AFRL-AFOSR-VA-TR-2019-0059

Ensemble Modeling and Data Assimilation within the Enlil Solar Wind Model

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03/14/2019
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTB1

Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
14-03-2019

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
01 Sep 2014 to 31 Aug 2018

4. TITLE AND SUBTITLE
Ensemble Modeling and Data Assimilation within the Enlil Solar Wind Model

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-14-1-0262

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Curt De Koning

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
REGENTS OF THE UNIVERSITY OF COLORADO
3100 MARINE ST 572 UCB
BOULDER, CO 80309-0001 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2019-0059

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Within the terrestrial weather community, ensembles are used regularly to forecast storms. However, for numerical space weather forecasting, which is several decades behind terrestrial weather modeling, the use of ensembles is still in its infancy. This AFOSR grant investigated how ensembles can be used with the Wang-Sheely-Arge Enlil model - the official numerical model used by the NOAA Space Weather Prediction Center - to improve forecast of coronal mass ejection (CME) arrival time at Earth. This grant resulted in several projects that relate to the originally proposed research: An investigation of the theoretical basis for ensemble forecasting of space weather; analysis of the 2012 July 23 energetic CME and the 2010 April 4 magnetic ejecta; and quantitative analysis of the uncertainty or spread in CME parameters that should be used to initiate a space weather ensemble. The grant resulted in two publications in refereed journals, three oral presentations at national or international meetings, and four poster presentations. The grant supported the research of three people - Dr. Cash, Dr. de Koning, and Ms. Devnani (a recent Computer

15. SUBJECT TERMS
Sun, CME

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			MOSES, JULIE
Unclassified	Unclassified	Unclassified	UU		19b. TELEPHONE NUMBER *(Include area code)* 703-696-9586

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Ensemble Modeling and Data Assimilation Within the Enlil Solar Wind Model

Original PI: Michele D. Cash, 2014–2016
NOAA/SWPC; formerly *University of Colorado at Boulder/CIRES*
Acting PI: Curt A. de Koning, 2016–2018
University of Colorado at Boulder/CIRES

Final Report

(2014/09/01–2018/08/31)
Award number *FA9550-14-1-0262*

Introduction

Within the terrestrial weather community, ensembles are used regularly to forecast storms. An example that most of us are familiar with is use of ensembles in the forecast of hurricane trajectories. However, for numerical space weather forecasting, which is several decades behind terrestrial weather modeling, the use of ensembles is still in its infancy. This AFOSR grant investigated how ensembles can be used with the Wang-Sheely-Arge (WSA) Enlil model – the official space weather model used by the SWPC – to improve forecast of coronal mass ejection (CME) arrival time at Earth.

Originally, this AFOSR Young Investigator Program (YIP) grant was awarded to Michele D Cash as a three year research project. In 2016, Michele Cash left the University of Colorado and transferred to a civil servant position within NOAA/SWPC. Consequently, Co-I, Curt A de Koning, became the Acting PI. The change in PIs led to a slow-down of research, which led the Acting PI to request a one-year No Cost Extension so that the originally proposed research could be satisfactorily completed. The No Cost Extension was awarded; therefore the project ended in 2018 instead of 2017.

This grant resulted in several individual projects that were well-connected to the research that was originally proposed. These projects will be described below.

Major Projects

Theoretical Basis for Ensemble Forecasting of Space Weather

This project investigated how variations in hypothetical CME inputs, such as speed, width, and direction of propagation, influence its arrival time at Earth. This project also considered how background solar wind conditions influence CME arrival time at Earth. This research resulted in a refereed paper, "Theoretical Basis for Operational Ensemble Forecasting of Coronal Mass Ejections," in the journal *Space Weather*.

Among the multitude of ensembles considered, we found regular patterns in CME's Sun to Earth transit time, dT, versus a wide range of CME inputs. Figure 1 shows color-coded scatterplots of dT versus CME inputs for three 21-member ensembles covering CME speeds between 300–2000 km/s injected into a 350 km/s ambient solar wind.

From this comprehensive investigation, we infer that the evolution of CMEs to 1 AU appears to be a non-chaotic process wherein the output is directly related to the input. That is, given a large range of variations in inputs, regular, repeatable, predictable variations in outputs occur. 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 with respect to CME parameters and to the ambient state. This outcome makes physical sense, because we are dealing with momentum-dominated flows in the hypersonic regime, where quite simple physics dominates the large scale evolution with which we are concerned.

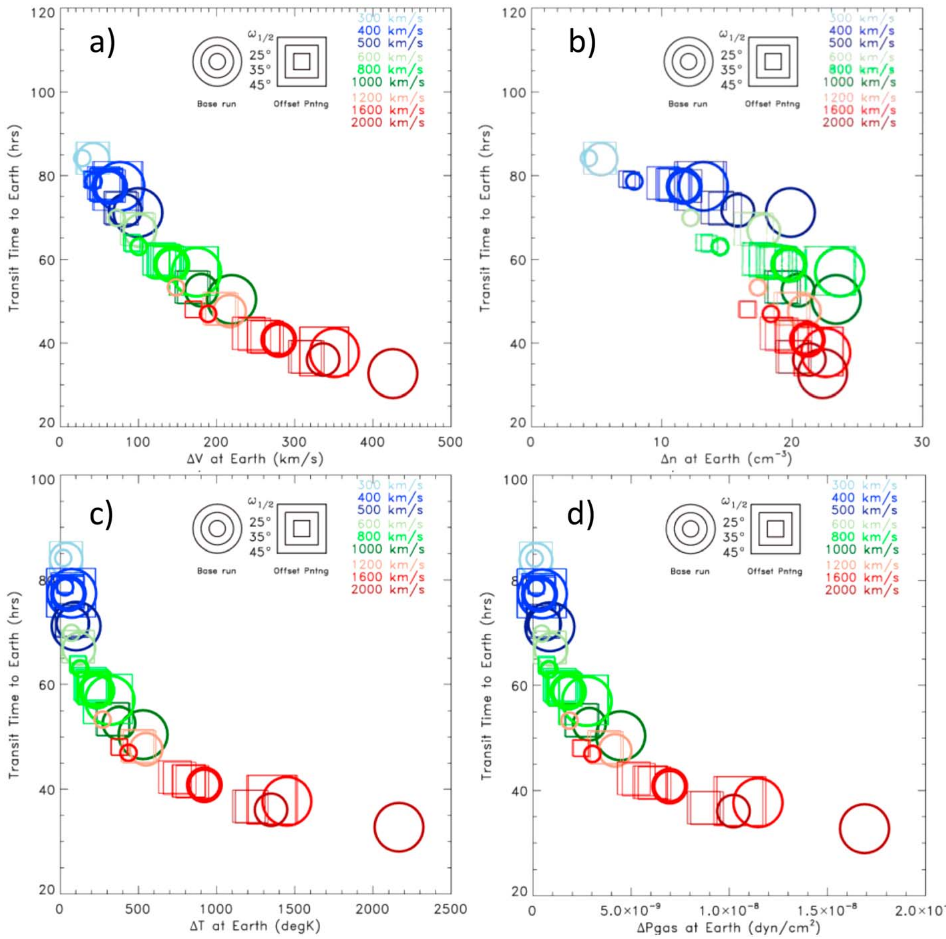

Figure 1: Scatterplots of arrival time at 1 AU versus in-situ observations of (a) velocity jump, (b) density jump, (c) single-fluid temperature jump, and (d) gas pressure jump across the CME front for a 21-member ensemble launched into a uniform HD ambient with a moderate 350 km/s flow speed. Moderate-speed CME data are in green, while blue signifies a slower ensemble and red a faster ensemble, as indicated at upper right. The round symbols indicate ensemble members aimed directly at Earth, and the squares indicate CMEs launched off the Sun-Earth line in varying combinations of 10° offsets. The size of the circles and squares corresponds to the CME half-widths indicated. The plots show a well-ordered systematic variation from the weakest to strongest CMEs in the ensemble, which is not indicative of the kind of clustering anticipated in a chaotic system. This is Figure 10 in Pizzo et al. [2015].

Analysis of the Very Energetic 2012 July 23 CME

On 2012 July 23 an extremely large and fast CME was detected in-situ by the Solar TErrestrial RElations Observatory (STEREO)-A. This CME was unusual due to its Sun-to-1 AU transit time of less than 21 hr and its exceptionally high impact speed of 2246 km/s. If this CME had been Earth-directed, it would have produced a significant geomagnetic storm with potentially serious consequences. Using WSA-Enlil, we investigated the sensitivity of this event to variations in the initial CME speed, angular width, and direction, as well as to variations in the ambient solar wind background. This research resulted in a refereed paper, "Ensemble Modeling of the 23 July 2012 Coronal Mass Ejection," in the journal *Space Weather*.

We found that the ambient solar wind background can significantly influence the CME arrival time. Without using an ambient solar wind background that is representative of the observed conditions, we were unable to accurately predict the CME arrival time when using realistic, data-driven CME parameters. Unfortunately, correcting the solar wind background speed in near-real-time is difficult to do since we do not definitively know the ambient solar wind background until the event reaches a solar wind monitoring satellite such as ACE or DSCOVR. In addition to correcting the Enlil ambient solar wind in near-real-time, we also found that including the mass as a CME input is critical for accurately modeling large events such as the 2012 July 23 event.

Simulated Ensemble Forecast of the 2012 July 23 CME

The previous section, *Analysis of the Very Energetic 2012 July 23 CME*, described research into the sensitivity of the 2012 July 23 CME to variations in the CME speed, angular width, direction, and mass, as well as to variations in the ambient solar wind background. However, the published paper does not clearly demonstrate the application of forecasting the CME arrival time at 1 AU from an ensemble of realistic, data-driven input parameters.

Figure 2 shows two separate ensembles of five members each. The top panel shows how the CME arrival time at 1 AU depends on standard CME parameters – speed, width, and direction of propagation – whereas the bottom panel shows how the CME arrival time at 1 AU depends on CME mass, speed, width, and direction of propagation. In both cases, the final forecast of CME arrival time at Earth is obtained by taking a simple average over all the ensemble members; this value is indicated by the solid orange line. Not surprisingly, the arrival time obtained by averaging is worse than some of the individual forecasts. Since we do not know the ground truth beforehand in near-real-time, such an averaging technique is the best we can do. One question for future research that has not been fully considered in this small project relates to the best measure to use for the central location of the ensemble – mean, median, or some other robust measure such as non-parametric Hodges-Lehmann Estimator?

A benefit of using ensembles to forecast CME arrival time at 1 AU is that the spread in the ensemble – either the standard deviation or the median absolute deviation about the median (MADAM) – can be used to estimate the uncertainty in the forecast; the spread in the ensemble forecast is indicated by the pink region in Figure 2. Currently, in a single run forecast, SWPC does not include a quantitative measure of uncertainty, such as is included in terrestrial weather forecasts. A measure of uncertainty is important since it gives an indication of how reliable the forecast is.

Results of this research were presented in a talk titled, "Ensembles, CME Mass, and Space Weather Forecasting" at an AFOSR sponsored meeting in 2017.

Analysis and Simulated Ensemble Forecast of the 2010 April 3 Magnetic Ejecta

One of the previous sections, *Analysis of the Very Energetic 2012 July 23 CME*, described analysis of the 2012 July 23 event. This event was analyzed by assuming that the CME could be described as an hydrodynamic blob, that is, an entity without any magnetic attributes. In reality, one of the most important attributes of a CME is its internal magnetic field. Using results from an other AFOSR funded project, we were able to estimate some of the magnetic properties of an event that occurred on 2010 April 3. Combined with the usual kinematic analysis of the CME we can define

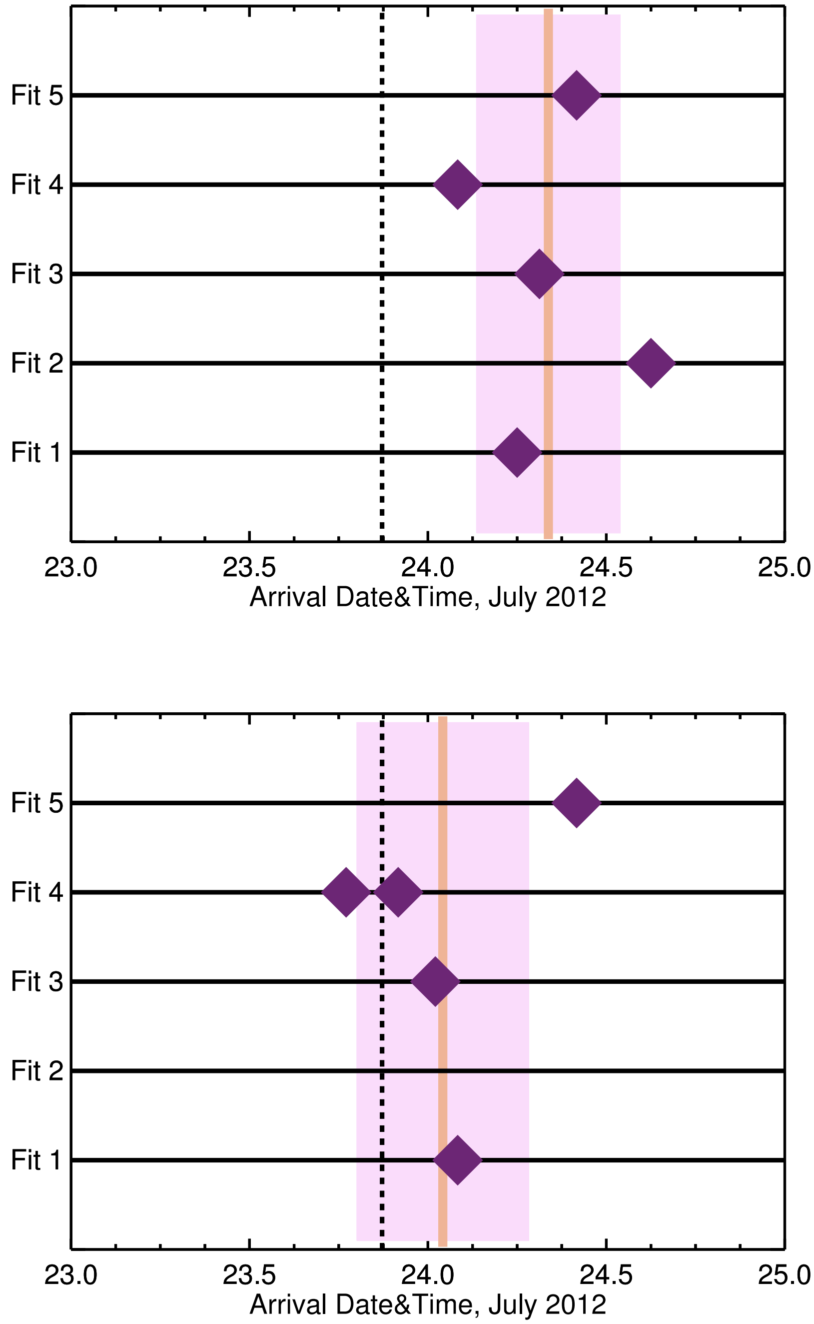

Figure 2: The top panel shows how the CME arrival time at 1 AU depends on basic CME parameters, such as speed, width, and direction of propagation, in a five-run ensemble. The bottom panel shows how the CME arrival time at 1 AU varies in a five-run ensemble that includes variation in CME mass, as well as the basic parameters listed previously. In both panels, the ensemble average is indicated by the solid orange line, the uncertainty in the arrival time is indicated by the pink region, and the observed arrival time is indicated by the dashed black line. Comparing the two figures, it is clear that including CME mass in the ensemble greatly improves the forecast.

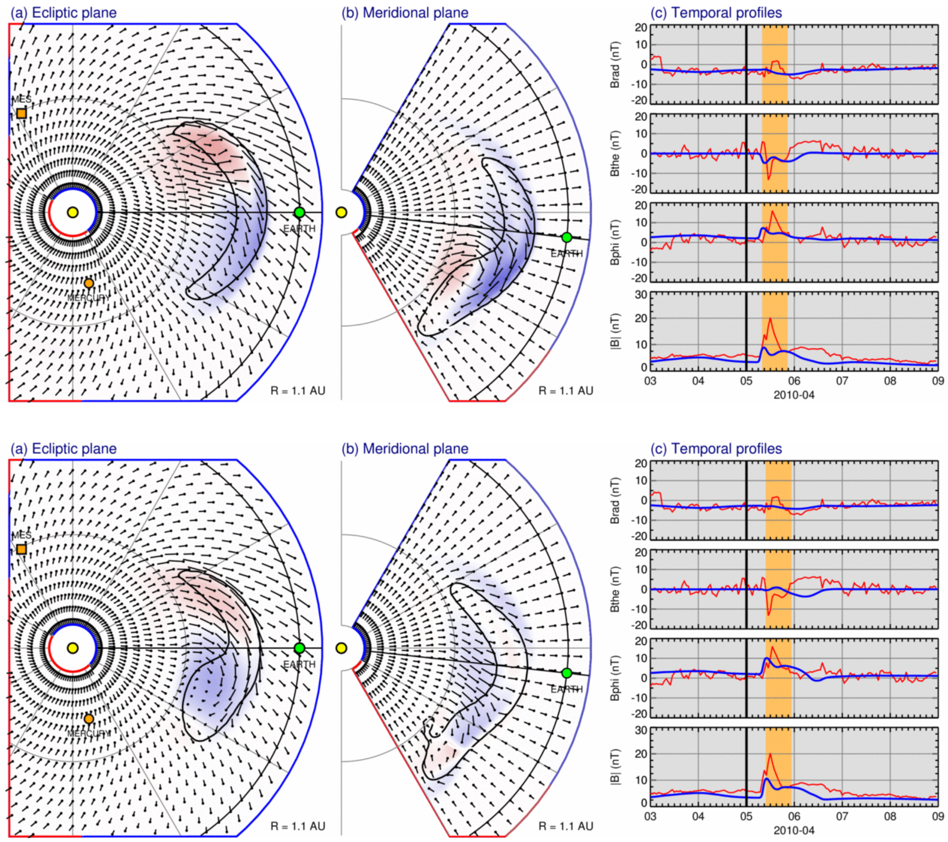

Figure 3: Output of two runs with WSA-Enlil that were initiated using magnetic ejecta with right-handed morphological chirality. The top panel assumed that the tilt of the magnetic flux rope was 10° relative to the horizontal, whereas the bottom panel assumed that the tilt of the magnetic flux rope was 10° relative to the vertical. In spite of the difference in magnetic tilts, both runs have very similar magnetic profiles at 1 AU, suggesting that the tilt has minimal influence on the ensemble output.

the following properties of this CME: its speed; longitude and latitude of propagation; longitudinal and latitudinal width – allowing for an elliptical cross-section; mass; magnetic flux rope tilt; and morphological chirality of the magnetic flux rope.

Most ensemble studies only consider variation in four CME parameters – speed; longitude and latitude of propagation; and a single width, assuming a circular cross-section – instead of the eight parameters listed above. Although forecasting CME magnetic properties at 1 AU is still many years away, due to a lack of reliable observations of the CME magnetic configuration at the Sun, it is clear that a full ensemble forecast which considers variation in kinematic and magnetic inputs will be more complicated than the studies we have described thus far.

In our initial study of this event, we focused on a limited ensemble that varied the CME magnetic properties only. We ran a four member ensemble with WSA-Enlil that included a magnetic flux rope with left- and right-handed chirality, each at two different flux rope tilts. Output from two of the ensemble runs are shown in Figure 3. This may be the first ensemble study involving CME magnetic parameters. Once again, as in the previous section, *Simulated Ensemble Forecast of the 2012 July 23 CME*, an important question that needs to be answered relates to the best technique to obtain an 'ensemble average' of the temporal evolution of CME magnetic profile at 1 AU.

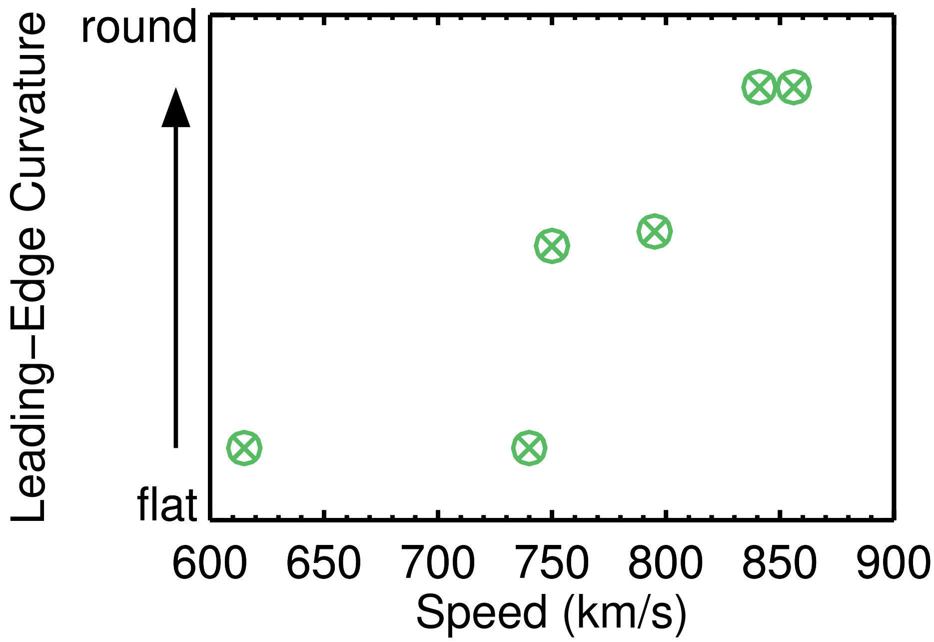

Figure 4: Quantitative analysis of CME error reveals how unchallenged assumptions about CME shape impact the estimation of error in the CME speed.

Results of this research were presented in a talk at the *Solar Wind 15* meeting in Brussels, Belgium, in June 2018. A paper based on this research will be written up for a refereed journal.

Estimating Errors in Ensemble Inputs

In the first section, *Theoretical Basis for Ensemble Forecasting of Space Weather*, it was pointed out that the main uncertainty in an ensemble forecast comes from uncertainty in inputs with respect to CME parameters and the ambient solar wind. The theoretical investigation described in that section used errors in the inputs that were based on many years of researcher experience. However, given how input errors contribute directly to forecast uncertainty, it is important to quantitatively measure the input errors, lest we under-estimate the input errors – resulting in an apparently reliable forecast that isn't justified – or we over-estimate the input errors – resulting in an unnecessarily unreliable forecast.

The CME parameters that are used to initiate an ensemble forecast are derived from white-light coronagraph images of a CME. Typically, one reconstruction technique only is used to estimate CME parameters from image data. In this project, we used a multi-method reconstruction technique, involving geometric localization, stereoscopic mass equivalence, and a three-spacecraft fitting technique that is based on the SWPC CME Analysis Tool used in the forecast center. These methods were used on various pairs of spacecraft images, and compared against a maximal three-spacecraft reconstruction.

One aspect of CME reconstruction that has not been fully appreciated is how assumptions about CME shape can impact the estimation of CME speed. Using a modified version of the SWPC CME Analysis Tool, we can vary the leading-edge curvature of the assumed CME shape. As shown in Figure 4, as the shape becomes more rounded, the CME speed that is derived from the coronagraph image analysis becomes faster. If we assumed a fixed shape for the CME we might assume an error in the speed of ± 25 km/s (as in the pair with the medium leading-edge curvature). However, this is a gross under-estimate of the true uncertainty. Since we do not know what the true shape of the CME is, we also need to take into consideration our epistemic uncertainty; for this particular event, this results in an uncertainty in the speed of about ± 125 km/s. In other words, quantitative analysis can uncover blind spots in what we think we know.

Results of this research were presented in a talk at *European Space Weather Week* meeting in Leuven, Belgium, in November 2018. Although the presentation falls outside the official time-frame of this grant, the research described here was conducted as part of this AFOSR grant.

Development of an Internal Research-and-Analysis Database at SWPC

In order to maintain the focus of this YIP grant, that is work accomplished by a *young* researcher, we hired Varsha Devnani, who was a recent computer science graduate, to lead the development of a SWPC database that would consistently record and track WSA-Enlil CME forecasts and make the relevant information available internally to SWPC researchers. The existence of this database has made it easier to carry out retrospective studies of historic CMEs that have been forecast by SWPC.

Ms. Devnani worked closely with the SWPC IT staff to create a new, research-and-analysis database that is linked directly to the official NCEI database. Such a direct linking results in an automatic update of the research-and-analysis database when new CMEs are forecast. This database provides a raw record of official CME runs, including the basic CME parameters, a coronagraph image of the CME, and an indicator of which run was held as the official run. Since the official NCEI database contains no records on what was actually observed at Earth, Ms. Devnani also linked the new research-and-analysis database to a database containing ACE/DSCOVR in-situ observations. Before her departure from SWPC, Ms. Devnani left the research staff with sample queries that demonstrate how to retrieve records from the new database. Through her work, the SWPC research staff now have an easily accessible database that will put some rigor into our assessment of the current state-of-the-art in CME forecasting.

Invitational Travel Offered to a Young Researcher

In addition to hiring Ms. Devnani (described above in *Development of an Internal Research-and-Analysis Database at SWPC*), we also invited another young researcher, Dr. Luke Barnard, to travel to SWPC and work with the PI for three months on a project related to the use of ensembles in space weather forecasting. As with Ms. Devnani's hire, the purpose of his visit was to maintain the focus of this YIP grant, that is research accomplished by a *young* researcher. The official letter of invitation, reproduced in Figure 5, states the purpose of the visit and makes it clear that this was an all-expenses paid trip. Although Dr. Barnard was eager to travel to SWPC and work on an ensemble project, unfortunately, he had to cancel his planned visit at the last minute for personal reasons.

University of Colorado
Boulder

January 29, 2018

Dr. Luke A. Barnard
University of Reading
Department of Meteorology
Earley Gate
PO Box 243 Reading
RG6 6BB
United Kingdom

Dear, Luke,

I would like to officially offer you a short-term Visiting Scientist position through the Cooperative Institute for Research in Environmental Science (CIRES) of the University of Colorado at Boulder. Your research station would be at the Space Weather Prediction Center (SWPC), part of the National Weather Service, in Boulder, CO.

While you are at SWPC, you would collaborate with myself and other CIRES scientists, as well as Federal scientists, on mutually agreeable projects related to the use of ensembles in space weather forecasting. Such ensembles could be used to explore parameter space – for example, how does CME mass impact CME transit time – or the ensembles could be used with STEREO/HI imagery for data assimilation studies.

As discussed previously, your starting date would be probably occur sometime during the week of 26 March–2 April 2018, although that is subject to change to best suit our schedules. (Are you going to the EGU?) The duration of your term as a Visiting Scientist would be about 90 days.

I am able to offer you return air fare from the UK to Denver, money for meals and incidental expenses ($59/day is the government per diem for Boulder), and paid housing.

I hope we can work together, both here and in Reading, in the future. I look forward to hearing from you soon.

Best Regards,

Curt Andrew de Koning

Curt

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Figure 5: Letter of invitation sent to Dr. Luke Barnard, a young researcher in space physics at the University of Reading.

Conclusion

As mentioned in the introduction, a change in PI was requested on this grant. The request was made on 2016 July 11, officially approved by AFOSR on 2016 September 19, but not visible in the University of Colorado grants system until 2016 December 16 – due to miscommunication between the University and the Department of Energy. As a result, work performed on this grant can be divided into two distinct periods. In the first approximately year and a half of the grant, Dr. Cash, the original PI, initiated the first two projects described above:

1. *Theoretical Basis for Ensemble Forecasting of Space Weather*;
2. *Analysis of the Very Energetic 2012 July 23 CME*.

During the final year and a half of the grant, including the No Cost Extension year, the acting PI, Dr. de Koning,worked on four projects:

1. *Development of an Internal Research-and-Analysis Database at SWPC*;
2. *Simulated Ensemble Forecast of the 2012 July 23 CME*;
3. *Analysis and Simulated Ensemble Forecast of the 2010 April 3 Magnetic Ejecta*;
4. *Estimating Errors in Ensemble Inputs*.

We conclude by highlighting three research lessons-learned. The most important lesson we learned is that space weather systems in the heliosphere are not chaotic; therefore, CME ensemble forecasting calls for different tactics than employed for terrestrial weather or hurricane forecasting. Second, because uncertainty in the ensemble forecast relates directly to uncertainty in the ensemble inputs, it is important to quantitatively measure the input errors, accounting for both the commonly used random error, as well as epistemic uncertainty. Finally, a realistic, data-driven space weather forecast needs a full set of realistic CME parameters, including CME mass.

Publications

1. Cash, M. D., D. A. Biesecker, V. J. Pizzo, C. A. de Koning, G. Millward, C. N. Arge, C. J. Henney, and D. Odstrcil. Ensemble Modeling of the 23 July 2012 Coronal Mass Ejection. *Space Weather* 13:611–625, 2015. doi:10.1002/2015SW001232.

2. Pizzo, V. J., C. A de Koning, M. D. Cash, G. Millward, D. A. Biesecker, L. Puga, M. Codrescu, and D. Odstrcil. Theoretical Basis for Operational Ensemble Forecasting of Coronal Mass Ejections. *Space Weather*, 13:676–697, 2015. doi:10.1002/2015SW001221.

Presentations

Oral

1. C. A. de Koning. Ensembles, CME Mass, and Space Weather Forecasting. At *AFOSR CME Team Meeting*, Arlington, VA, Aug 2017.

2. C. A. de Koning, D. Odstrcil, and C. E. DeForest. Using Polarized White-Light Triplets Measured by STEREO to Constrain CME Propagation in the Solar Wind. At *Solar Wind 15*, Brussels, Belgium, Jun 2018.

3. C. A. de Koning. What Does “Realistic, Data-Driven Simulation of CMEs” Mean?. At *Fifteenth European Space Weather Week*, Leuven, Belgium, Nov 2018.

Poster

1. M. D. Cash, V. J. Pizzo, C. A. de Koning, D. A. Biesecker, and D. Odstrcil. Ensemble Modeling within the WSA-Enlil Solar Wind Model. At *Fall AGU Meeting*, San Francisco, CA, Dec 2015.

2. M. D. Cash, V. J. Pizzo, C. A. de Koning, D. A. Biesecker, and D. Odstrcil. Ensemble Study of Real CMEs Using the WSA-Enlil Solar Wind Model. At *Fall AGU Meeting*, San Francisco, CA, Dec 2016.

3. C. A. de Koning and M. D. Cash Ensembles, CME Mass, and Space Weather Forecasting. At *Space Weather Workshop*, Broomfield, CO, Apr 2018.

4. C. A. de Koning, D. Odstrcil, and C. E. DeForest. Using Polarized White-Light Triplets Measured by STEREO to Isolate Internal Structure. At *SHINE*, Cocoa Beach, FL, Jul 2018.

Personnel Supported

- Michele D Cash – Original PI
- Curt A de Koning – Acting PI
- Varsha Devnani – Recently graduated Computer Science student

Program Managers

Original program managers:

- Dr. Kent Miller, AFOSR/RTB;
- Dr. John Luginsland, AFOSR/RTB.

Current program managers:

- Dr. Julie Moses, AFOSR/RTB;
- Dr. John Luginsland, AFOSR/RTB.