 2015b]. These two documents describe (1) how the U.S. Federal Government will coordinate efforts to address space weather and its effects and (2) how the U.S. Federal Government plans to engage academia, industry, and other governments to enhance preparedness for space weather events. Both documents build on past government, industry, academic, and international activities to enhance the preparedness of the United States to a space weather event [Jonas and McCarron, 2015].

The Strategy identifies six high-level goals: (1) establish benchmarks for space weather events; (2) enhance response and recovery capabilities; (3) improve protection and mitigation efforts; (4) improve assessment, modeling, and prediction of impacts on critical infrastructure; (5) improve space weather services through advancing understanding and forecasting; and (6) increase international cooperation. The Action Plan identifies approximately 100 distinct activities with associated deliverables and timelines (ranging from 4 months to 5 years) to achieve the six goals identified in the Strategy. The Action Plan assigns each activity to at least one Federal agency and emphasizes the need for collaboration with industry, academia, and other nations. Six teams of subject matter experts from the Federal Government developed the activities by integrating existing efforts of the space weather and national preparedness communities with feedback from the public.

Development of the Strategy and Action Plan

In November 2014, the White House Office of Science and Technology Policy (OSTP) chartered the Space Weather Operations, Research, and Mitigation (SWORM) Task Force under the National Science and Technology Council (NSTC). The NSTC was established in 1993 to serve as an interagency coordinating body for science and technology policy agenda and budget (58 FR 62491). The SWORM task force drew its membership from a diverse group of over 20 Federal departments and agencies and Executive Office of the President (EOP) components that represent the range of relevant science, technology, critical infrastructure, national security, and homeland security missions.

The task force was cochaired by Tamara Dickinson, Principal Assistant Director for Environment and Energy at OSTP; Caitlin Durkovich, Assistant Secretary for Infrastructure Protection at the Department of Homeland Security; and Louis Uccellini, Assistant Administrator for Weather Services at the National Oceanic and Atmospheric Administration and Director of the National Weather Service. William Murtagh, Assistant Director for Space Weather at OSTP, coordinated the development of the Strategy from its inception in close collaboration with staff from the White House National Security Council and the Office of Management and Budget.

The SWORM task force took an inclusive approach to developing the Strategy and Action Plan by building upon the already significant efforts of the space weather and national preparedness communities and by engaging the public in a whole-community approach to preparedness. This approach leveraged frameworks and authorities established by recent U.S. policies, including Presidential Policy Directive (PPD)-21: *Critical Infrastructure Security and Resilience* [PPD-21, 2013] and PPD-8: *National Preparedness* [PPD-8, 2011]. It also incorporated previous work on space weather science, including the 2010 Office of the Federal Coordinator for Meteorology Strategy [*National Space Weather Program Council*, 2010] and the National Academies Decadal Survey in Solar and Space Physics [*National Research Council*, 2013].

On 30 April 2015, OSTP posted a notice in the Federal Register for a 30 day period for public comment (80 FR 24296). The Federal Register is the official journal of the U.S. Federal Government and contains agency rules, proposed rules, and public notices. Throughout 2015, representatives from the SWORM task force presented and discussed the approach to and content of the Strategy with the space weather, national security, and preparedness communities at a number of public events and workshops that included the April 2015 Space Weather Workshop [Hemmick and Berger, 2015] and the July 2015 Electric Infrastructure Security Summit (Electric Infrastructure Security Summit, 2015, <http://www.eissummit.com/>). The SWORM task force also engaged the critical infrastructure community through the Critical Infrastructure Partnership Advisory Council and its associated infrastructure sector coordinating councils.

Launch of the Strategy and Action Plan

On 29 October 2015, the White House hosted an event to launch the Strategy and Action Plan and to highlight commitments by industry and governments to improve U.S. preparedness for space weather events [White House, 2015; Lanzerotti, 2015]. The White House event featured presentations by senior leaders from the U.S. Government, industry, academia, and other nations. The event underscored the importance of interagency cooperation and coordination and public and private collaboration to improving U.S. space weather preparedness.

The simultaneous release of the *National Space Weather Strategy* and the *National Space Weather Action Plan* represents a critical next step in enhancing national and international preparedness for space weather events. As a result, numerous activities and collaborations are expected to be launched between the science and technology enterprise and the national and homeland security enterprise. The Action Plan states that an interagency body coordinated by the EOP will help oversee the specified activities, deliverables, and timelines. The EOP-led interagency body will reevaluate and update the Strategy and Action Plan within 3 years of its release, or as needed.

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Biographies

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Eoin D. McCarron is a Science Policy Fellow at STPI and provided OSTP and the SWORM task force with subject matter expertise, policy analysis, and research support on the topic of space weather throughout the development of the National Space Weather Strategy and the National Space Weather Action Plan.

Citation: Jonas, S., and E. D. McCarron (2016), White House Releases National Space Weather Strategy and Action Plan, *Space Weather*, 14, doi:10.1002/2015SW001357.

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USAFA Integrated Miniaturized Electrostatic Analyzer (iMESA)—An Undergraduate Space Weather Constellation

Geoff McHarg, Parris Neal, Nikolas Taormina, Alex Strom, and Richard Balthazor

The United States, and those that defend it, depend on space-related technologies. The natural space environment poses significant risks to Air Force as well as civilian satellites and missions, [Baker, 2000]. Two of the most important risks are radiation effects [Welling, 2010] and spacecraft charging [Fennel *et al.*, 2001]. Current responses to these risks include various engineering solutions to these problems [Gubby and Evans, 2002]. A comprehensive understanding of the physical processes involved, and how the environment affects the overall mission, requires that data on the environment be collected and injected in appropriate models. This article details a small constellation of in situ ionospheric sensors being developed to provide these data.

Over the course of their careers, many United States Air Force Academy (USAFA) cadets will operate in space and/or deal with space operational issues. For some cadets, the first steps in a space-related career start with payloads developed by the Space Physics and Atmospheric Research Center (SPARC) in the Department of Physics at USAFA. Faculty and cadets in SPARC are developing a constellation of miniature ionospheric

space weather instruments to be hosted on four different Department of Defense (DoD) small satellites. Experience gained in developing this constellation is critical in the development of the next generation of US Air Force space professionals.

The space weather constellation will measure plasma density, temperature, and spacecraft charging, along with total dose and dose rate using an Integrated Miniaturized Electrostatic Analyzer (iMESA) developed by SPARC. Cadets and faculty from the departments of Physics and Electrical and Computer Engineering at the Air Force Academy are engaged in the multi-disciplinary project to design, test, and deploy the instruments. The small size (~10 cm × 10 cm × 5 cm), light weight (<1 kg), and low power (~2.5W) of the instrument allows implementation on almost any size platform. iMESA is made up of two printed circuit boards, the head and the brains board, and a series of metal plates. These boards are encased in an aluminum frame to protect them, see Figure 1 (left). Figure 1 (right) is a picture of the flight iMESA instrument for the upcoming Green Propellant Infusion Mission (GPIM).

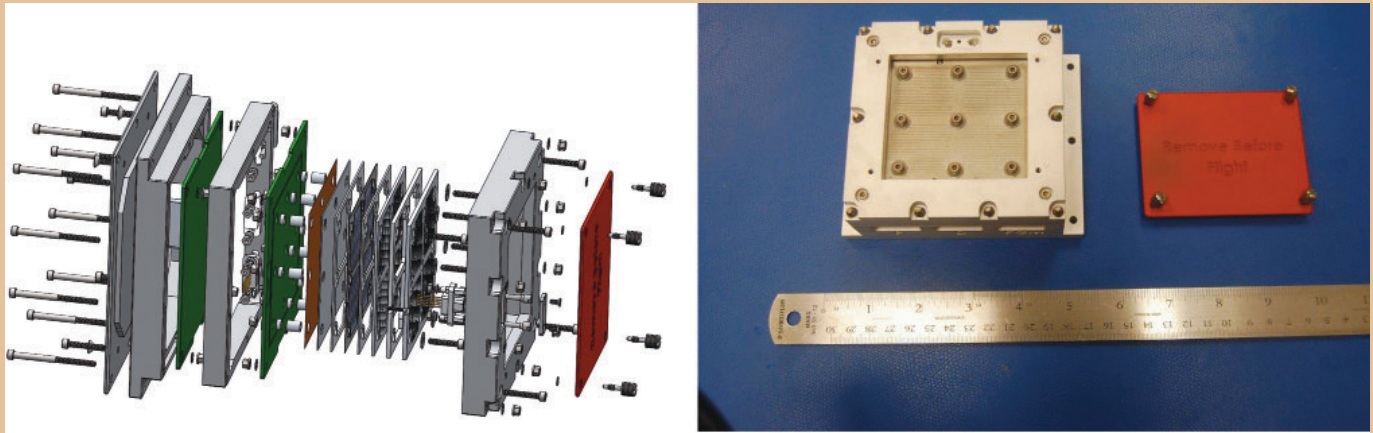


Figure 1. (left) iMESA exploded view. (right) GPIM flight iMESA instrument.

The instrument uses a new laminated electrode design, which provides a high-pass energy filter (similar to a retarding potential analyzer) for ions or electrons [Enloe *et al.*, 2002; Enloe *et al.*, 2015]. By varying the voltage across the electrodes, while measuring the received current at the anode, we measure the energy distribution function of the charged particles up to 95 eV. This is sufficient to fully characterize the atomic oxygen ions which dominate the low Earth orbit (LEO) ionosphere up to approximately 600 km altitude [Kelly, 2009]. From the measured energy distribution function we derive the plasma density, temperature, and spacecraft charging. Effectively, the ion density is proportional to the area under the distribution, and the width of the distribution is proportional to the temperature of the ions. The instrument measures the total energy of the ions, and by subtracting the kinetic energy (approximately 4.5 eV for oxygen ion in LEO) from the measured mean energy of the distribution function, we derive the remaining potential energy, which is due to spacecraft charging. The derived ion density and temperature can then be assimilated into ionospheric models, improving both the “nowcast” and forecast of the ionosphere.

The current design includes an improved electrostatic analyzer design, as well as a dosimeter. The dosimeter is sensitive to ionizing radiation from 60 keV to 15 MeV and is similar to that flown on the Lunar Reconnaissance Orbiter [Mazur *et al.*, 2011]. The dosimeter will provide a useful measure of the total dose, as well as dose rate during the mission. An earlier iMESA design, which did not have the dosimeter, is presently flying on the DoD Space Test Program Satellite-3 (STPSat-3) mission. We are currently building four newer flight instruments, which will fly on the Green Propellant Infusion Mission (GPIM), the Orbital Test Bed (OTB), STPSat-4, and STPSat-5. All four missions are

sponsored for integration and launch by the DoD Space Test Program (STP). Details of the upcoming launches of iMESA are shown below in Table 1.

An example of the data products from the prototype iMESA flying on STPSat-3 is shown below in Figure 2. Since the instrument on STPSat-3 is ram facing, with a 500 km, 40.5° inclination orbit, iMESA detects a combination of atomic oxygen and hydrogen ions. Each sweep of the instrument measures one complete energy distribution function. We then “stack” these sweeps to produce an energy time spectrogram, seen in Figure 2 (top). We fit the energy distribution function with a drifted Maxwellian function and obtain the plasma density, ion temperature, and spacecraft charging as described above. Examples of these fitted parameters are shown in the panels below the energy time spectrogram. As can be seen in Figure 2, the STPSat-3 iMESA is only producing derived parameters during part of the orbit. Effectively, the instrument dynamic range only responds to higher densities seen during the sunlit portions of the orbit, depicted by the yellow band at the bottom of Figure 2. These higher densities are seen between 30 and 40 eV as the blue portion of the spectrogram. Subtracting off the ~4.5 eV kinetic energy of the oxygen ions, we are left with a negative spacecraft charging potential between 25 and 35 V. This negative potential is due to the solar panel arrays on the spacecraft [Hastings, 1995]. Following typical US engineering practices, the STPSat-3 spacecraft is grounded to the negative side of the solar arrays. The potential drop on the solar arrays then drives the potential of the entire spacecraft negative. The change in the energy of the detected ions in Figure 2 is presumably in response to the details of how the solar array switches in an out of the charging circuit and is an area

Table 1. iMESA Launch Schedule

| Satellite | Launch Date | Altitude (km) | Inclination (degrees) |
|-----------|-------------------------------|---------------|-----------------------|
| GPIM | Mid-2016 | 650 then 550 | 24 |
| OTB | Mid-2016 | 720 | 24 |
| STPSat-4 | Launch Readiness NLT Aug 2017 | 400 | 51.6 |
| STPSat-5 | TBD | 575 | 97 |

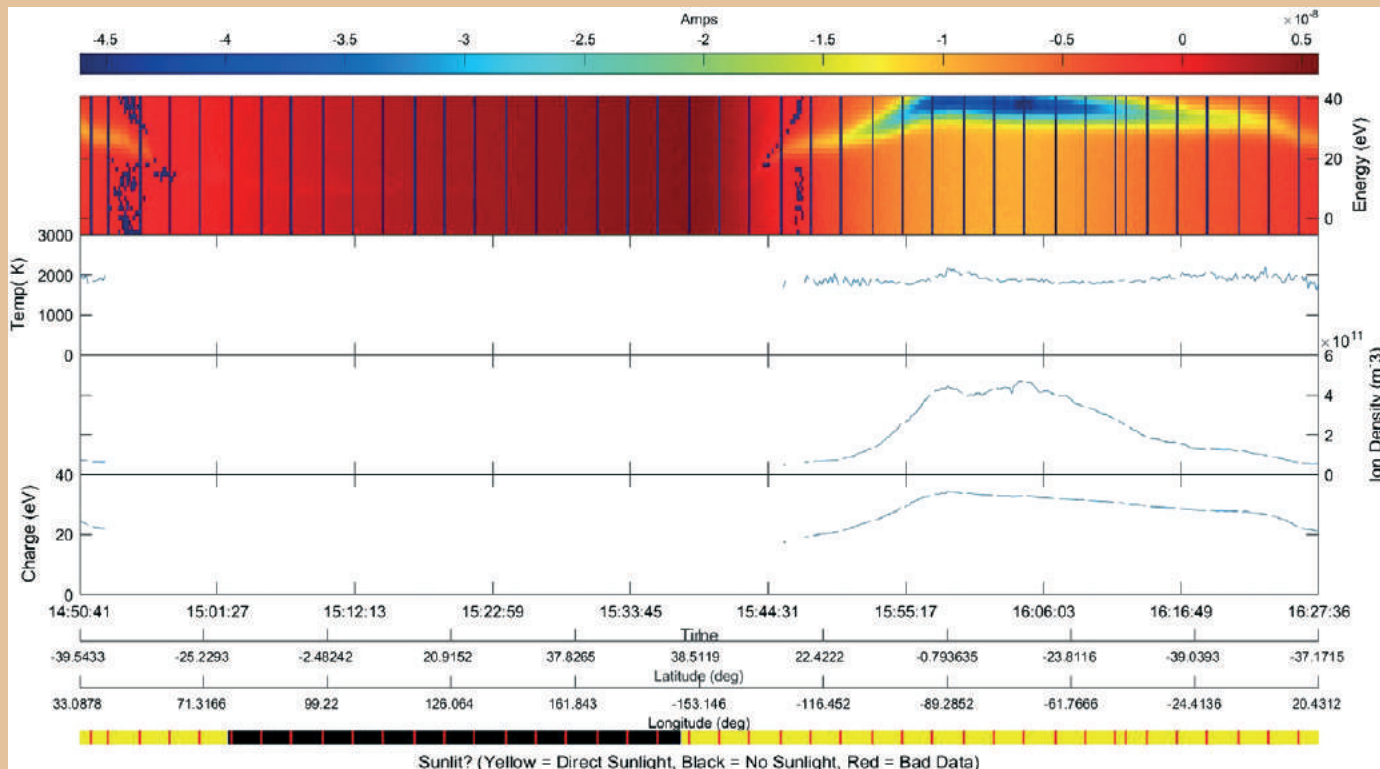


Figure 2. Example iMESA data set from STPSat-3.

of active investigation using these data. Several improvements in the instrument resulted from the STPSat-3 experiment. The improvements include a new electrostatic analyzer design with lower $\delta E/E$ allowing higher fidelity temperature measurements, a programmable gain amplifier providing increased dynamic range, and the addition of the microdosimeter.

We have undertaken a modelling study of the improvement of nowcasts of the ionosphere when provided data similar to what iMESA will provide once the constellation is complete. Balthazor *et al.* [2015] developed a methodology of evaluating the science benefit of various satellite/sensor orbital configurations to an assimilative data forecast model. Using a “full physics” version of the Global Atmospheric Ionosphere Model (GAIM) as truth and an ensemble Kalman filter forecast version of GAIM, Balthazor *et al.* were able to show a significant reduction in the root-mean-square (RMS) deviation of the $h_m F_2$ (height of the F_2 ionospheric peak) when using a proposed Walker constellation (five sensors each in five equally longitudinally spaced orbital planes) of 25 iMESA sensors compared to using only ground-based total electron content (TEC) measurements (see Figure 3). While our constellation is only four sensors, we look forward to ingesting the resulting data to see if we can validate improvements in the ionospheric models.

In summary, iMESA is a multidisciplinary project including cadets and faculty from the departments of Physics and Electrical and Computer Engineering at the Air Force Academy. The project is an exciting chance for undergraduate cadets to become involved in a real space weather mission. To date, over 50 cadets have participated in development and analysis of the instrument and the data it provides. Academy cadets and faculty

are looking forward to finishing construction and delivery of the last three flight iMESA instruments, and analyzing the data from the first undergraduate space weather constellation.

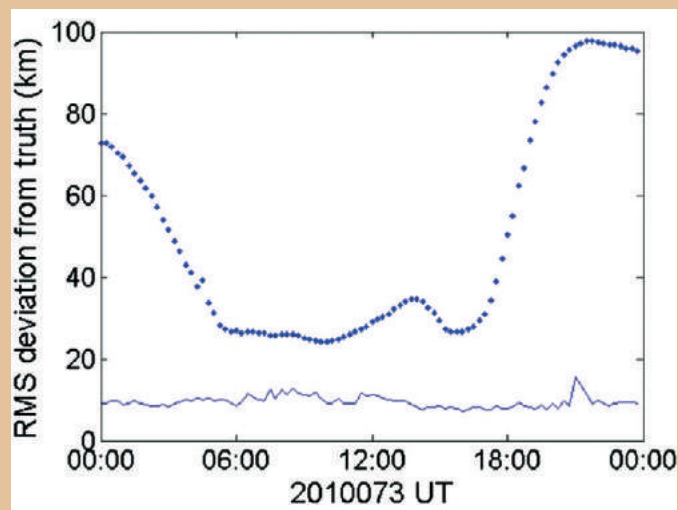


Figure 3. Root-mean-square (RMS) deviation of $h_m F_2$ (the height of the F_2 ionospheric peak) of the GAIM forecast model compared to the GAIM aftercast model, summed globally over the model grid. The data are shown over the course of an arbitrarily chosen day (2010 day 073). The upper dotted line shows the forecast model when only GPS-TEC data are ingested, compared to a priori truth. The lower solid line shows the (quantifiably improved) forecast model when both GPSTEC data and simulated in situ iMESA-R data are ingested, compared to a priori truth. The simulated in situ iMESA data come from a Walker Constellation of 25 iMESA satellites.

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Biographies

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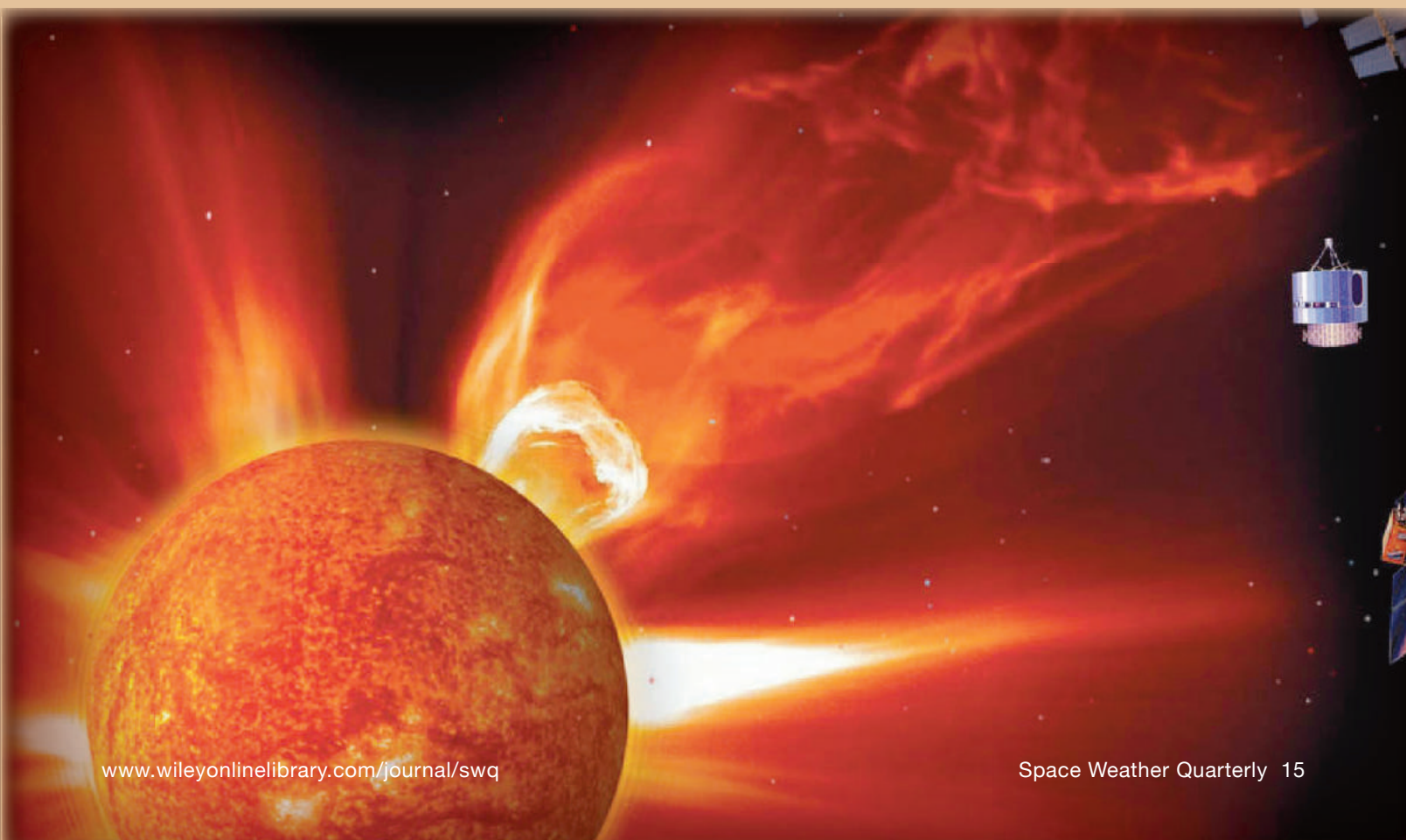
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RESEARCH ARTICLE

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Key Points:

- Develop ensemble CME forecast system and pertinent analytic and graphical tools
- Nonchaotic propagation implies different tactics than for terrestrial weather
- Establishes solid theoretical basis for forecast and analysis of real events

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Theoretical basis for operational ensemble forecasting of coronal mass ejections

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Abstract We lay out the theoretical underpinnings for the application of the Wang-Sheeley-Argé-Enlil modeling system to ensemble forecasting of coronal mass ejections (CMEs) in an operational environment. In such models, there is no magnetic cloud component, so our results pertain only to CME front properties, such as transit time to Earth. Within this framework, we find no evidence that the propagation is chaotic, and therefore, CME forecasting calls for different tactics than employed for terrestrial weather or hurricane forecasting. We explore a broad range of CME cone inputs and ambient states to flesh out differing CME evolutionary behavior in the various dynamical domains (e.g., large, fast CMEs launched into a slow ambient, and the converse; plus numerous permutations in between). CME propagation in both uniform and highly structured ambient flows is considered to assess how much the solar wind background affects the CME front properties at 1 AU. Graphical and analytic tools pertinent to an ensemble approach are developed to enable uncertainties in forecasting CME impact at Earth to be realistically estimated. We discuss how uncertainties in CME pointing relative to the Sun–Earth line affects the reliability of a forecast and how glancing blows become an issue for CME off-points greater than about the half width of the estimated input CME. While the basic results appear consistent with established impressions of CME behavior, the next step is to use existing records of well-observed CMEs at both Sun and Earth to verify that real events appear to follow the systematic tendencies presented in this study.

1. Introduction

Ensemble modeling has played an important role in terrestrial weather forecasting and other applications for some time. A well-known example is in the area of hurricane prediction, where the familiar plots of likely storm paths are generated either from a variety of model runs with slightly different initial conditions (as in Figure 1, top), or from a series of runs with different models, each with its own set of detailed descriptions of physical processes, or from both. The bulk of the work in hurricane prediction has been developed with the realization that the underlying physical system—terrestrial weather—is dominated by such a plethora of sources and sinks of energy and momentum that it must be characterized as “chaotic.” This means that starting from some initial state, the future state of the system can be forecast only for a short period, beyond which error due to uncertainties in all the myriad competing processes grows exponentially. That is, the output for simulations whose initial states differ only infinitesimally can diverge wildly after a certain time, or simulations with quite different initial conditions may all coalesce to some “attractor” state.

Not all terrestrial physical systems evolve chaotically. In particular, the Center for Tsunami Research at the National Centers for Environmental Prediction (NCEP) generates tsunami forecasts under entirely different assumptions—namely, that the propagation of tsunamis is contingent upon a small set of knowable factors, such as the magnitude and location of the initial earthquake pulse, the geometry of the ocean basins, and the wave properties of water. Specialized models can then be run to forecast the impact of the tsunami in any area of the globe, given the inputs mentioned above. Since each such computer run can take longer than for the tsunami to propagate to shore, a vast array of simulations is computed in advance, covering a broad range of inputs of varying magnitudes and locations likely to be encountered sometime in the future. Then, once an undersea event is detected (e.g., Figure 1, bottom, the great tsunami of 2006 along the coast of Japan), the propagation forecast is made by using a lookup table, with the prediction at any location being made on the basis of the run or runs most nearly matching the properties of the current event [Gubler *et al.*, 2013]. All of this hinges upon the fact that the propagation of tsunamis in the oceans is a “nonchaotic”

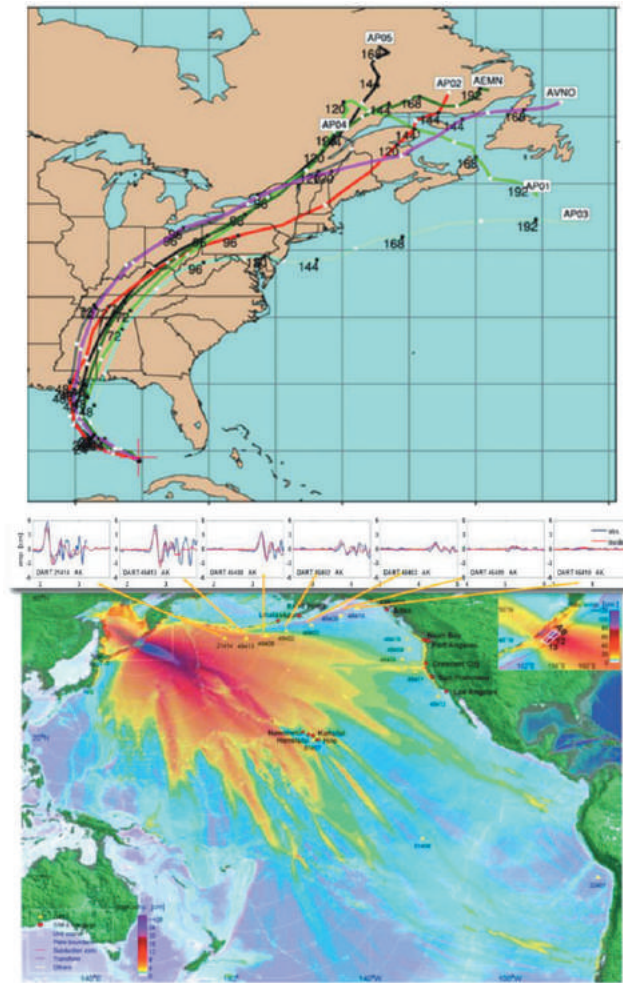


Figure 1. Examples of chaotic (e.g., hurricane) and nonchaotic (e.g., tsunami) model forecasting in operations at NCEP. (top) Advance Global Forecast System ensemble forecast tracks for Hurricane Katrina (courtesy <https://www.e-education.psu.edu/worldofweather/s12.html>); (bottom) a tsunami propagation forecast comparison with buoy data for the 15 November 2006 Kuril tsunami (<http://nctr.pmel.noaa.gov/Jpg/kuril06-dart.jpg>).

physical system, wherein the outputs are directly—and repeatedly—related to the inputs and small changes to inputs result in consistent, corresponding departures in outputs. This is in stark contrast to the chaotic nature of terrestrial weather, for which such an approach would be useless on all but the very shortest time scales.

It is useful to understand which kind of physical system is involved in forecasting the timing and impact at Earth of coronal mass ejections (CMEs) detected in the solar corona. Indeed, as described above, very different tactics are mandated depending upon whether the forecasting is undertaken under chaotic versus nonchaotic regimes.

Ensemble modeling of CME propagation has historically seen a bit of both approaches. Accurate prediction of ambient solar wind properties lying in the path of CMEs has long been recognized as an essential component of CME forecasting [e.g., Case et al., 2008; Shen et al., 2014]. (The term “ambient” in this paper means the pre-CME background solar wind, which may be either uniform or structured, and we consider both cases here.) More recently, variations in ambient flow forecasts stemming from model specifics, from differences in input parameterizations, and from varying numerical grid resolutions have been studied using ensembles [Riley et al., 2013]. Ensembles also play an integral role in the Air Force Data Assimilative Photospheric Flux Transport approach to improving

the Wang-Sheeley-Argge (WSA) solar wind modeling system [Arge et al., 2003, 2013; Linker et al., 2013; Hickmann et al., 2015]. Ensemble methods have also been applied to the study of specific CME events [Lee et al., 2013, 2015] using what amounts to a nonchaotic approach, while Emmons et al. [2013] employed random-member ensembles more in line with chaos methods. Recently, Mays et al. [2015] have reported on the application of ensemble concepts to CME forecasting in a near-real-time (NRT) environment. Finally, it is worth noting that ensemble modeling efforts are also being undertaken in the broader context of space weather studies [e.g., Godinez and Koller, 2012; Murray et al., 2015].

What has been particularly lacking in the CME ensemble studies to date, though, is a comprehensive, step-by-step analysis of the underlying physics of the combined ambient flow (e.g., WSA) and CME propagation (e.g., Enlil) modeling approach used in the operational environment [Pizzo et al., 2011]. There is a need to establish across a broad spectrum of assumed CME properties (speed, size, direction, etc.) and ambient states (i.e., global corotating interaction region (CIR) structure) just how these inputs relate systematically—if they do—to what is seen at Earth or any other observing point. We will also be able to see whether there is any evidence of chaotic behavior, as laid out above. The Riley et al. [2013] study suggests that there will not be, and, if so, that will guide the approach we take toward constructing a formalism for quantitative assessment of operational model forecasts.

Table 1. Physical Variables for the Enlil “a5b1” Uniform Steady State at the Inner Boundary (Left) and at 1 AU (Right), for a Range of Input Conditions

| $R = 21.5 R_{\odot}$ | | | $R = 1 \text{ AU}$ | | |
|----------------------|--------------------------|-----------|--------------------|--------------------------|-----------|
| V (km/s) | n (cm^{-3}) | T (K°K) | V (km/s) | n (cm^{-3}) | T (K°K) |
| 250.0 | 1,176.0 | 255.1 | 256.9 | 11.27 | 11,599.0 |
| 300.0 | 816.7 | 367.4 | 319.6 | 7.262 | 16,321.0 |
| 350.0 | 600.0 | 500.0 | 380.6 | 5.441 | 21,925.0 |
| 400.0 | 459.4 | 653.1 | 440.6 | 4.114 | 28,401.0 |
| 450.0 | 363.0 | 826.5 | 499.9 | 3.223 | 3,574.07 |
| 500.0 | 294.0 | 1,020.4 | 558.9 | 2.595 | 43,961.0 |
| 550.0 | 243.0 | 1,234.7 | 617.5 | 2.136 | 53,042.0 |
| 600.0 | 204.2 | 1,469.4 | 675.9 | 1.789 | 62,988.0 |
| 650.0 | 174.0 | 1,724.5 | 734.1 | 1.520 | 73,801.0 |

Toward that end, we enunciate a succinct logic for minimizing the number of ensemble members needed for operational applications, and we develop a set of well-conceived, readily understood analysis tools for quantifying and ultimately reducing error in CME forecasts in the longer term. Finally, armed with that broader understanding, we will be in a position to develop meaningful and feasible tests of the efficacy of the forecast system by data-mining collections of past events for which adequate observational information is available. On that basis, we can then evaluate the performance of the system going forward against NRT events, for which we do not know the outcome in advance.

These latter two aspects, data-mining and NRT applications, will be deferred to a later paper. However, we do introduce some ideas on how we may best proceed in those directions and how we may possibly simplify the ensemble modeling tactics that are ultimately to be applied to NRT CMEs.

2. Modeling System and Approach

For all these simulations, we use the coupled WSA-Enlil model (WSA V2.6 and Enlil V2.7e [Odstroil *et al.*, 2005]). Enlil V2.7e is quite similar to that currently used in Space Weather Prediction Center (SWPC) operations (V2.6.2) and elsewhere. The main difference between the two is a small quantitative variation in the way that the ambient solar wind is specified. Since the flow density and temperature at the Enlil inner boundary (located at $R_0 = 21.5$ solar radii) cannot be measured directly, these quantities are specified so as to mimic the mean values seen at Earth orbit. The range of values that can meet this general requirement is relatively broad, and various combinations have been employed, some providing a good match to observed parameter ranges during one epoch, others during another. Within the WSA-Enlil system, these are distinguished by a simple naming convention that is invoked at compilation. For example, the “a3b2” specification is the default in the SWPC operational version, whereas “a5b1” is the default in V2.7.e. Table 1 provides a listing of the thermodynamic specifications and their corresponding 1 AU values for the “a5b1” variant used in this study. (In general, “a5b1” provides a better parameterization for active solar conditions, but the overall effect upon corotating stream and CME propagation is minor, as compared to all the other uncertainties and approximations involved in such simulations.)

Commensurate with the considerable uncertainties in CME inputs and the unavoidable crudeness of characterizations of CME structure, it suffices to conduct ensemble studies with the WSA-Enlil system run in the $4^\circ \times 4^\circ$ “coarse” angular resolution mode. (Moreover, practical computational resource considerations dictate that ensemble studies be run as efficiently as possible, which also implies coarse grid. SWPC operational simulations, which are run in “medium” $2^\circ \times 2^\circ$ resolution over about the same radial domain, take over an hour, whereas coarse-grid solutions can be obtained in a minute or two.) In the radial direction 240 grid nodes cover the range from the 0.1 AU inner boundary out to 1.7 AU. Simulations are run with 24 processors on the NCEP development machine “Zeus” (see <https://nescdocs.rdhpcs.noaa.gov>). Although these coarse-grid solutions are somewhat smooth (not featuring substructure likely to be associated with CMEs propagating in a structured medium), gross properties such as arrival time and relative CME strength (as measured by velocity and density jumps across the front) are nonetheless representative of real CMEs. Moreover, we find that in practice these basic properties differ insignificantly from those obtained by the SWPC operational model at medium grid resolution.

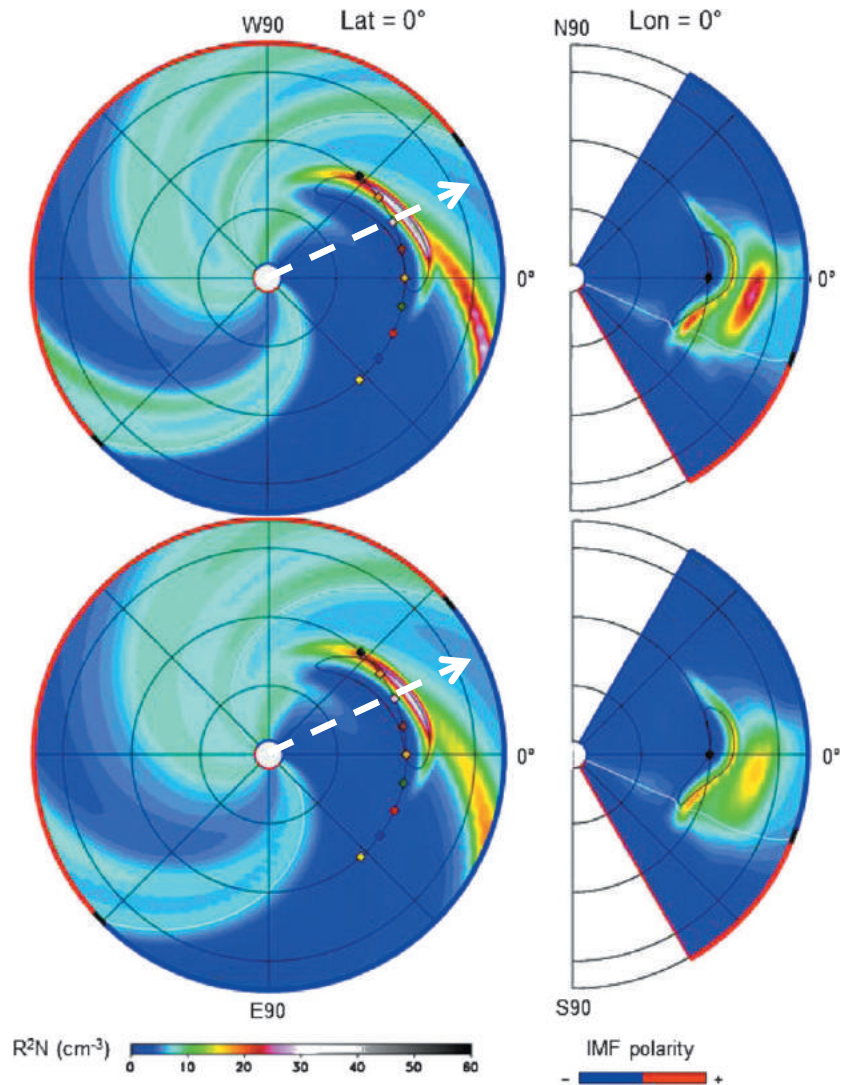


Figure 2. Comparison of mass density distributions in two CME simulations, (top row) one using a purely HD ambient flow, (bottom row) the other including the spiral IMF in the ambient. (left column) The solution in the solar equatorial plane and (right column) meridional slice along $\varphi = 0$. The locus of the injected HD CME mass is indicated by the fine black line. Both simulations were run in coarse-grid mode, with 240 evenly spaced radial steps between the inner boundary at 21.5 R_s and the outer boundary at 1.7 AU and an angular grid spacing of $\Delta\lambda = \Delta\varphi = 4^\circ$.

For this study we restrict attention to the default Enlil CME cone inputs, which include the estimated speed V_{CME} , the north-south (λ) and east-west (φ) launch directions (latitude and longitude of the CME centerline, in Heliocentric Earth Equatorial coordinates), and the angular half width $\omega_{1/2}$ (here, assuming a circular cross section). For our hypothetical CMEs, the final operational input—the time of arrival of the nose of the CME at the Enlil inner boundary R_0 —is arbitrary. The injected CME material is modeled as a sphere of uniform density crossing R_0 at the rate V_{CME} , with the density being 4 times that of the a5b1 reference density (see Table 1). This results in a direct relationship between total mass injected and angular width, functionally similar to, but quantitatively different from, that reported by *Gopalswamy et al. [2005]*, for instance.

A number of additional modifications to the cone inputs are provided for in the Enlil code, but we defer consideration of those to a later paper. Finally, we note that magnetic cloud content is not in this model, and it can be expected that its inclusion would affect the internal CME evolution and its impact upon Earth (duration and strength of a geo-event) quite substantially. However, that is outside the scope of this study, which is restricted to properties near the leading edge of the CME, where the evolution is dominated by hydrodynamic considerations.

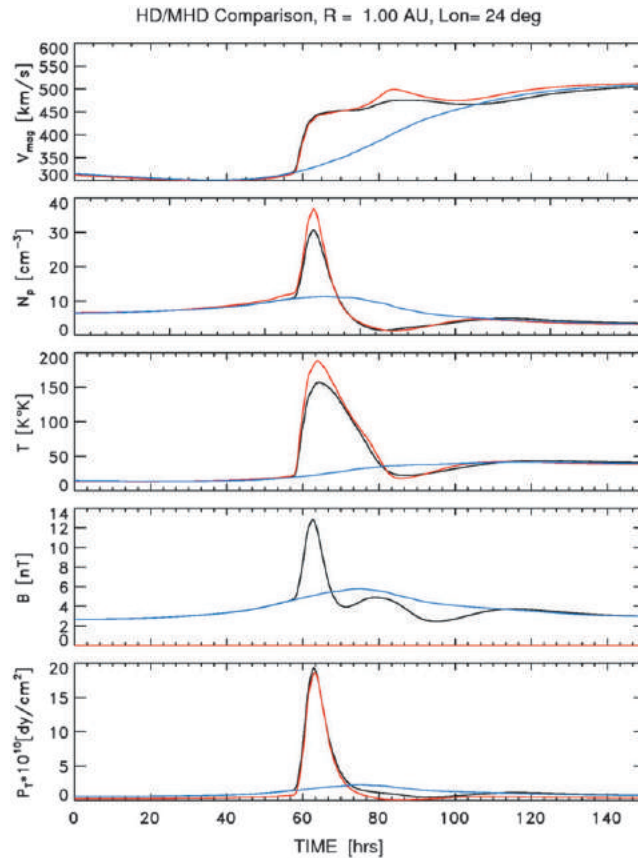


Figure 3. Overlay of time profiles of several flow parameters along a line near the center of the CME in Figure 2. The MHD solution with spiral IMF is shown in black, the pure HD solution is red, and, for reference, the undisturbed MHD ambient is in blue. The gas pressure in the HD solution is higher than in the MHD case because the IMF pressure in the latter helps oppose the pileup of momentum at the leading edge of the CME. The amplitudes of all relevant variables in the two CME solutions are very similar, and the arrival time is affected hardly at all.

interplanetary magnetic field (IMF). That is, a 3-D MHD Enlil simulation of a CME interacting with ambient stream structure in the inner heliosphere, as driven by typical WSA map information and cone inputs, will exhibit only minimal differences at 1 AU as compared to a 3-D HD Enlil simulation (i.e., where the magnetic field $|B|$ has been set to zero everywhere) driven by the same velocity, density, and temperature variations at $21.5 R_S$. In terms of the effect upon CMEs—in particular, fast CMEs—interacting with the ambient stream structure, there is essentially *negligible* difference in CME front properties such as arrival time and overall velocity jumps across the CME fronts, as compared with all the very real uncertainties in the inputs. The underlying reason for this is that the distribution of input radial momentum flux dominates the evolution in the interplanetary medium, with the thermal and magnetic pressures playing a secondary role [Pizzo, 1980].

To illustrate, Figure 2 (top row) shows an Enlil time slice pair of plots for an HD simulation wherein a moderate-speed CME has been launched into the back end of an ambient corotating stream front driven by an actual WSA map (the one included in the V2.7e release of the Enlil software). The input cone parameters were $V_{CME} = 800 \text{ km/s}$, $\lambda_{CME} = 0^\circ$, $\varphi_{CME} = 30^\circ$, and the full angular width $\Omega_{CME} = 60^\circ$. The plots present an overview of the resulting structure in the inner heliosphere, about 3 days after CME launch. Figure 2 (top, left) is a color-coded representation of the density in the solar equatorial plane, and Figure 2 (top, right) is a north-south cut along a plane passing through Earth (the gold diamond at 1 AU and 0° longitude). Figure 2 (bottom row) shows the equivalent MHD simulation, otherwise the same as the one at the top but including a typical spiral interplanetary magnetic field (IMF). Comparing the two sets of plots, it can be

Our approach is to study the impacts of variations in CME cone inputs—speed, width, and direction—upon CME transit time to 1 AU in a comprehensive way, including explicit consideration of the effects of varying ambient speeds upon the propagation time in conjunction with the different cone inputs. This is a purely hypothetical study intended to scope out the range of behaviors and responses over a representative sample of cone inputs and ambient conditions. This will lay the groundwork for quantitative follow-on studies involving real CMEs that have previously been modeled and forecast in the SWPC operations center.

Here we consider two broad classes of single-CME evolution: (1) CMEs launched into uniform hydrodynamic (HD) backgrounds, and (2) CMEs launched into the midst of a substantial tilted-dipole stream structure. The uniform HD background study provides a useful introduction into the basics of ensemble CME composition, gross dynamic evolution, and the specifics of analysis techniques. This sets the context for handling and understanding CMEs cast into a more realistic tilted-dipole global stream configuration in the second stage of this study.

It may come as a surprise to some, but for our purposes there is no loss of generality in neglecting the ambient spiral

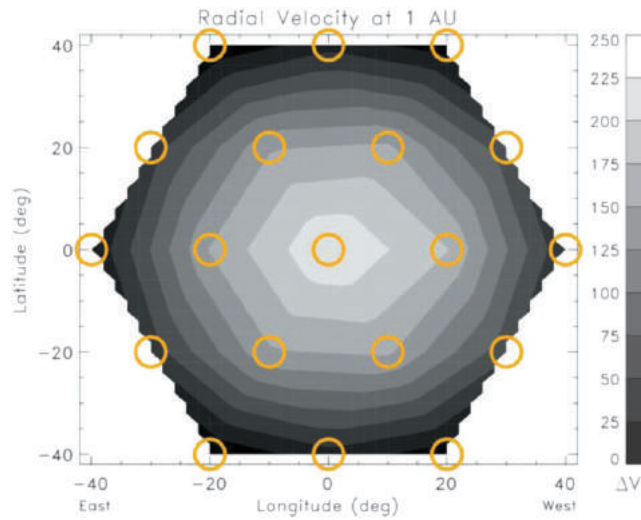


Figure 4. Latitude-longitude contour map of 1 AU radial velocity amplitude across a sample moderate-strength CME launched into a uniform HD solar wind background. The contours indicate the velocity jump relative to the pre-CME background, and the yellow circles denote the loci of radial lines along which the properties of the CME are measured for purposes of analysis.

seen that the density peaks in the HD CME front are a bit higher and sharper than in the MHD case, but the locations and timing of both ambient and CME features are almost indistinguishable.

To appreciate more keenly how little the inclusion of a spiral IMF affects the CME propagation, consider Figure 3, which shows 1 AU time series plots along $\varphi = 24^\circ$, in the direction of the dashed white arrow in the equatorial plane in Figure 2 (left column). The first panel of Figure 3 presents overplots of HD (red) and MHD (black) solar wind velocity, the second panel number density, the third panel temperature, the fourth panel magnetic field intensity, and the fifth panel total pressure. The blue curves represent the undisturbed MHD ambient solution (no CME).

Experiments with MHD versus HD solutions across a range of CME inputs like

that explored in section 4.1, below, confirm the generality of the conclusion that use of a purely HD versus an MHD model calculation causes negligible change in the bulk dynamics. Indeed, it is the case that the higher the CME speed—and the greater the potential for geospace disruption—the more rigorous is this finding.

3. Quantifying and Organizing Results—A Sample Ensemble

We illustrate the process of composing, running, and analyzing CME ensemble simulations in the simplest of all scenarios: an ensemble of CMEs is launched into a uniform HD ambient flow, set to a moderate 350 km/s at R_0 . We build our ensemble about a base CME of moderate speed and angular width $\{V_{CME} = 800 \text{ km/s}, \omega_{1/2} = 35^\circ\}$ as follows.

First, we establish the spread in cone input variables about a base member. Given all the inherent uncertainties in cone specification derived from coronagraph observations, it is reasonable to start with an ensemble composed of values bracketing some base member. In terms of V_{CME} , we select a spread of $\pm 200 \text{ km/s}$, for $\omega_{1/2}$ a spread of $\pm 10^\circ$, and for λ_{CME} and $\varphi_{CME} \pm 10^\circ$. These values are representative only and are based on experience in fitting cones to real CMEs; they are, moreover, gauged to provide enough variation in 1 AU CME properties to support systematic investigation of ensemble properties, as developed below. For just this simple ensemble, 81 members ($=3^4$) would thus be needed to cover all potential combinations. Since each coarse-grid solution requires about 30 s of CPU time on a modern parallel supercomputer like Zeus, a full ensemble would entail about 40 min of computing in the optimum case. In itself, that poses no practical issue, but when one contemplates running hundreds of such ensembles (as undertaken in this study), the computational load does become a consideration. Regardless, a far more compelling motivation for minimizing the number of members in each ensemble is the task of extracting useful information from the large amount of output. Although it is possible to automate that process to some extent (see below), there is a huge advantage in not complicating the problem anymore than absolutely necessary. Also, it must always be kept in mind that the objective is to draw relatively general conclusions from a system that is built upon crude inputs that are coarsely modeled.

For each ensemble member, certain information must be efficiently extracted and saved in an organized way for subsequent analysis. Since we are dealing with structural variations across a broad front, we gather data on such features as local transit time (TT) and velocity and density amplitudes (ΔV and Δn) at a variety of observing points, as illustrated in Figure 4. Here we view a representation of the velocity distribution in our

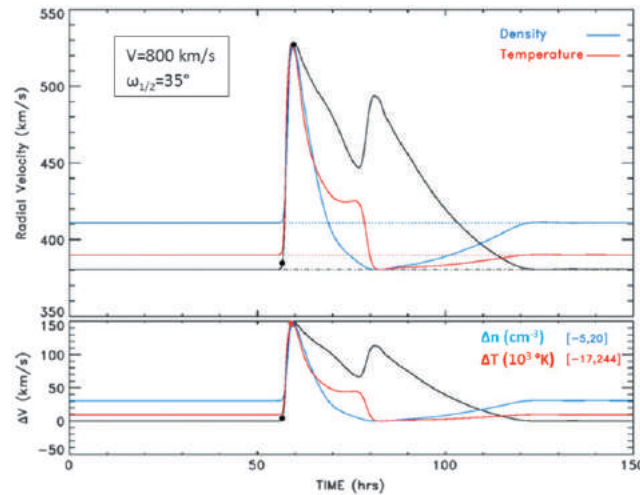


Figure 5. Illustration of automated methodology for collecting parameter variations across CME fronts used in the study. (top) Raw parameter values as a function of time from CME launch, with the scale at left referring to the velocity (black), while the density (blue) and temperature (red) are arbitrarily scaled to the velocity amplitude. Dotted lines indicate the undisturbed ambient values. (bottom) The parameter amplitudes relative to the pre-CME background, with the Δn and ΔT ranges as indicated. The amplitude data and timings (colored dots) are collected and stored in comma-separated values (CSV) files for subsequent processing and display. For CMEs propagating in structured backgrounds, the location of the several parameter peaks may vary slightly.

parameter jumps across the front, which is not typically the same as the shock jump. (In these coarse-grid simulations shocks are typically quite smeared, particularly where they are weak and/or oblique.) These data are collected for each sampling location in Figure 4, along with other metadata from each run, to be used in further processing.

Transit times for two members of an ensemble, computed as above, can also be represented by contour maps, as shown in Figure 6. Here we view the relative transit times at 1 AU across the front of the CME aimed directly at Earth (top) and another CME aimed 10°N and 10°W (bottom). Blue/red denotes later/earlier arrival time relative to that along the Sun-Earth line. The figure shows that because this CME is aimed away from Earth, its front crosses the 1 AU sphere at 10°N and 10°W a few hours before it arrives at Earth.

Collecting these data for all ensemble members into CSV-format files facilitates the creation of the transit time parameter plots shown in Figure 7. Since we will encounter many of these plots throughout the paper, we take pains here to explain what these plots are intended to convey. Figure 7 presents a 21-member subset of the full 81-member ensemble described above (we explain why we use a reduced, 21-member subset in section 5, below). Each symbol indicates the relation between the transit time of one of the CME ensemble members and the associated velocity (top) and density (bottom) jumps across that front at 1 AU along a radial line from the Sun to Earth. The colors indicate the launch speed, the round symbols indicate ensemble members aimed directly at Earth, and the squares indicate CMEs launched off the Sun-Earth line (here in varying combinations of 10° offsets in N and/or S pointing, not differentiated in this figure and intended only to suggest the resulting scatter in arrival time and strength). For both circles and squares, the size indicates the angular half width, according to the black scale located at top center on the figure.

We see that the slower CMEs (light olive green) take longest to get to 1 AU and produce relatively weak flow parameter jumps, whereas the fastest, biggest CMEs (dark green) arrive most quickly and produce sizeable jumps. Moderate-speed CMEs (green) fall in between, depending upon size and pointing. While the trends of the individual velocity groups are quite similar, there is a noticeable tendency toward lesser travel time for the faster ensemble members (more obvious in the density plot). Note that in this simple case of a uniform

base CME, with the contours depicting the distribution of maximum velocity jump across the CME front. It is to be emphasized that the contours are not a snapshot at a given time but rather are created (by irregular grid triangulation) by sampling the velocity jump (relative to the pre-CME background) at 1 AU at each of the 19 locations indicated by the gold-colored circles. Each ΔV determination contributing to the contours is made as shown in Figure 5. The points at the base and peak of the velocity jump are determined by an automated analysis routine, and the midpoint of the rise is taken as the local CME front arrival time. The associated density and temperature jumps (Δn and ΔT) are determined and stored as well. (For uniform backgrounds this process is straightforward, but in the case of significant stream structure we subtract point by point from the CME run the corresponding interpolated values from a purely ambient simulation, run separately.) Note especially that the marker points denote the peak parameter

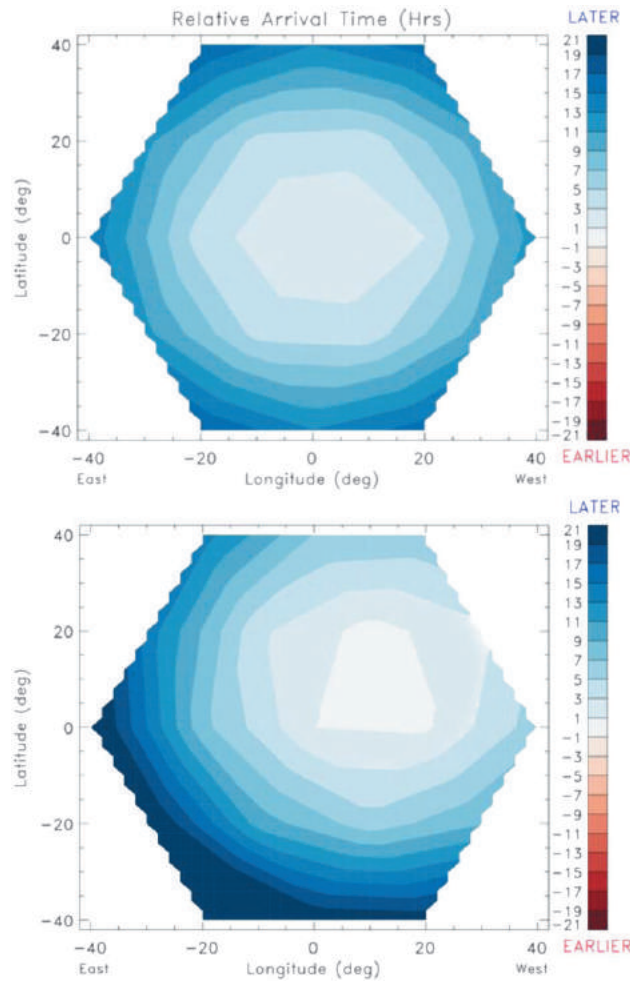


Figure 6. Latitude-longitude maps of relative arrival time at 1 AU for two model CMEs (for both, $V_{CME} = 800$ km/s, $\omega_{1/2} = 35^\circ$) (top) one aimed directly at Earth, (bottom) the other 10° to the north and west. In both cases the blue contours indicate arrival times delayed relative to that at Earth.

HD background, all the off-pointed CMEs for each particular speed take longer to reach Earth, relative to those aimed directly at it.

Yet another way to gauge the 1 AU impact of the CMEs in our ensemble is shown in Figure 8, where—for those CMEs in the ensemble aimed directly at Earth—we view transit times (top), velocity jumps (middle), and density jumps (bottom) as a function of the angle from the CME centerline, stated in terms of the half width. Note that the angular widths of the velocity and density jumps at 1 AU are commensurate with the input half widths, with the amplitudes within $\pm \omega_{1/2}$ of centerline varying only slightly but dropping off rapidly beyond this range. This effect also becomes more accentuated with CME strength, whereas weaker CMEs show more rounded parameter jump profiles. The transit time plots (top), however, display decidedly broader, smoother profiles, even for the most powerful CMEs in this group. This difference is attributable to the fact that the transit time reflects directly the propagation of the shock front at the nose of the CME, whereas the velocity and density jumps—as measured here—include the effects of the ejecta, i.e., compressed ambient plus CME driver gas. This is consistent with what has been known for over 40 years [e.g., *DeYoung and Hundhausen, 1973*] that the shock front leading CMEs—being a wave—is intrinsically broader in angular extent than

the ejected material driving it, much as the bow wave of a ship is wider than the vessel driving it. Thus, while CMEs off-pointed more than $\omega_{1/2}$ from Earth may still drive some disturbances at Earth, they mainly constitute “glancing blow” events or miss Earth altogether. In a practical sense, those CMEs whose estimated centerline offset from Earth (as given by $\psi_{CME} = \text{acos}(\cos(\lambda_{CME})\cos(\phi_{CME}))$) lies near and beyond $\omega_{1/2}$ should prove the most troublesome to predict accurately, since the impacts vary substantially in that range.

4. Ensemble Runs

In this section we present results of two extensive studies of hypothetical CME ensembles in unstructured and structured backgrounds covering a broad range of inputs, including variations in the ambient speed.

4.1. CME Ensembles in Uniform Hydrodynamic Ambients

We expand upon the demonstration ensemble introduced above to cover a broad range of CME parameter space, such as typically encountered in the course of operations. Figure 9 conveys a sense of the relevant parameter space. On the horizontal axis we have uniform ambients at three different levels (250, 350, and 450 km/s at R_0), while on the vertical axis we sort according to relative CME strength, which actually involves an amalgam of input speed (running from weak 300 km/s CMEs to very “strong” ones at 2000 km/s) and half width (and also pointing, relative to the 1 AU location of interest—so the real domain

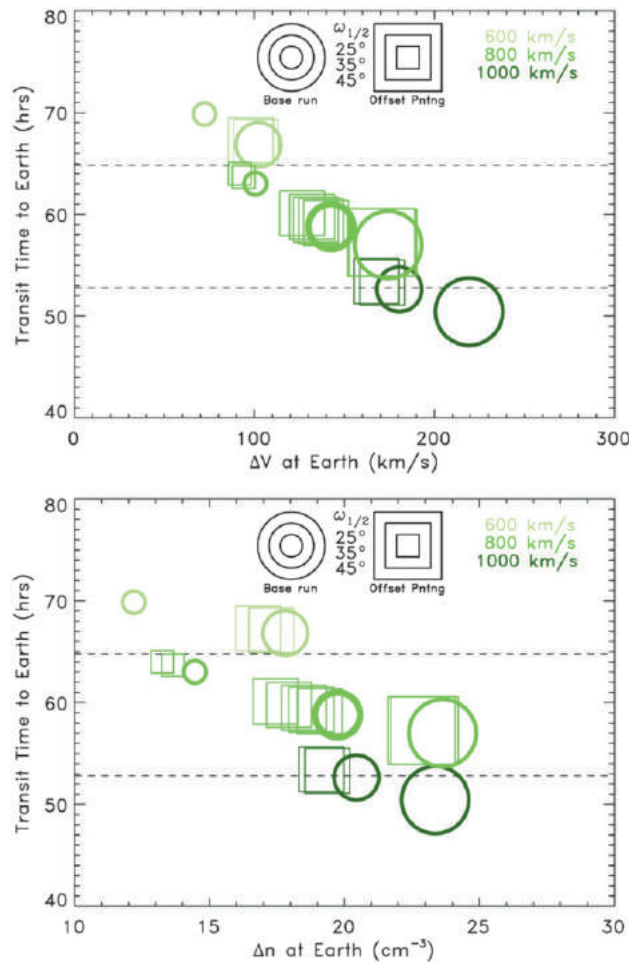


Figure 7. Scatterplots of arrival time at 1 AU versus (top) velocity jump and (bottom) density jump across the CME front for a 21-member ensemble launched into a uniform HD ambient with a moderate 350 km/s flow speed. Symbols in {light olive green, green, dark green} denote parameters for CMEs launched at {600, 800, 1000 km/s} with varying angular half widths $\omega_{1/2}$ and pointings relative to the Sun-Earth line: circles indicate those directed head-on, while squares indicate those at $\pm 10^\circ$ offset (a value chosen for illustrative purposes only). The size of the circles and squares indicates $\omega_{1/2}$ in each case. The plots show a well-ordered systematic variation from the weakest to strongest CMEs in the ensemble. (The motivation for using 21-member ensembles is detailed in section 5.)

is indeed a multispace that cannot be adequately represented here). Thus, in the lower left corner we have ensembles of slow CMEs injected into slow, dense ambient, while at upper right we have very fast CMEs propagating in faster, more tenuous ambient. Real CMEs and ambients may indeed fall outside these limits, but this range suffices to lay out the key issues in CME propagation (at least within the modeling realm).

For the purposes of this paper, we will focus upon the band of possible ensembles represented by the vertical red arrow (CMEs of varying strength propagating in a 350 km/s ambient) and by the green arrow (moderate-strength CMEs propagating in a range of ambients). Considering first ensembles in the vertical red arrow domain, the results in terms of the transit time versus parameter jump measure are presented in Figure 10. Here three sets of 21-member ensembles are depicted on a single plot, a blue-shaded set for slower, weaker CMEs, a similar green-shaded set for the moderate CMEs of Figure 7, and a reddish set for strong, fast CMEs. A fairly regular progression in the transit time versus parameter jump relation is seen in the velocity jump (Figure 10a), but something odd happens in the density jump plot (Figure 10b), where the density jump appears to approach some kind of limit (Δn is capped in the low twenties). Clustering about a limit like this can be a sign of chaotic behavior, but the most likely explanation is that shock heating is coming into play, with the stronger CMEs driving ever larger nonadiabatic temperature jumps at their leading edge. Figure 10d vividly confirms

that the gas pressure jump (ΔP_{gas}) across the CME front—the product of the density and temperature (ΔT) jumps (Figure 10c)—varies regularly with CME strength. Hence, the limit in the density jumps in Figure 10b stems from dissipative energy deposition across the CME shock front. The coarse grid probably overemphasizes heating in the shock compressions, which in reality should be narrower spatially and with a somewhat higher density. The Δn shown here should thus be taken as a lower bound and the ΔT as an upper bound.

We now turn to the role the ambient speed plays in the evolution of CMEs. Figure 11 displays an overlay of three ensembles, as in Figure 10, but this time all three feature the same moderate-strength CMEs (600/800/1000 km/s) launched into a different ambient (250/350/450 km/s at R_0). In Figure 11 (top), the run of bluish symbols near the top indicates the 600/800/1000 km/s set of 21 CMEs in a 250 km/s ambient, the next lower set (greenish) is the same set of CMEs in a 350 km/s ambient (again, as in Figure 7), and the lowest, reddish set is for the same CMEs in a 450 km/s ambient. Figure 11 (bottom) portrays the density

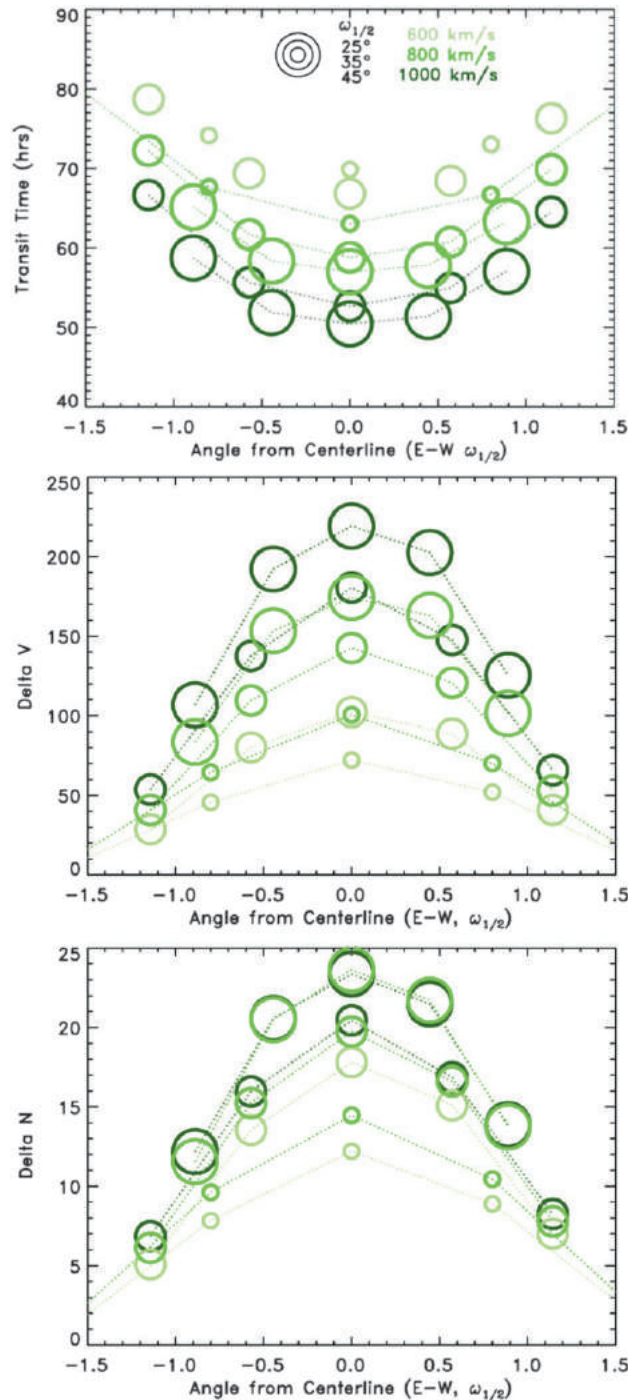


Figure 8. Angular distribution of (top) transit time, (middle) velocity jump, and (bottom) density jump relative to CME centerline at 1 AU for ensemble of Figure 7. The ordinate is presented in terms of CME half width (to provide broader context across CME). Color scheme denotes velocity at launch (as in Figure 7), while relative size of circle denotes $\omega_{1/2}$. Velocity and density jumps fall off sharply beyond $\omega_{1/2}$ from the CME centerline (reflecting the widths of the ejecta), whereas the transit time has a broader profile (since that is indicative of the shock width at the CME front).

amplitude at Earth for the three sets of data, in the same color scheme. The faster speed ambients are also less dense (see Table 1), so the pileup of material at the CME front is correspondingly reduced, whereas dissipative heating at the shock fronts rises (not shown). Comparing Figures 10 and 11, we see that the speed of the ambient background can have nearly as much to do with transit time and 1 AU CME front properties as intrinsic CME properties (launch velocity, half angle).

4.2. CME Ensembles in Structured Ambients

Accounting for the interaction of CMEs with preexisting stream structure is a basic element of space weather forecasting. Just where a CME encounters a dense stream front with its associated velocity gradients obviously affects the propagation characteristics, and this sort of interaction is routinely taken into account in operational CME forecast modeling efforts at SWPC and by other groups around the world. Although some exploratory studies in this direction have been published [e.g., Case et al., 2008; Lee et al., 2013, 2015], no comprehensive modeling effort has been attempted. In particular, what has been lacking is an assessment of 1 AU CME properties in the spirit of that undertaken in section 4.1 but which includes interaction with significant, representative stream structure. It is the intent of this section to lay the basis for the interpretation of ensemble modeling of CME propagation in realistic ambient flows that include significant stream structure.

4.2.1. CME Ensembles in a Tilted-Dipole Stream Structure

The most useful generic background stream structure for this purpose is the tilted-dipole configuration described in Pizzo [1982, 1991]. In view of the operationally oriented nature of this study, we will simplify the specification of the input stream structure at $R_0=0.1$ AU as follows. First, we define the velocity structure in a coordinate system that assumes no tilt of the stream configuration to the solar equator (i.e., velocity and density are functions of heliolatitude λ only) as

$$V = (V_{\text{fast}} - V_{\text{slow}}) \times \sin^p(\lambda) + V_{\text{slow}},$$

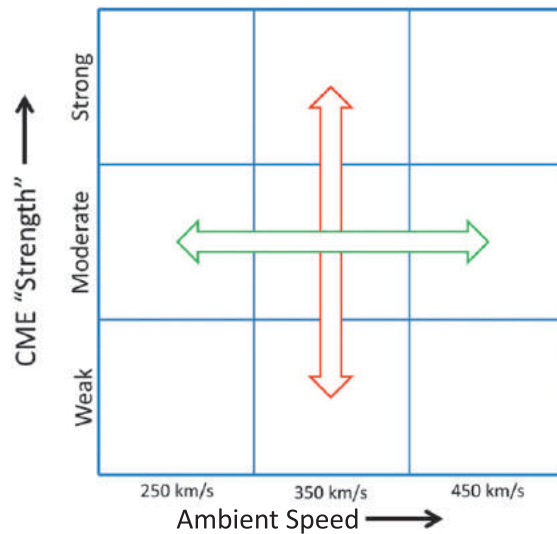


Figure 9. Schematic of CME input parameter space to be explored in section 4.1. The term “strength” refers to a combination of input CME speed and half width (which, in turn, is correlated with mass). Along with the CME pointing relative to the observer, the possible inputs thus actually constitute a hypercube, which for simplicity has here been collapsed to a square. This part of the study thus covers everything from “weak” CMEs in a slow ambient (lower left corner) to “strong” CMEs launched into a “fast” ambient (upper right corner). For tractability, we present here only results indicated by the red (range of CME strength in moderate-speed ambient) and green (moderate-strength CMEs over range of ambients) arrows.

where p is an arbitrary constant used to sharpen the velocity distribution about the equator and is set here to 16, $V_{fast} = 600$ km/s, and $V_{slow} = 250$ km/s. The density is given by

$$n = n_{fast} \left(\frac{V_{fast}}{V} \right)^2,$$

and the total (gas only) pressure is held constant on R_0 , with the result that the temperature variation is the inverse of the density variation. Given these specifications, it is trivial to impose any desired tilt of the coordinate system (and thus the large-scale flow parameter configuration) via the appropriate 3-D coordinate rotation.

The result, for a 30° tilt, is the velocity and density distributions on R_0 shown in Figure 12. Here we view a sinuous band of high-density, low-speed material weaving about the solar equator. Quantitative results quoted in this paper clearly depend upon the specified tilt and would also vary if some other geometry were imposed. However, configurations like this typically apply over a substantial part of the solar cycle, and imposing this assumption also facilitates interpretation via comparison with papers already in the literature.

The first simulation at hand is indicated by the red circle in the middle of both plots. This represents

the location and cross section of CME material (parameterized as in section 4.1) that is injected into the structured tilted-dipole ambient at some time T_0 after the full 3-D ambient numerical solution has evolved into a stable, fixed state. Just before CME launch, the structured 3-D ambient is characterized by two large, steady-stream structures, one (near 0° longitude) with a northward leading tilt (i.e., the normal to the front points up and to the right, in the sense of rotation) and the other (at $\pm 180^\circ$) with a complementary southward leading tilt. Thus, the properties of the steady, evolved, pre-CME ambient are similar to that discussed at length in Pizzo [1982, 1991].

This case, where the CME is injected directly into the heavy stream material at the center of the plot, ensures the maximum interaction of the CME with the stream. A major portion of the CME will plow through the densest part of the stream right near the inner boundary, thereby experiencing the maximum slowing by momentum exchange. As the CME propagates out from R_0 , the residual extra momentum in the CME material will break out around the dense stream, as parts of the CME above and below the initial center of the CME will be less encumbered by the dense stream front material and race out ahead of the slower part near CME center. Eventually, the injected CME material flattens into a distorted, bent shape like that depicted in Figure 2 of Odstrcil [2009].

The flow pattern at 1 AU is illustrated in Figure 13 (top), which shows a ΔV plot like Figure 7 for the same CME input speed and $\omega_{1/2}$ as that case but launched directly into the midst of the stream structure depicted in Figure 12. The ΔV distribution at 1 AU is bifurcated as a consequence of interaction with the dense, heavy stream component lying across its path near the Sun. The dark, low- ΔV region running diagonally from upper left to lower right marks the impeded flow in and around the dense stream front material, whereas the bright contours of high ΔV indicate areas off to the side (upper right, lower left) where the interaction between the stream front and the CME is much weaker. The associated arrival time plot (Figure 13, bottom) is color scaled to show the delayed (blue) arrival along the low- ΔV corridor; the earliest (red) arrivals for this CME are coincident with the high- ΔV band running from lower left to upper right. More generally, the precise distributions

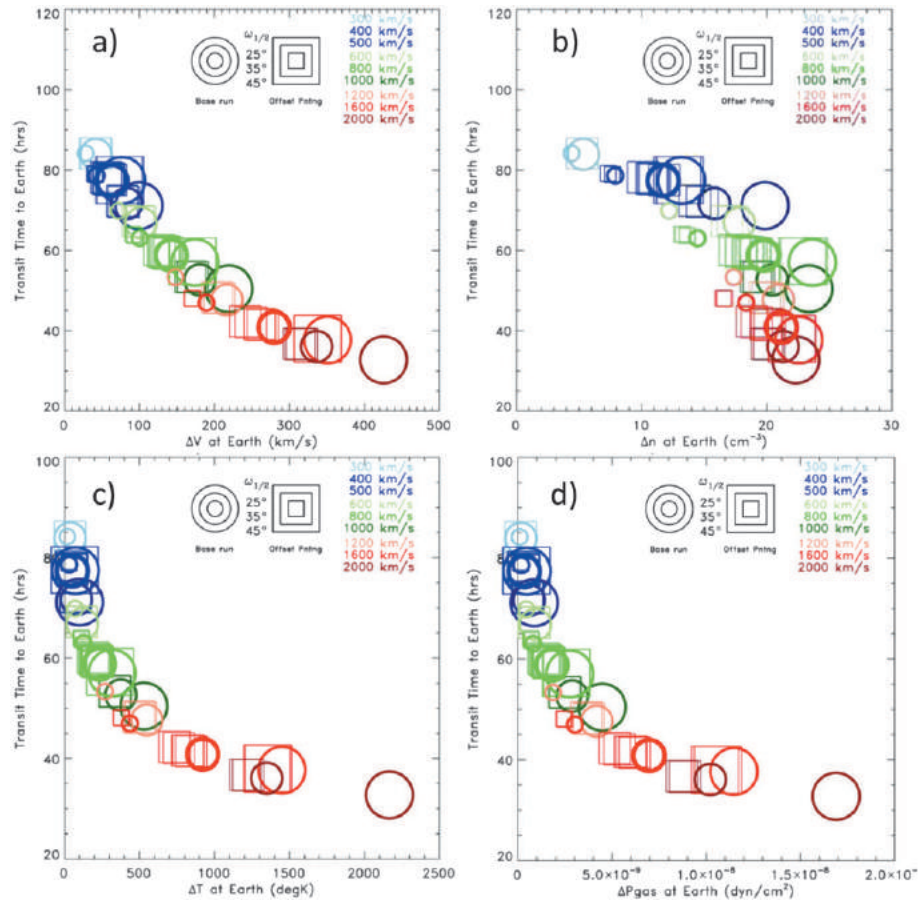


Figure 10. Color-coded scatterplots of transit time versus fluid parameter jumps for three 21-member ensembles covering input CME speeds between 300 and 2000 km/s, injected into a 350 km/s ambient. (a) ΔV , (b) Δn , (c) single-fluid temperature jump (ΔT), and (d) gas pressure jump (ΔP_{gas}). The moderate-speed CME data are in green (as in Figure 7), while blue signifies a slower ensemble and red a faster ensemble, as indicated at upper right. Square and round symbols are defined as before. The 1 AU velocity jump increases monotonically with input speed, while the number density jump reaches an apparent limit of $\sim 25 \text{ cm}^{-3}$. The continuity in ΔP_{gas} shows that the limit on Δn stems from shock heating (as exemplified by the monotonic increase in ΔT) and is not indicative of the kind of clustering anticipated in a chaotic system.

of the transit time and ΔV will vary from CME to CME, depending upon the pointing relative to the dense stream material and the size and speed of the CME. In addition, the magnitude of the interactions will vary for weaker to stronger velocity and density contrasts and stream topologies near the Sun.

To assess quantitatively the 1 AU properties of CMEs propagating through the structured ambient of Figure 12, three 21-member ensemble sets are injected into it, with CMEs of varying size and speed being launched over an angular spread of $\pm 10^\circ$ about the center of the red circle in Figure 12. The result is seen in Figure 14, which is in the same format as Figure 10, for reference. Here we see the now-familiar arc of members in the TT- ΔV plot but a more sharply truncated TT- Δn distribution relative to that in Figures 10a and 10b. Again, shock heating, as measured by ΔT and ΔP (not shown but similar to Figures 10c and 10d) is at play in imposing the peak Δn limit. The ensemble distribution in Figure 14 is very regular and systematic, with no clumping or other indications of chaotic behavior.

4.2.2. Ensemble Interactions for CMEs Injected at Different Locations in the Stream Structure

The 21-member ensemble in section 4.2.1 is launched into the midst of the dense stream material where it crosses the equator, guaranteeing the strongest possible interaction with the background structure. We now consider the more general case of ensembles launched at various offsets about the centroid of that ensemble.

First, we address the case of ensembles injected at small offsets ($\pm 20^\circ$ in both latitude and longitude) about the stream front. The results of this experiment provide a feel for the sensitivity of the previous results to CME directionality in the presence of a strong background structure. We find that scatterplots in ΔV and Δn (not shown)

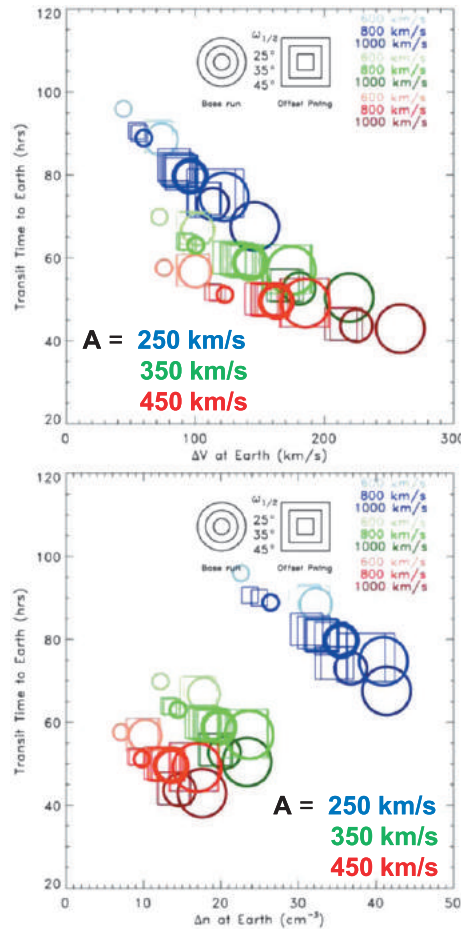


Figure 11. Scatterplots of (top) ΔV and (bottom) Δn for three 21-member ensembles injected at moderate speeds into ambient flows of {250, 350, 450 km/s}, which are color coded {blue, green, red}. The slowest ambients have higher intrinsic densities, while the faster ambients are progressively more tenuous (see Table 1). Hence, a fast CME in a slow ambient will get bogged down as it sweeps up considerable material at its front, while the same CME injected into a faster, more tenuous ambient will accumulate less material and transit more rapidly to 1 AU. On the other hand, the ambient also acts somewhat as a conveyor belt—a slow CME launched into faster ambient wind will propagate to Earth more quickly than its intrinsic speed might suggest.

jumps are muted; the somewhat asymmetric peaks in both are localized about the CIR front. The same CME injected far from the CIR front (-80° , purple; $+80^\circ$, blue) propagates into a broad area of fast stream and therefore evolves nearly as it would in a uniform, fast background.

For a CME injected 40° ahead or behind the CIR front, however, the story is more complicated. For a CME injected 40° to the west (red, positive longitudes) of the CIR front, the easternmost portion ($\varphi \approx 0^\circ$) of the CME is greatly weakened (very low ΔV) and slowed through strong interaction with the CIR, which also pushes up the already high CIR densities. On the other hand, the western segments of this CME expand freely into the back of the preceding fast stream, such that the peak ΔV location occurs some 20° to the west of that CME centerline. Conversely, the CME launched 40° to the east of the CIR front (green, negative longitudes) runs up upon the CIR from behind and exhibits a basically inverse evolution. That is, the peak ΔV location now occurs 20° to the east of the CME centerline, while high Δn is experienced in the vicinity of the CIR. Similar plots can be constructed for faster or slower and narrower or wider examples, with corresponding variation in the angular response.

Finally, in terms of transit time versus ΔV and Δn plots, the most interesting deviations from Figure 14 (CMEs in the vicinity of the stream front) and Figure 10 (CMEs in uniform flow far from a stream front) occur near

are quite similar in range and form for all six of the offset ensemble members, looking much like that in Figure 14. There is slightly more differentiation according to speed and size in those ensembles injected just ahead of the stream front and rather less for those injected behind, but the effects are overall very minor. More scatter occurs in the Δn than in the ΔV plots for these offset pointing cases, but all exhibit approximately the same “knee” in the Δn distribution as in Figure 14 (bottom).

But what of CMEs that are injected farther from the slow stream front? The general run of results can be understood by consideration of sample CMEs introduced at various places with respect to the CIR front. Figure 15 presents plots of ΔV and Δn for a CME configuration $\{V_{cme} = 1000 \text{ km/s}, \omega_{1/2} = 35^\circ\}$ injected in the equatorial plane at five discrete locations [$\varphi = \{80^\circ, 40^\circ, 0^\circ, -40^\circ, -80^\circ\}$] relative to the nominal Figure 12 stream front, as marked by the colored crosses in that figure. In each case, the transit times and jump parameters every 20° across the front are denoted by the colored symbols. From top to bottom, the plots represent the transit time TT to 1 AU, the local velocity jump ΔV , and the density jump Δn . The black curves near center of each plot indicate 1 AU CME properties for the case where the CME is injected directly along the CIR front near the Sun (as in Figure 14). There, the density jumps are relatively high (since the CME is running directly into the stream front), while the velocity

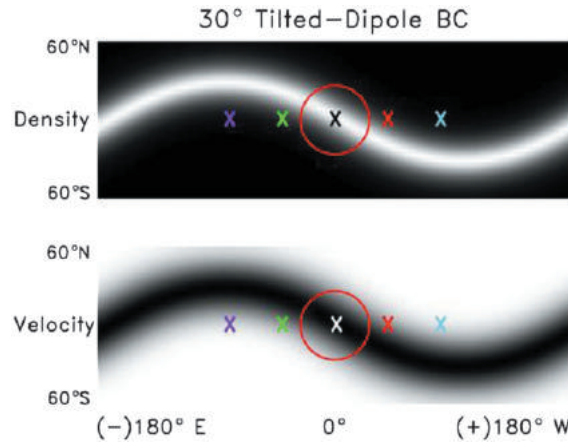


Figure 12. Tilted-dipole ambient flow geometry used to illustrate how an idealized, highly structured solar wind background may affect CME propagation. This kind of structure is most commonly associated with the declining phase of the solar cycle. The centroid of the ensemble discussed in section 4.2.1 is indicated by the black/white cross in the red circle; the other colored crosses denote the centroids of similar, additional ensembles discussed in conjunction with Figure 15.

$\pm 40^\circ$ relative longitude. Figures 16a and 16b illustrate how ensemble sets of moderate and fast CMEs react to being launched at 40° W into the rarefaction region trailing the fast stream preceding (in the sense of rotation) the CIR front; conversely, Figures 16c and 16d show the case where the CMEs are launched into the fast flow 40° E, behind the CIR front. In the former, it can be seen that the CME fronts develop very large ΔV but also very small Δn , since those CMEs are accelerating “downhill” into the very tenuous material at the back of the preceding fast stream. In the latter, however, where the CMEs are overtaking the stream front compression, we see that the Δns become considerably larger even as the ΔVs are somewhat reduced, though still substantial.

The net of all this is that in the presence of a sufficiently strong CIR background, the 1 AU manifestation of any given CME can depend greatly upon where it is injected with respect to that particular CIR structure. The severity of the interaction also depends upon the input strength of the CME (as given by its speed and half angle) relative to the velocity-density contrast of the ambient structure. That is, for cases (not shown) where the amplitude of the CIR structure is reduced (by decreasing the velocity and/or density contrast in Figure 12), the 1 AU impact of any given CME will vary, such that the structure in the ambient at some point has little influence on the CME propagation.

5. Taylor Analysis

To complement the expositions of transit time versus parameter jump plots presented above, we develop a mathematics-based way of describing and assessing the results (as opposed to a graphical approach, e.g., as in *Taktakishvili et al.* [2010]). Since we are dealing with coarse-grid solutions that are inherently smooth and regular, it makes sense to adopt a Taylor expansion approach for the analysis of our numerical solutions. In this way, we can quantify systematically the relative contributions of the various input parameters individually and in concert, and we can distill the analysis of any given ensemble to one simple graphic.

Viewing the CME transit time as a function of the four input cone parameters leads naturally to the following second-order Taylor expansion for dT , the (signed) variation in the transit time to 1 AU directly attributable to changes in the inputs:

$$dT = \frac{\partial T}{\partial v} \delta v + \frac{\partial T}{\partial \omega} \delta \omega + \frac{\partial T}{\partial \lambda} \delta \lambda + \frac{\partial T}{\partial \phi} \delta \phi + 1/2 \left[\frac{\partial^2 T}{\partial v^2} \delta v^2 + \frac{\partial^2 T}{\partial \omega^2} \delta \omega^2 + \frac{\partial^2 T}{\partial \lambda^2} \delta \lambda^2 + \frac{\partial^2 T}{\partial \phi^2} \delta \phi^2 \right] + \left[\frac{\partial^2 T}{\partial v \partial \omega} \delta v \delta \omega + \frac{\partial^2 T}{\partial v \partial \lambda} \delta v \delta \lambda + \frac{\partial^2 T}{\partial v \partial \phi} \delta v \delta \phi \right] + \left[\frac{\partial^2 T}{\partial \omega \partial \lambda} \delta \omega \delta \lambda + \frac{\partial^2 T}{\partial \omega \partial \phi} \delta \omega \delta \phi + \frac{\partial^2 T}{\partial \lambda \partial \phi} \delta \lambda \delta \phi \right],$$

where all the derivatives like $\partial T / \partial v$ and $\partial^2 T / \partial v^2$ are evaluated from centered finite differences derived from the solutions for the various ensemble members (e.g., $v_0, v_0 \pm \Delta v$) and $\delta v, \delta \omega$, etc., are observational error estimates, as described in the next paragraph. From the associated finite difference expressions it can quickly be ascertained that only 21 of the full set of 81 runs are needed to second order (see Table 2 and caption),

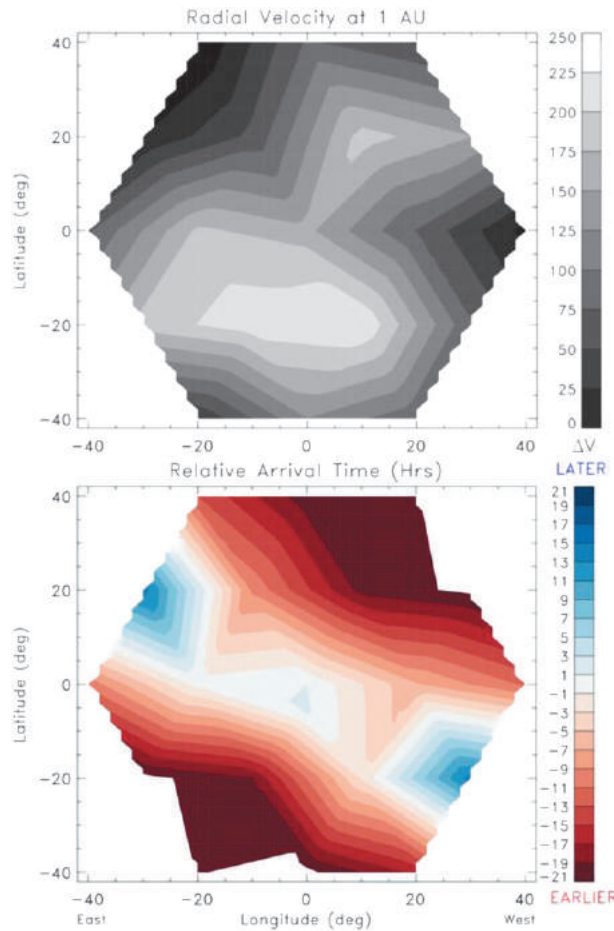


Figure 13. Latitude-longitude maps of (top) ΔV and (bottom) 1 AU arrival time for a $\{V_{CME} = 800 \text{ km/s}, \omega_{1/2} = 35^\circ\}$ CME launched into the ambient at the center of the red circle in Figure 12. The presence of the structured ambient profoundly affects the CME properties near Earth, as compared to the same CME launched into a uniform ambient (cf. Figure 6)—where as the CME encounters the CIR front it is slowed down considerably, while away from the front it propagates much faster.

representing a considerable reduction in simulation time. (Because of the coarse grid used in the simulations, little to nothing is lost in the reduced set.)

It is essential to understand that the derivatives in the above expression are evaluated from the model runs (based upon the given model spreads Δv , etc.), but the net dT requires accurate estimation of the error in the input cone parameters (δv , etc.). These errors come independently from observations and experience with the cone-fitting method used; for any given CME we also need to know how well we think we have estimated the velocity, the half width, and the direction. These depend upon many factors for CMEs, ranging from isolated weak disturbances to highly energetic full-halo events, where the disturbed background corona can make their estimation very difficult. Unavailability of NRT multiview spacecraft images or poor coronagraph configurations (such as at present, when the STEREO spacecraft lie nearly along the Sun-Earth line) also contribute to the error estimates.

Figure 17 depicts the results of the Taylor analysis at three different locations relative to CME centerline, for the simple ensemble of CMEs injected into a uniform hydrodynamic background (Figure 7). From the left in Figure 17, each set of colored symbols presents, in order, the (signed) magnitude of the transit time uncertainty stemming from the four first derivatives (symbolized as $\{v, \omega, \lambda, \phi\}$), then the four second derivatives $\{vv, \omega\omega, \lambda\lambda, \phi\phi\}$, and finally the six cross derivatives $\{v\omega, v\lambda, v\phi, \omega\lambda, \omega\phi, \lambda\phi\}$. These are computed from $(\partial T/\partial v) \delta v$, and so on, for each term in the Taylor expansion. In the figure, “Mdl ΔP ” is the ensemble parameter spread $\{\Delta v, \Delta\omega, \Delta\lambda, \Delta\phi\}$, and “Est δP ” is the estimated magnitude of the uncertainty in each parameter, not necessarily the same as the ensemble model spread. (Here we simply posit a reasonable guess at Est δP , as indicated in the figure, for purposes of exposition only.) Finally, “RMS₁” refers to the net root-mean-square error for the first-order terms only, since that is where the bulk of the uncertainties come from.

In Figure 17, green denotes the 14 Taylor components along the CME centerline (i.e., $\phi = 0^\circ$), brick red the components evaluated along $\phi = +20^\circ$ to the west, and purple along $\phi = +40^\circ$. (Evaluation to the east is essentially the same but with the ϕ component contributing negative dT .) Discussing first the Taylor components along the centerline of this ensemble of moderate-strength CMEs (green symbols), the largest contribution of uncertainty comes from the first-order velocity term, then the half width, and lastly the second-order velocity and half width (of opposite sign). All the other contributions are quite small. We conclude that for the range of parameters applying to this ensemble, the uncertainties in the CME velocity and half width dominate the accuracy of any forecast. Pointing is a much lesser issue, at least within the range of offsets considered. Taylor analysis for the same CMEs viewed from $+20^\circ$ (brick red) and $+40^\circ$ (purple) to the west (or, equivalently, for a CME offset by the same amount to the east), shows rapid increase in the ϕ and ω contributions. On the basis of Figure 8, this should come as little surprise, as the uncertainties

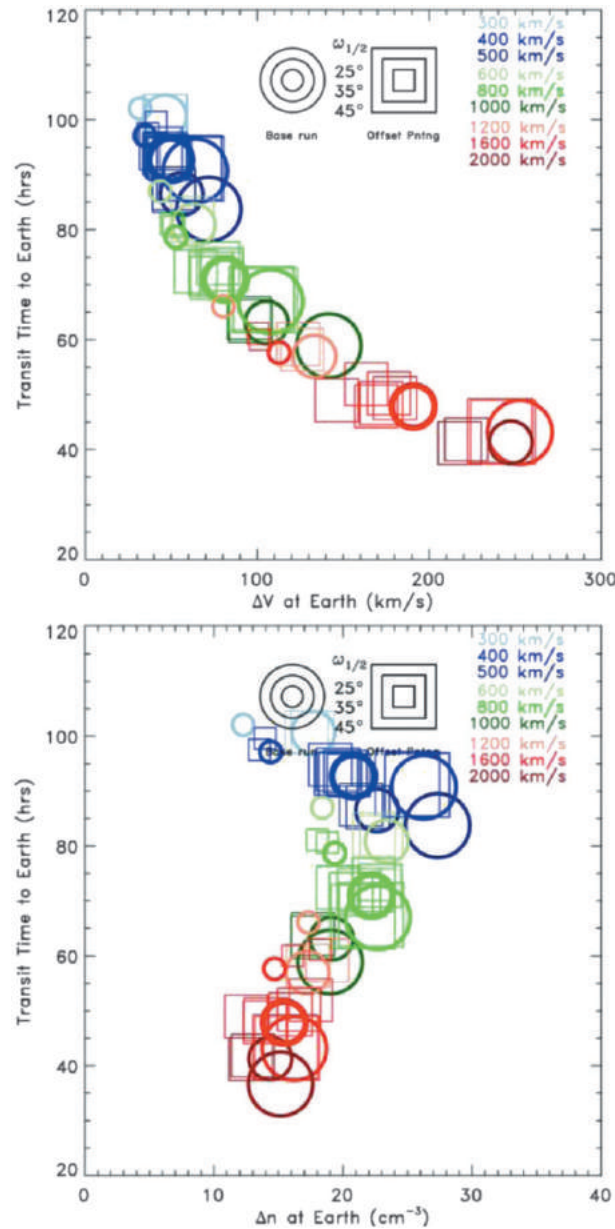


Figure 14. Scatterplots of arrival time at 1 AU versus (top) velocity jump and (bottom) density jump across the CME front for three 21-member ensembles launched into the middle (center of red circle) of the structured ambient of Figure 12. Compared with Figure 10 (the uniform ambient case), it is evident that the CMEs propagate a bit slower to 1 AU and the velocity jumps are reduced, all by virtue of interaction with the dense material at the core of the structured ambient front. The peak density jumps in the slower (blue) CMEs are somewhat increased, but those in the faster sets (green and red) reflect the onset of serious shock heating and are systematically reduced with increasing CME speed.

the CME speed. Physically, what is happening is that since the density in the slow ambient is roughly thrice that in the fast ambient, the ability of a CME to punch its way through the dense slow wind depends upon the input CME mass and momentum (V and $\omega_{1/2}$), whereas the lightweight background in the fast ambient poses much less of an obstacle, enabling the CME to barrel along relatively unimpeded by the solar wind ambient. It should also be noted that the RMS_1 uncertainties in transit time

increase dramatically for glancing blow CMEs seen farther off centerline. (Were these CMEs displaced from the Sun-Earth line in latitude, the Taylor λ component could likewise become significant.)

The results from such analyses can vary from ensemble to ensemble, with the magnitude and sign of the v and ω derivatives and those of λ and φ switching about, depending upon the specific conditions of the ambient stream structure. It is the overall picture of the variation in sensitivities that matters, as will now be developed.

Figure 18 (top) depicts the relative magnitude of the Taylor components (henceforth we evaluate only along the ensemble axis) for ensembles of slow (300–500 km/s; blue) CMEs, moderate-speed CMEs (600–1000 km/s; green, from Figure 17), and fast (1200–2000 km/s; red) CMEs propagating into a uniform 350 km/s background. We see in Figure 18 (top) a systematic progression from slow CMEs, where the input speed dominates the possible variation in transit times, to fast CMEs, where the CME half width becomes more important. In the former case, the interaction plays out gently over a longer propagation time, so the relative difference between CME and background speed tends to be preserved; in the latter, the interaction between CME and ambient is so strong and impulsive that the relative momentum, as set by the input half width, determines how fast the CME can punch through the background flow.

To assess in the same way the impact that differences in the ambient speed have upon these processes, we compare in Figure 18 (bottom) the Taylor component plots for moderate-speed CMEs (600–1000 km/s) propagating through slow (250 km/s; light blue), moderate (350 km/s; green), and fast (450 km/s; gold) uniform backgrounds. Here we find that in the slow ambient (light blue) the dominant inputs are the CME speed and width, yet for the fastest ambient (gold) it is mainly

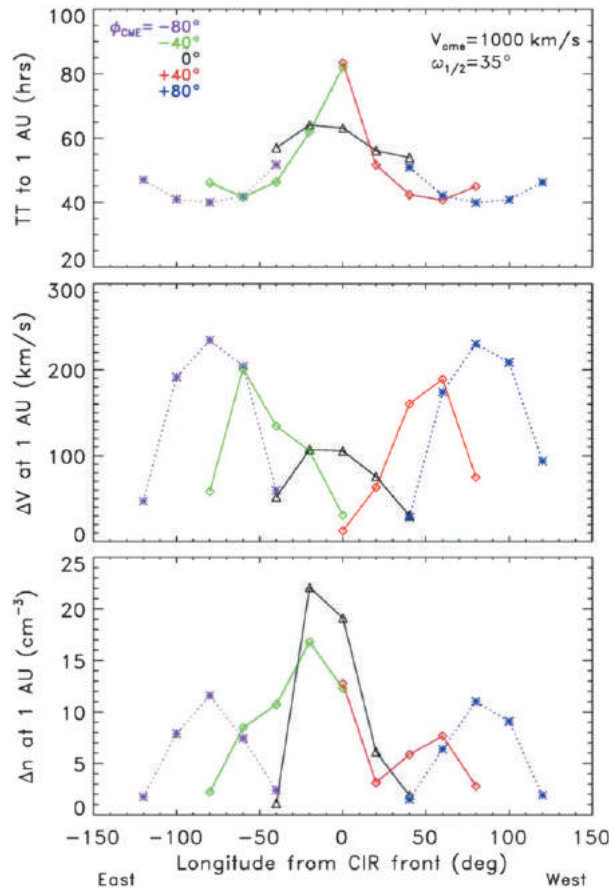


Figure 15. Illustration of the spatial variation of CME front properties spanning a variety of ambient structures. For each set of colored curves, the symbols mark (top) the transit time, (middle) the velocity jump, and (bottom) density jump in the equatorial plane at the indicated longitudes with respect to the CME front. For example, the black curves depict CME front properties for the $\{V_{CME} = 1000 \text{ km/s}, \omega_{1/2} = 35^\circ\}$ case where the CME is launched into the midst of the ambient CIR front. Although the transit times across the front do not vary too much, the velocity and density jumps do. For the same CME launched $\pm 80^\circ$ from the CIR front (purple; blue), where it propagates freely into more uniform ambient conditions, more regular, rounded variations are seen. The same CME launched at intermediate distances from the CIR (green; red) show much more distortion due to variations in the localized interactions.

attributable to variations in the assumed ambient speed are (at least over the range 250–450 km/s) not substantially different from those due to input speed and mass (Figure 18, top).

Taylor analysis for the tilted-dipole ambient configurations we have considered (section 4.2 and Figures 13–15) reveals that for modest offsets about a substantial stream front near the Sun (i.e., ensembles centered at the yellow locations), a high degree of order nevertheless persists in the distribution of the various Taylor components. The primary results are illustrated in Figure 19 (top), which compares the Taylor analysis for the ensemble of moderate-speed CMEs (top) centered at the heart of the red circle in Figure 12 to that of a fast ensemble (Figure 19, bottom) similarly centered (i.e., the moderate and fast ensembles depicted in Figure 14). Each plot presents Taylor components assessed at 1 AU along the equatorial plane at five different longitudes ($0^\circ, \pm 20^\circ, \text{ and } \pm 40^\circ$) with respect to CME center. (Here black symbols represent Taylor analysis taken along 0° , with Taylor analyses along offset directions being color coded as indicated in the RMS_1 insets.) For the moderate-speed CMEs (Figure 19, top), the five subplots exhibit considerable and varied scatter, with the first-order components clearly dominating. For the fast CMEs (Figure 19, bottom), even more scatter is evident, and the half width and east-west pointing components become more prominent. The net effect is that in the presence of strong ambient structure, error in all the CME inputs can have an effect, with the relative proportions depending upon the observing position.

Taylor analyses for CMEs offset much farther from the CIR front (not shown) exhibit similar behavior, though differing somewhat in detail. From this we conclude that the utility of Taylor analysis will in general depend nearly as much upon accurate knowledge of the ambient structure as upon that of the CME inputs. Careful study and analysis of historical data sets will hopefully provide telling guidance in this regard.

Finally, we note that Taylor component plots for ΔV and Δn may be generated the same way to quantify the uncertainties in parameter responses other than transit time, but that would be best addressed against historical data.

6. Summary

We have established a general basis and methodology for evaluating systematic relations among projected 1 AU CME properties across a broad range of near-Sun inputs used in an operational forecast model. In particular, we have (a) justified why the modeling of CMEs for forecast purposes may be approached in the

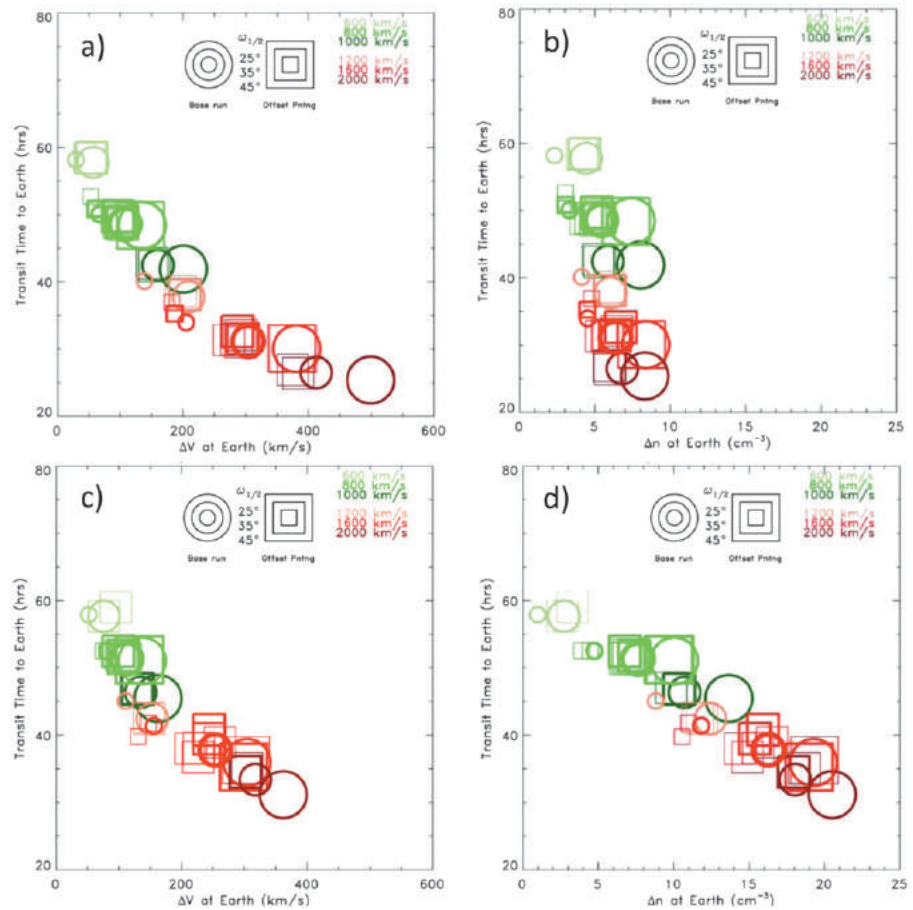


Figure 16. Medium (green) and fast (red) 21-member CME ensembles centered on the equatorial plane and (a and b) 40° to the west and (c and d) 40° to the east of the ambient CIR. Because the westward set can propagate out ahead of the CIR front into the back of the preceding fast stream, its velocity jumps are high while the density jumps are relatively low. The CMEs launched to the east, however, eventually encroach upon the rear of the CIR front, where they are slowed due to the pileup of material there.

coarse-grid HD limit; (b) included CMEs across a wide range of input parameters; (c) considered both uniform and structured background cases, in on-axis and off-axis regimes, over a range of presumed ambient flow speeds; (d) developed both graphical and analytic approaches for interpreting the results, for both research and operational applications; and (e) provided a mathematical basis for ensemble composition, including the specification of observational error estimates in the CME inputs.

Among the multitude of ensembles considered (including many not shown), we invariably found regular patterns in dT versus ΔV and dT versus Δn across a wide range of inputs for CMEs launched into various uniform and structured backgrounds. While monotonic behavior was the norm, a noted exception was the characteristic “bend” or limit in Δn as a function of dT (Figure 10), which we demonstrated was due to shock heating in the model and is definitely not clustering indicative chaotic behavior. These same trends persist in test runs where the spiral magnetic field was included (not shown), with only minor adjustments to Δn as the magnetic field compression in that case also contributes to the ΔP_{total} across the CME front.

We infer from all this that in practical terms the evolution of CME fronts to 1 AU appears to be a nonchaotic process, wherein the output is directly related to the input. That is, over even a large range of variations in inputs regular, repeatable, predictable variations in outputs accrue.

We find no indication of chaotic behavior (such as clustering of results), even when there is significant interaction with structured ambients. The main uncertainty in forecasting thus comes from uncertainty in inputs

Table 2. Specification of the Individual CME Runs Needed to Support Second-Order Taylor Analysis of the Ensemble Sensitivity to the Inputs^a

| Member # | | $v_0 + dv$ | v_0 | $v_0 - dv$ | $\omega_0 + d\omega$ | ω_0 | $\omega_0 - d\omega$ | $\lambda_0 + d\lambda$ | λ_0 | $\lambda_0 - d\lambda$ | $\phi_0 + d\phi$ | ϕ_0 | $\phi_0 - d\phi$ |
|----------|------------------------|------------|-------|------------|----------------------|------------|----------------------|------------------------|-------------|------------------------|------------------|----------|------------------|
| 1 | Base (and d2/dx2) | | x | | | x | | | x | | | x | |
| 2 | d/dv | x | | | | x | | | x | | | x | |
| 3 | | | | x | | x | | | x | | | x | |
| 4 | d/d ω | | x | | x | | | | x | | | x | |
| 5 | | | x | | | | x | | x | | | x | |
| 6 | d/d λ | | x | | | x | | x | | | | x | |
| 7 | | | x | | | x | | | | x | | x | |
| 8 | d/d ϕ | | x | | | x | | | x | | x | | |
| 9 | | | x | | | x | | | x | | | | x |
| 10 | d2/dvd ω | x | | | x | | | | x | | | x | |
| 11 | | | | x | | | x | | x | | | x | |
| 12 | d2/dvd λ | x | | | | x | | x | | | | x | |
| 13 | | | | x | | x | | | | x | | x | |
| 14 | d2/dvd ϕ | x | | | | x | | | x | | x | | |
| 15 | | | | x | | x | | | x | | | | x |
| 16 | d2/d $\omega d\lambda$ | | x | | x | | | x | | | | x | |
| 17 | | | x | | | | x | | | x | | x | |
| 18 | d2/d $\omega d\phi$ | | x | | x | | | | x | | x | | |
| 19 | | | x | | | | x | | x | | | | x |
| 20 | d2/d $\lambda d\phi$ | | x | | | x | | x | | | x | | |
| 21 | | | x | | | x | | | | x | | | x |

^aAlong with an ambient run, each ensemble member is a variant about a “base” CME run (subscript “0”). Only 21 CME runs are needed, since the second-order cross derivatives can be efficiently computed as $f_{x,y}(x,y) \approx \frac{f(x+h,y+k) - f(x+h,y) - f(x,y+k) + 2f(x,y) - f(x-h,y) - f(x,y-k) + f(x-h,y-k)}{2hk}$ where $\{x, y\}$ represent any two of the physical variables $\{v, \omega, \lambda, \phi\}$, and $\{h, k\}$ are the corresponding $\{\Delta x, \Delta y\}$. (From http://en.wikipedia.org/wiki/Finite_difference.)

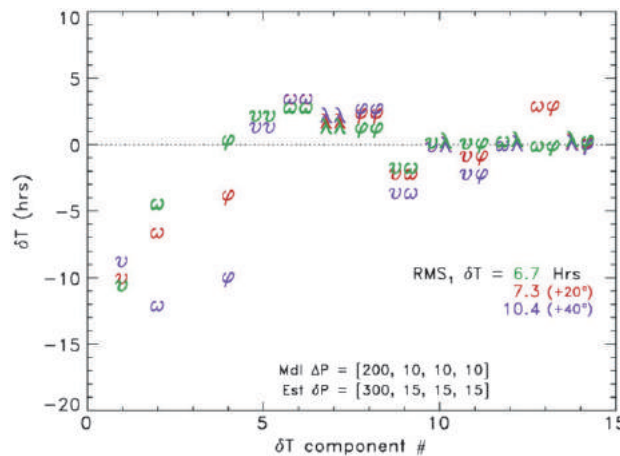


Figure 17. Taylor analysis diagram for a 21-member ensemble launched into a uniform, 350 km/s ambient (cf. Figure 7). From the left, each Greek letter corresponds to the value of the signed first derivative of each of the four parameters (v, ω, λ, ϕ), followed by their second and mixed second derivatives, as indicated by double symbols (e.g., vv , and $v\omega$). The green set of symbols represents the derivative values evaluated head-on to the CME; brick red and purple sets correspond to Taylor components evaluated 20° and 40° off axis, all in the equatorial plane. “RMS₁ δT ” values refer to the root-mean-square of the first-order terms for each set, as indicated by color. “Mdl ΔP ” is the corresponding model spread used in the ensemble (e.g., ± 200 km/s, $\pm 10^\circ$ for the angular parameters), and “Est δP ” is the estimate of the uncertainty in the input CME parameters (as supplied from empirical analysis of operational CME fits). In each case, net error in the velocity estimate remains about 10 h, while that in the half angle and east-west pointing becomes important off axis to the CME centerline (cf. Figure 8).

with respect to CME parameters and to the ambient state. On a physical basis, this outcome makes eminent sense, since we are dealing here with momentum-dominated flows in the hypersonic regime, wherein quite simple physics dominates the large-scale evolution with which we are concerned.

These findings constitute a basis for developing improvements in our forecasting abilities. Explicitly, the primary advances will come from better characterization of CME and ambient inputs, as opposed to better propagation models. They also suggest that some simplification in forecasting for very fast, high-mass CMEs may be possible, in that a lookup table approach may provide a viable forecast strategy, as for tsunamis. Such a strategy would be limited to the most energetic events, since the ambient should then not matter much—but these are the very cases that demand immediate, accurate forecasts. Given that the structured ambient considered in this study is near a worst case example, it must be left to the NRT experience to see if and when specific consideration of the ambient structure may be dispensed with and a

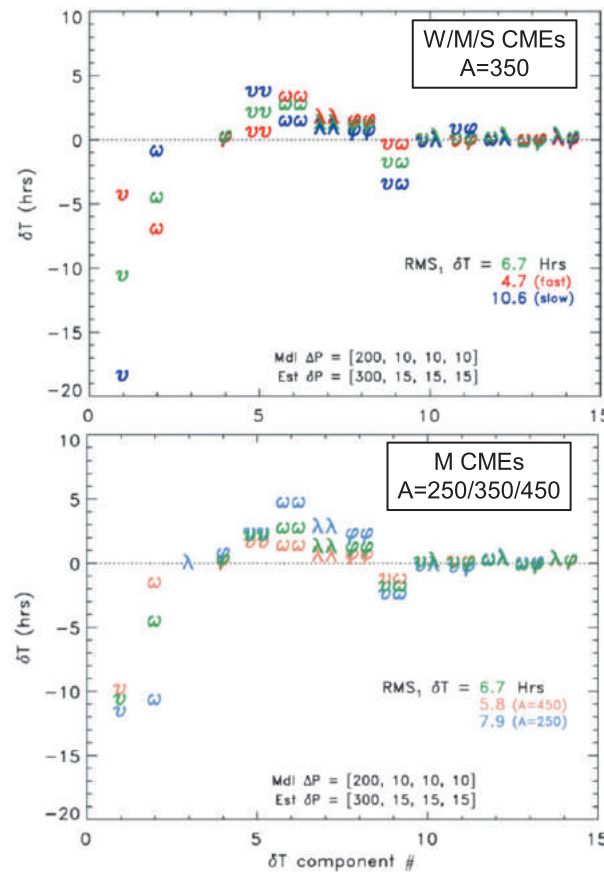


Figure 18. (top) A color-coded Taylor analysis diagram for weak (W, blue), moderate (M, green), and strong (S, red) CME 21-member ensembles launched into a uniform 350 km/s ambient. It can be seen that error in the CME velocity estimate dominates transit time error for slower CMEs. (bottom) Taylor analysis diagram for a moderate 21-member ensemble launched into uniform $A = \{250, 350, 450 \text{ km/s}\}$ ambients. Green corresponds to the on-axis 350 km/s ambient of Figures 10 and 11, while gold and light blue depict Taylor components for CMEs launched into 450 km/s and 250 km/s ambients, respectively. While the error in transit time attributable to error in the CME velocity estimate does not vary much (assuming the ambient speed is known accurately), uncertainty in angular size becomes as important for slow ambients.

representative uniform outflow may suffice. For the immediate future, it would be prudent to run coarse-grid ensembles routinely to derive the likely spread in outcome for any given CME.

To that end, one of the more important outcomes of this study is the development of reliable statistical means to evaluate the anticipated dT for any given ensemble. We introduced a Taylor expansion approach to enable the identification of the input parameter or parameters exerting the greatest leverage on the transit time forecast. Moreover, while the ensemble pointing spreads $\Delta\lambda$ and $\Delta\phi$ and the observational uncertainties δ employed here were for illustrative purposes only, we stressed that the formal error associated with each input parameter must be specified from observational experience. It can only be expected that these error estimates may vary widely. Where a CME has a well-defined shape and there are sufficient images from multiple well-situated spacecraft, we can expect the error to be minimal. For truly impulsive, fast events with a strong halo component, having only two views with spotty image availability, the error can expand substantially. These debilitations are a fact of life in NRT forecasting, so any feasible approach must incorporate allowance for error in inputs—adjustable on a case-by-case basis—accordingly. The uncertainties are further exacerbated by error in the specification of the ambient into which the CMEs are cast, as discussed in conjunction with Figures 11, 15, and 16.

As a final caveat to what we have presented, it must be borne in mind that the validity of the results applies strictly to single CMEs, and it remains to be seen whether these analyses can be extended to multiple, interacting CMEs. We would also expect the present results to hold—although with some quantitative adjustments—for CMEs with magnetic cloud as opposed to purely HD drivers, since the dynamics at the CME front should remain largely the same in the hypersonic solar wind.

7. Next Steps: Connection to the Real World

It has to be recognized that everything presented to this point is idealized, even if it is based quite rationally upon an operational model with some proven track record of success [e.g., Millward *et al.*, 2013]. Moreover, the strategies espoused above are based upon the assumption that the chaotic component of the real system must be small. Certainly, it is true that the most obvious signs of chaotic behavior are totally lacking in our modeling exercises, but compelling evidence of that proposal can only be had by direct comparison with the appropriate data. That is, Does convincing evidence for the fundamental trends and relationships described in our exposition actually exist in the observational record?

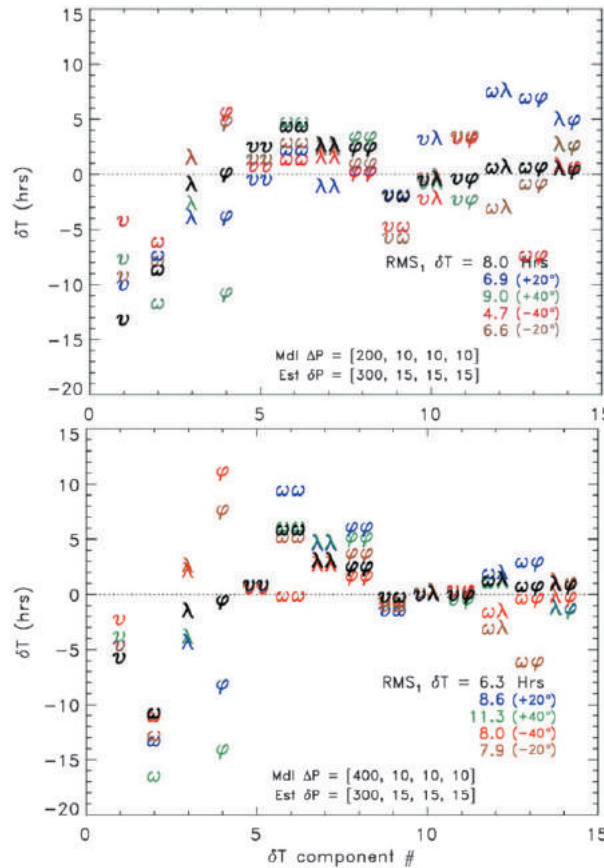


Figure 19. Taylor analysis diagrams for the (top) moderate-speed and (bottom) fast-speed 21-member ensembles of Figure 14, launched into the midst of the CIR front. The several colored symbol sets refer to Taylor analyses done at five different azimuths (0° , $\pm 20^\circ$, and $\pm 40^\circ$) along the equatorial plane, with black denoting that head-on to Earth (0° longitude). The fast-CME ensembles show more spread in the component distribution, and it is clear that CME size and pointing matter most for the faster CMEs. However, this figure is intended mainly to emphasize that in the presence of strong ambient structures the Taylor analysis implies that the overall forecast uncertainties become more complicated and increase in severity.

computational effort in producing NRT ensembles, but would anything useful be lost? And precisely what should guide how the model spreads Δv , etc., are specified in practice? For example, would $\Delta \lambda = \Delta \varphi = \omega_{1/2}$ make more sense than using some fixed value, as herein?

Finally, we speculate that adding two more parameters, α (related to the ambient speed) and μ (related to the CME mass) to the ensemble formalism may well prove more fruitful. Variations in the ambient speed would be assessed by adding two ensemble members having some spread $\Delta \alpha$ about the ambient value pertaining at the time the ensemble forecast is composed. Variations in the other parameter, μ (which can be adjusted via an Enlil internal parameter), would enable separating injected mass from geometric extent ω . The motivation is that the correlation between mass and angular width is only known on a statistical basis [e.g., Vourlidas *et al.*, 2010] and quite loosely at that. Also, we have at present no accurate way to gauge in NRT what the true mass may be for any given CME. While it appears CME mass and size may be in some sense related, we at least need to allow for separate contributions. Taylor analysis of ensembles covering the present first-order parameters require only nine members, and including both α and μ to first order would thus add only four more, for a total of 13 for an NRT run. Strategies such as this should be explored in the data-mining and NRT studies yet to come.

Fortunately, there is a body of data available that should go a long way toward answering this and other questions concerning the forecast strategies laid out in this paper. Namely, the SWPC record of official CME forecasts made in NRT since November 2011 can be mined to gauge the credibility of many of the assertions made in this work. Will, for example, a collection of real events exhibit the systematic behavior so prominent in the parameter jump versus transit time plots presented here? Even if that proves the case, can it be established that the plots and Taylor analysis developed here can in fact be used in real time to make forecasts more accurate, precise, and effective? Carefully drawn retrospective studies that may also include the full STEREO/LASCO CME record of CMEs not aimed toward Earth (i.e., not appearing in the SWPC record) should help pin down sources of error in this process and thus facilitate improvements in CME forecasting overall. It is only through comprehensive studies of real events that we can make sense of the sources of error and the overall credibility of this kind of forecast system.

Perusal of the Taylor component plots presented above raises a number of tactical questions. Given all the uncertainties and unknowns in this process, does it make any sense to include the cross derivatives in the analysis, and to what extent do even the second-order derivatives convey any actionable information? Does just the first-order set suffice, in the face of the observational unknowns? Limiting the analysis to only those terms would dramatically reduce the

Acknowledgments

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of the WSA-Enlil model would likely benefit from including better characterization of the CME configuration and mass.

Pizzo *et al.* [2015] presented the theoretical underpinnings for applying the WSA-Enlil modeling system to ensemble forecasting of CMEs in an operational environment. They investigated whether CME propagation is chaotic or nonchaotic. If the former, then propagation is dominated by a multitude of sources and sinks of energy and momentum. If the latter, then the propagation relates to a finite set of inputs, and small changes to the inputs will result in consistent departures in propagation. Evidence from the ensemble study points to nonchaotic propagation, which in turn, narrows the methodology and treatments in ensemble forecasting of CMEs.

Guerra *et al.* [2015] presented the results from a four-member ensemble prediction for major solar flares. They determined that ensemble flare prediction has the potential to outperform individual member prediction using a simple linear combination method. However, use of appropriate metrics in training and validating the ensemble method is required. They also report that as with terrestrial weather forecasting, the human factor is still valuable in making flare forecasts.

Pesnell [2016] used an ensemble of 105 Solar Cycle 24 predictions parsed into six classes of metadata/methods: climatology, recent climatology, precursor, dynamic model, spectral, and neural networks to review the progress on forecasts of the current solar cycle and to give insight into how solar cycle 25 forecasting could be improved for Cycle 25, which should begin sometime after the year 2020.

These published results along with ensemble studies from previous years that addressed the ionosphere, radiation belts, and solar radiative emissions illustrate the potential for even more rapid improvements in SW forecasting. Submission of additional ensemble forecasting papers and/or comparative diagnostic manuscripts similar to Jian *et al.* [2015] who diagnosed model strengths and weaknesses under varying combinations of solar wind drivers and Rastaetter *et al.* [2016] who compared the capabilities of multiple models to reproduce energy input to the thermosphere are strongly encouraged.

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