Natural Hazards and Decision Science: An Interdisciplinary Insight for Critical Infrastructure Protection in Space Weather Events

*Amaury Carruzzo, Ph.D.**
Department of Atmosphere & Oceanic Sciences
McGill University
Email: amaury.carruzzo@mail.mcgill.ca

*John Gyakum, Prof.**
Department of Atmosphere & Oceanic Sciences
McGill University
Email: john.gyakum@mail.mcgill.ca

Abstract
Natural hazards impacts are particularly important for Critical Infrastructure (CI) protection. In this instance, like other natural hazards, geomagnetic storm events can occur at any time, and a single space weather episode may produce multiple effects. Facing them demands CI stakeholders to take early decisions that involve trade-offs among impacts, probability and lead-time of a natural hazard forecast. Nevertheless, an interdisciplinary research could provide an innovative approach for customizing the decision aid process to CI managers dealing with those natural events. This paper offers some insights that could bring a new paradigm in natural hazard-related decisions for CI protection, applying up-to-date techniques from space weather science and cutting-edge methods from decision analysis.

I. INTRODUCTION

It has been known throughout human history that different types of natural hazards can affect life on Earth. The potential impacts of natural hazards (e.g., floods, heatwaves, tornados or geomagnetic storms) are particularly important for Critical Infrastructure (CI) protection; such as water systems, energy power facilities, satellite communications, transportation systems, and so on (Gaetano et al., 2013; Quigley et al., 2017). As a part of the decision-making process for disaster risk reduction, it is fundamental to find a set of mitigation actions for the CI protection in a given natural hazard event (Wachinger et al., 2013).

However, mitigation selection under natural hazard uncertainty can be a challenging procedure to the design of a new suite of environmental services, as interdisciplinary research (Wong-Parodi and Small, 2019). According to Hardy (2019), interdisciplinary research "*implies integration that combines separate perspectives through the development of connections between them.*" Furthermore, the development of such a study requires input from teams of natural scientists, engineers, social and behavioral researchers to understand how different stakeholders use natural hazard information (observation and forecast) to decide. For example, the ability for CI managers to engage mitigation plans based on early warning systems to avoid both damages to facilities and potential loss of human life following a CI disturbance (Oughton et al., 2019).

To improve the quality of natural hazard management and risk analysis, a customized decision aid model could provide information about impacts, uncertainties, the set of mitigation alternatives, and their associated benefits based on personal preferences (Caruzzo et al., 2018). In the context of a space weather hazard, according to Fiori et al. (2015), and Ngwira and Pulkkinen (2016), a physicist might provide content expertise about solar activity and potential extreme events (Figure 1), such as Solar Flares (explosions of large quantities of energy and radiation) or Coronal Mass Ejections – CMEs (ejections of plasma).

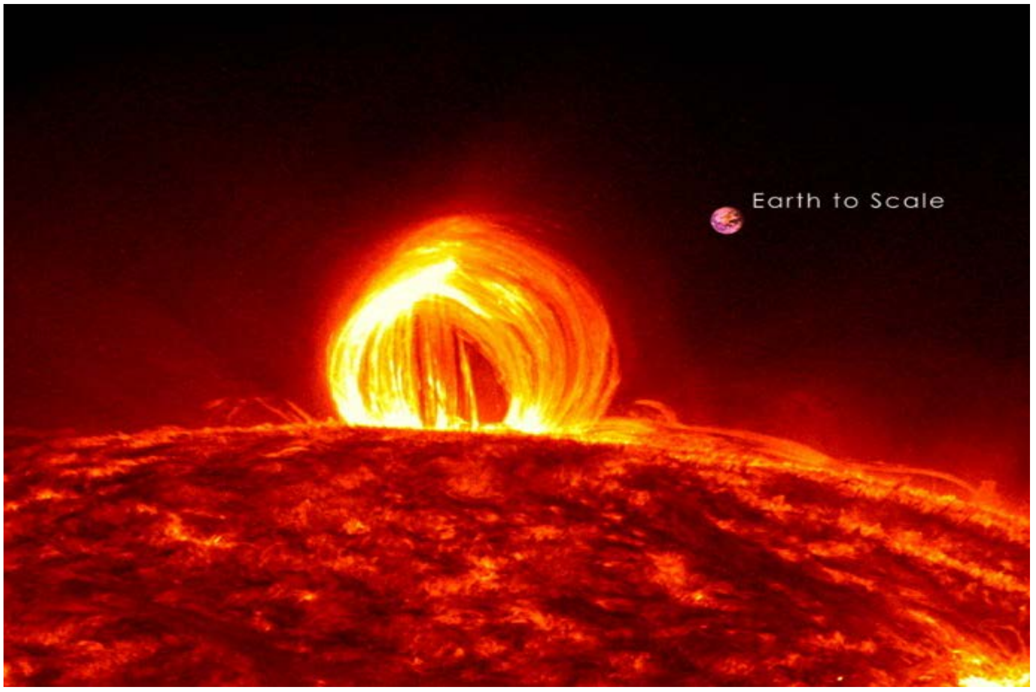

Figure 1: Arcs of plasma on the Sun's surface captured by a high-definition telescope aboard NASA's Solar Dynamics Observatory (Source: courtesy of NASA/GSFC/SDO)

The Sun, our nearest star, is the primary source of space weather. The Northern or Southern Lights (or Auroras, Figure 2) are caused by space weather events (Boteler, 2018). The Auroras are considered to be spectacular examples of space weather, but extreme events could be devastating for our modern technological society because they could directly affect several infrastructure/facilities, such as the power grid or satellite systems (see details in section II).

Figure 2: Images of Aurora Boreal in Yellowknife, Canada (Source: PIXABAY)

Supporting decision-making using space weather data (observation and forecasting) is a very demanding process in which several stakeholders can often have different interpretations of vulnerabilities and impacts. It is important to note that, like other natural hazards, extreme solar events can occur at any time and a single space weather event may produce multiple effects (Cannon, 2013; Krausmann et al., 2016). Boteler (2018) also points out that different space weather events exhibit differences in occurrence across a wide range of temporal scales (minutes to days).

We therefore, intend to provide an interdisciplinary insight as an innovative research design for a natural-hazard decision aid process from the user's perspective. As a demonstration, we applied it in a simplified case study for a Satellite in Geostationary Orbit (GEO) against an extreme space weather event.

II. Background

a) Critical Infrastructure Protection and Space Weather Threats

According to Public Safety Canada (Canada, 2009), critical infrastructure *"refers to processes, systems, facilities, technologies, networks, assets and services essential to the health, safety, security or economic well-being of Canadians and the effective functioning of government."* As pointed out by Klatt (2016) and Quigley et al. (2017), the risk to specific CI in Canada is variable, and the overall risk is not well known. In this regard, the resilience of CI may depend on natural hazard forecasts that warn stakeholders to take selected mitigation actions to safeguard their systems and reduce the potential negative consequences.

Space weather impacts are relatively unfamiliar to the general public, but geomagnetic storms are recognized as a new natural hazard of the modern technological age (WEF, 2019). According to Oughton et al. (2019), space weather is a high impact, low frequency (HILF) event. Also, as pointed out by Wasson (2018) and Boteler (2018), space weather phenomena are an international issue and not restricted by national borders. Furthermore, increasing reliance on technological systems is creating new potential vulnerabilities to extreme space weather; for example, interference in Global Navigation Satellite System (GNSS) signals for the timing of financial and control systems (Klatt, 2016).

Despite the clear benefit of taking an anticipated measure to protect against and prepare for natural hazards (Oughton et al., 2019), most organizations that are responsible for CI do not have a systemic emergency plan for extreme space weather events (Krausmann et al., 2016). As discussed by Cannon (2013) and Boteler (2018), there is a lack of awareness of the extent of space weather impacts on CI around the World. Furthermore, Fergunson et al. (2015) and Wasson (2018) present that other crucial operations (e.g., water supply) may be affected by space weather-related outages as a cascade effect. Fergunson et al. (2015) also discuss that with the advent of space-based communication systems since the 1950s, the potential space weather impact on long-distance telecommunications has increased extensively. So, all kinds of satellites in space are subject to space weather threats. Alongside space debris (Ribeiro et al., 2018), space weather remains a major concern for all aerospace operations today (North, 2017).

b) Space Weather Events and Economic Impacts

At present, several space-based and ground-based platforms are monitoring the Sun and the near-Earth space environment (Lam, 2016; Fiori et al., 2018). These data provide essential information for the mitigation of extreme space weather events (Ngwira and Pulkkinen, 2016). Although the impacts of geomagnetic storms are broadly recognized in past events (see Balch, 2015; Ferguson et al., 2015), establishing all the potential vulnerability and consequences of such an extreme event has proven to be very hard (Krausmann et al., 2016).

Regardless of the capability limitation for forecasting geomagnetic storms with relatively long lead times, Oughton et al. (2019) demonstrated that with a tailored warning system, early mitigation actions could reduce economic losses to £2.9 billion instead of £15.9 billion (only in the United Kingdom), based on current space weather forecasting capabilities. Despite the space weather 'deniers' (Ferguson et al., 2015), studies based on solid technical-scientific articles discuss the economic impacts of a severe space weather event. In the satellite segment alone, Odenwald et al. (2006) projected economic damage at around 70 billion USD. Eastwood et al. (2017) highlight the economic impact of an extreme event could reach 3.4 trillion USD worldwide.

Past Episodes and Lessons Learned

In September of 1859, the British astronomer Richard Carrington recorded the biggest solar storm ever observed (Elvidge and Angling, 2018). According to Odenwald et al. (2006) and Ferguson et al. (2015), a major event, such as the 'Carrington-event' would devastate civil and military communications and could collapse the global economy. Assessing potential impact, MacAlester and Murtagh (2014) say a Carrington event impacting the Earth could result in an extreme increase in the anomalies experienced across the satellite constellation in Earth's orbit.

In other natural hazards, several researchers have to assess the impact on critical infrastructure interdependence. For example, MacAlester and Murtagh (2014) and Krausmann et al. (2016) concluded that from previous experience of disaster events; such as hurricanes or earthquakes, the impact of power loss would build over time and affect others' CI in sequence (e.g., healthcare facilities or banking/finance systems). So, any facilities without backup power will fail immediately, even though the comprehension of extreme space weather's impacts on modern technology assets is incomplete (Cannon, 2013).

Despite the uncertainties inherent in space weather hazards, the threats are real. On July 23, 2012, the Sun launched a massive Coronal Mass Ejection (CME) that was not Earth-directed, but the fastest ever observed by NASA's STEREO-A (Solar Terrestrial Relations Observatory) spacecraft (Ngwira et al., 2013). This 2012 event offers an excellent opportunity to explore the effects of extreme space weather event, in particular, a massive CME (Carrington-caliber superstorm) within situ observations (Ngwira et al., 2013), as in Figures 3 and 4.

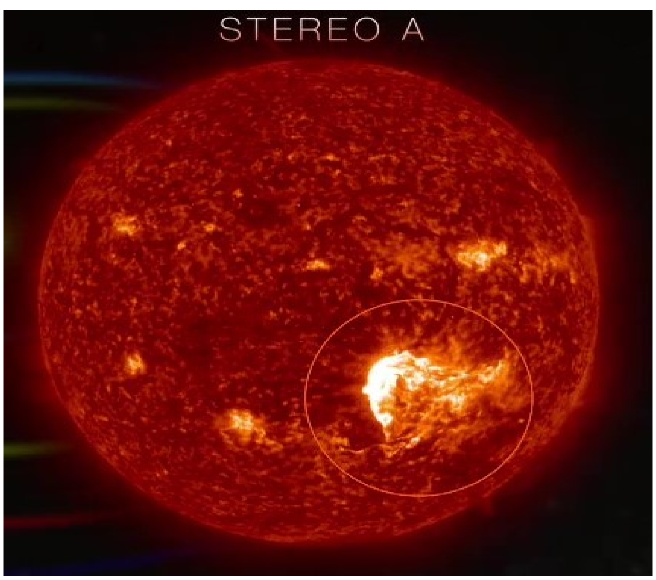

Figure 3: Image of a CME in July/2012 captured by NASA's STEREO-A spacecraft (Source: courtesy of NASA/GSFC)

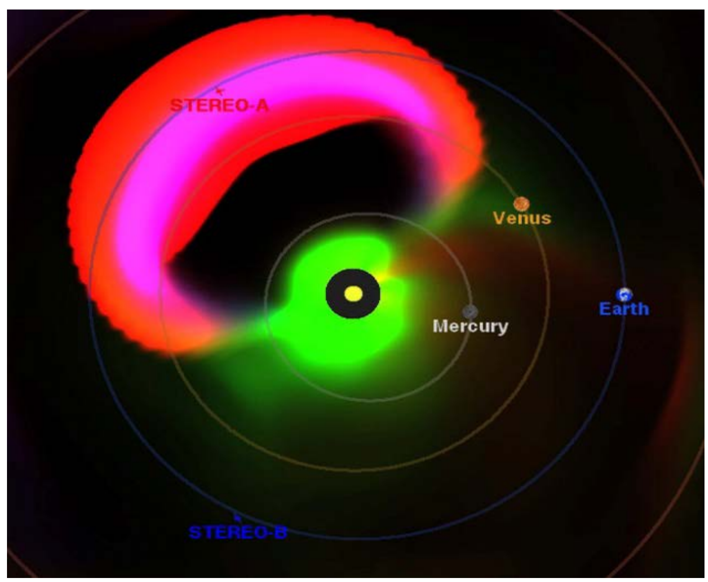

Figure 4: Simulation of CME that hit the STEREO-A spacecraft on July/2012 (Source: courtesy of NASA/GSFC).

In this view, North (2017) stresses that this prompted the need for increased risk analysis of space weather threats. Based on this assessment, some authors call this as “Space Situational Awareness” and it has concerned several military and civilian organizations (Ferguson et al., 2015). To do so, space weather prediction and real-time observation are essential for CI protection (Oughton et al., 2019).

c) Decision Under Uncertainty and Inter-Disciplinary Research

In everyday situations the effects of natural hazards on tasks may be trivial, but in an extreme event the impacts are considerably more significant (Kox et al., 2015; Elvidge and Angling, 2018). Decision making for these high impact events typically involves many stakeholders, frequently with different interpretations of the natural hazards, which further complicates the process (Caruzzo et al., 2018). In this context, using an interdisciplinary research design has been gaining attention in natural hazard studies in recent years (Hardy, 2019; Wong-Parodi and Small, 2019). These examples also demonstrated that successful interdisciplinary studies incorporate the main ideas by each contributing area.

From a behavioral point of view, Kox et al. (2015) and Caruzzo et al. (2018) have demonstrated that the process by which practical problems are simplified into a decision aid model could be subjective, dependent on the stakeholders and the type of decision. For such problems, the users of natural hazard forecasts want to choose an alternative decision that minimizes the impacts or/and maximizes monetary gain. For example, shutting down a power station to prevent harm from geomagnetically induced currents will result in a loss of income, but could prevent serious damage to electrical power systems (Weigel et al., 2006; Fiori et al., 2015). In fact, according to MacAlester and Murtagh (2014), the vulnerability of electric power to an extreme geomagnetic storm remains the primary concern from an emergency management perspective.

Forecast-based action

In certain extreme events, stakeholders are required to identify the best mitigation actions to save human life and/or protect infrastructure. To address these challenges on the practical side, one of the innovative approaches shows a prediction based on actions, instead of the natural hazard variable (Caruzzo et al., 2018). For example, “tomorrow all schools will be closed,” as an alternative for “tomorrow there will be 60 cm of snow.” In accordance with this new design, some humanitarian organizations have been applying a similar approach, e.g., Forecast-based Financing – FbF (Coughlan-de-Perez et al., 2015) or Early Warning Early Action Systems – EWEA (FAO, 2018). These methods use impact levels as a trigger to take early mitigation action. From the end-user perspective, that is a new way to customize products/services to anticipate measures and tailor risk communication based on natural hazard impacts for each decision context.

Probability and lead-time trade-off

Deciding under natural hazard uncertainty can be a subjective and complex process. That is, non-expert stakeholders choose according to their personal experience and natural hazard perception (Wachinger et al., 2013; Kox et al., 2015). Several recent studies used decision theory related to or motivated by analysis of space weather hazard problems (Elvidge and Angling, 2018). Weigel et al. (2006) evaluated a prediction model’s performance from the user’s perspective based on the user seeking to maximize monetary gain. Park et al. (2017) applied decision-making based on skill scores to a Solar Flare Forecast Model in cost-loss ratio situations. They propose a minimum probability threshold for the action to minimize economic expense based on data from the flare forecast model.

Some best practices from other areas are also of interest (Henley and Pope, 2017). In the hydro-meteorological community, there have been alot of practical studies done to improve decision making using terrestrial weather information (Uccellini, 2016; Alley et al., 2019). For example, the analysis of the users’ weather hazard perspective shows evidence that individual characteristics are related to probability and lead-time weighing variations (Caruzzo et al., 2018). There are alot of potential explanations for this finding: a lack of risk perception, prior experience, human behavior under uncertainty, and risk profile, among others (Wachinger et al., 2013; Caruzzo et al., 2015; Kox et al., 2015). Applying questionnaires, surveys, and interviews (as methods of eliciting preferences), these studies showed that evaluating preferences may be best understood by considering how the decision makers interpret the natural hazard resulting from uncertain information or warning messages, and the trade-off between probability and lead-time.

The findings about the relationship among natural hazard information, risk communication, and early decision under uncertainty could be a good starting point for the space weather community. For example, according to Caruzzo et al. (2018), the key element is the understanding of the temporal (lead-time) and uncertainty (likelihood) dimensions of the natural hazard impacts (Figure 5).

According to current practice (Fiori et al., 2015; Lam, 2016), the end-user (e.g., critical infrastructure manager) receives a space weather bulletin or warning message and makes a decision according to their personal experience and space weather risk perception. They may have a question if the probability is high enough (e.g., above 70%) and lead-time is short enough (e.g., less than 10 hours) to take action for preventing economic loss (Scenario A on Figure 5).

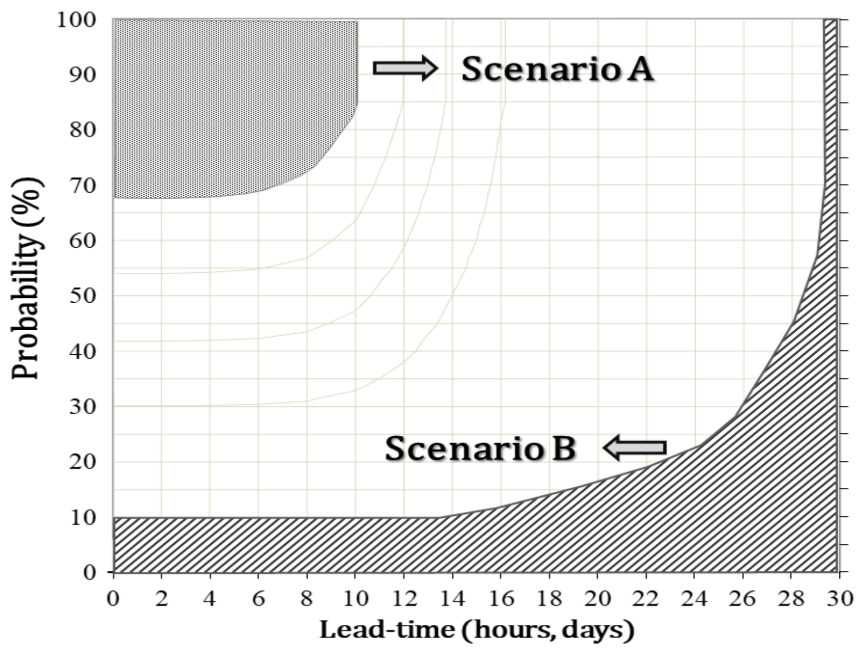

Figure 5: Natural hazard probability and lead-time trade-off, where Scenario 'A' has a high probability and short lead-time, and Scenario 'B' has a low probability or long lead-time (Source: adaptation Caruzzo et al., 2018)

d) Probabilistic Space Weather Forecast and Decision Making

Over the last few years, significant progress has been made in space weather observation and forecasts, and there are a number of ongoing efforts to apply several techniques (e.g., Nikitina et al., 2016; Fiori et al., 2018). Research and modeling of space weather and solar-terrestrial geomagnetic activity have been extensive and operational forecast centers, such as the Canadian Space Weather Forecast Centre – CSWFC (Fiori et al., 2015; Lam, 2016).

More broadly, according to Henley and Pope (2017) and Murray (2018), the international space weather community is trying new approaches used by other research communities to enhance current predictions (e.g., probabilistic forecasting). That is, when mathematical techniques or multiple predictions from different methods are combined to create an ensemble forecast with a likelihood (Figure 6). One of the most recognizable examples of probabilistic weather forecasting for the public is a prediction for a hurricane (Figure 7).

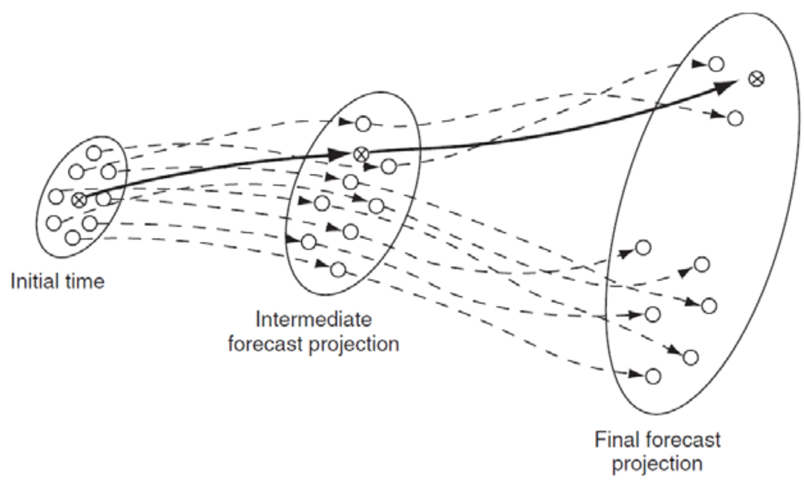

Figure 6: Illustration of ensemble forecasting, where the dashed lines represent the individual ensemble members (probabilistic), and the solid line represents the deterministic forecast (Reproduced with permission: Wilks, 2011, p.271)

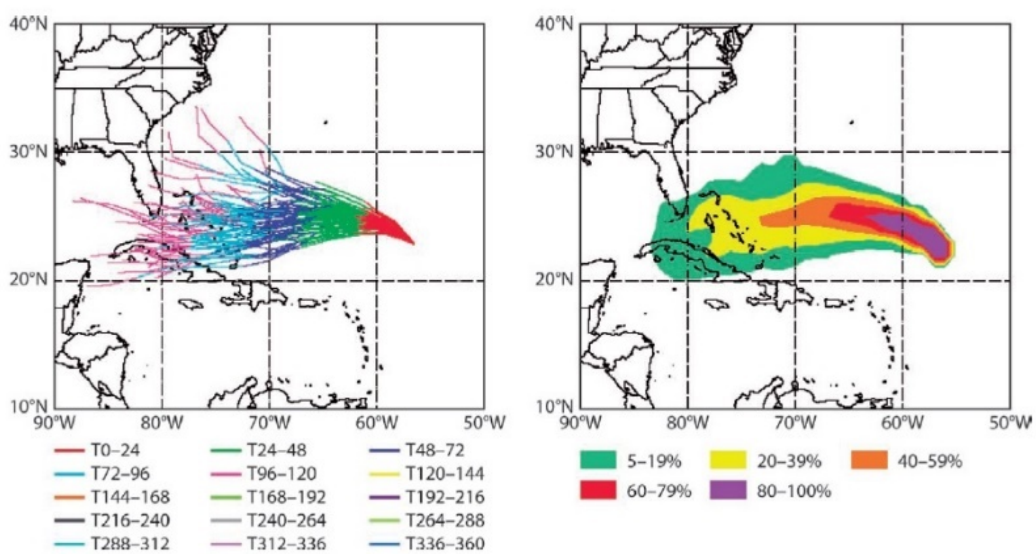

Figure 7: Ensemble forecast tracks (left) and strike probabilities (right) for hurricane Ike (Reproduced with permission: Bougeault et al., 2010, p.1071)

Probabilistic space weather forecasting based on a numerical model or other probabilistic techniques has been applied in several initiatives (see examples in Murray, 2018). On the other hand, while researchers have focused on the physical characteristics of extreme space weather events or the effects on the GNSS/power grids (Klatt, 2016; Ngwira and Pulkkinen, 2016), there is almost no research on the links between those impacts and decision behavior under uncertainty from the end-user's perspective. It is surprising that, so far, this real-world decision problem has received hardly any attention in scientific/technical papers. Nevertheless, this gap is a good opportunity for interdisciplinary research.

It should be noted that there has been a lot of progress by space weather researchers using probabilistic forecasts for uncertainty estimation in extreme events. However, following atmospheric science's example (Uccellini, 2016; Alley et al., 2019) the space weather community should apply decision analysis approaches, such as behavioral or risk perception. The important point here is not only to gain a better understanding of the physics of solar events, but also how stakeholders interpret and use probabilistic space weather forecasts and early warning messages. Henceforth, we could develop an innovative set of products, then, for better risk communications and a shift toward action-based decision support and early warning services. As a best practice, it is widely recognized that customized Early Warning Systems (EWS) are an excellent option, enabling advance implementation to select mitigation actions.

Further research will encompass the relationship between natural hazards and decision science. Although, these insights identify several subjects to develop innovative and customized decision support and early warning systems for CI protection (Figure 8).

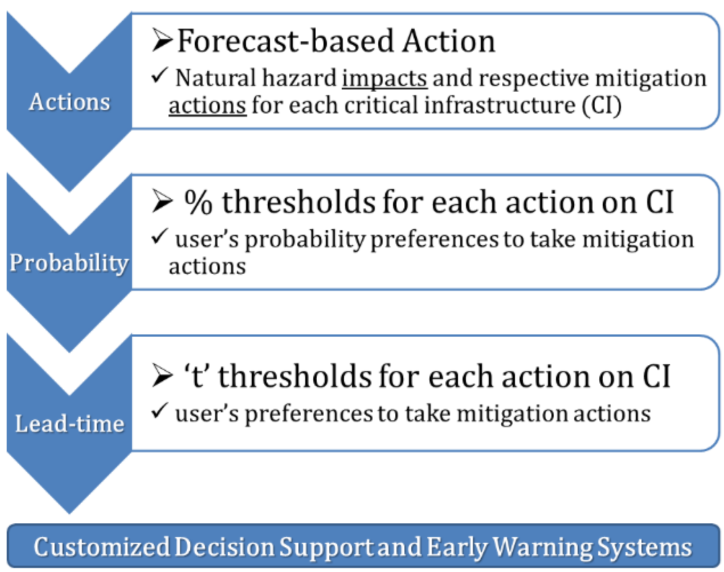

Figure 8: Flow chart for customized decision support and early warning systems based on user`s preferences about impacts, probability, and lead-time in natural hazard prediction.

III. Practical Application For Space Weather Hazards

By way of demonstration, we put together a simple application for an orbital maneuver of a Satellite in Geostationary Orbit (GEO) under emergency conditions. The GEO operator receives two independent early warnings at the same time: a) space debris proximity in the next 48 hours, and b) potential extreme geomagnetic storm. So, the decision problem (see details in Figure 9) is selecting one of two alternatives:

1) perform the orbital maneuver as planned in the procedure
2) postpone the orbital maneuver for 24 hours to avoid telecommand signal failures to the satellite

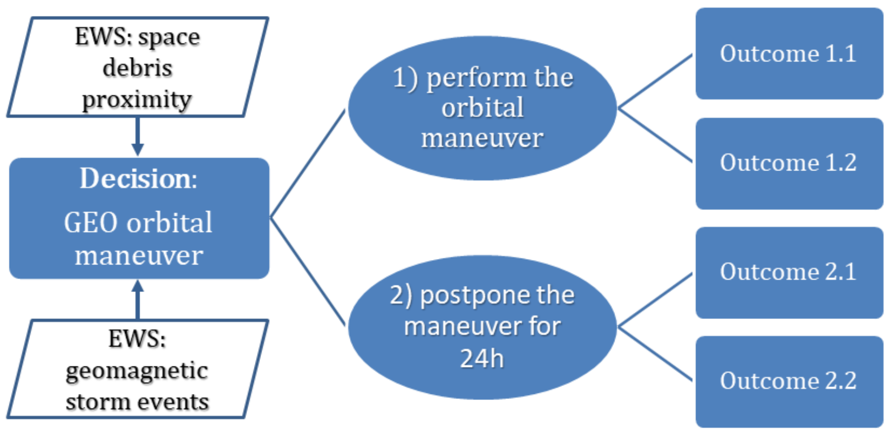

Figure 9: Traditional decision analysis with simplified decision-tree based on Early Warning Systems (EWS) for space debris proximity and geomagnetic storm event information.

Naturally, various criteria should be assessed in the satellite operation, but as a hypothetical application we used the scenarios in Figure 5 as a probabilistic space weather prediction:

- Scenario A: high probability (above 70%) and short lead-time (below 10h)
- Scenario B: lower probability (below 10%) or long lead-time (after 24h)

The final decision is related to two hazard impacts: debris; and a geomagnetic storm. In traditional decision analysis, the best outcome is the highest expected value (for details, see Clemen, 1997). However, equally important, the decision is based on stakeholder preference profile, that is, their trade-offs between probability and lead-time. These characteristics are consistent with several studies in the literature (Wachinger et al., 2013; Kox et al., 2015; Caruzzo et al., 2018). For example, in Scenario B, the satellite manager can continue the maneuver schedule because of the low likelihood forecasts or longer lead-time (alternative 1 on Figure 9). On the other hand, with Scenario A, the manager could decide to postpone the action (alternative 2 on Figure 9). In fact, Park et al. (2017) point out in a solar flare forecast, the decision makers may tend to choose a larger probability threshold when cost becomes relatively higher. These conditions suggest the existence of motivational risk-decision-making biases related to probabilistic natural hazard forecast issues and should affect decisions related to space weather and CI protection as well.

IV. Summary and Directions For Future Research

This article has discussed some aspects for interdisciplinary research into natural hazard decision problems in real-world situations. Improving early decision using a probabilistic forecast is a grand challenge all over the world. It is our understanding, then, that an interdisciplinary research design provides what stakeholders think about all aspects of the decision problem. The potential application of this innovative research could bring about a paradigm shift in natural hazard-related decisions. That is, selection of mitigating action alternatives no longer depends only on 'impacts table' or 'risk matrix,' but also on end-users' preferences about the trade-offs between probability and lead-time.

From a space weather hazard perspective, the new Solar Cycle (number 25) will start in the next two years, and the Solar maximum of sunspots is expected in 2025 (Pesnell and Schatten, 2018). It is important to note that space weather centers around the world have been developing numerous products that provide general information about solar activities. In spite of their usefulness, however, it is possible to advocate that space weather-hazard impacts alone for critical infrastructure protection is not at all recommendable or able to support a good decision-making choice. In other words, a single criterion approach centered on 'impact only' is no longer supportive and robust enough in contemporary decision problem evaluation.

Though all of these advances are relatively recent in other operational communities (e.g., hydro-meteorology), it is widely accepted that this issue requires an interdisciplinary research approach, applying the up-to-date techniques from space science (observations and forecast) and robust methods from decision sciences. Nevertheless, to reduce economic impacts associated with space weather threat prediction, it is essential that CI has an effective operational mitigation plan. Based on the insights, we believe this research design could provide a step toward new procedures and protocols for space weather-risk assessment.

As a final comment, it is interesting to notice that in the upcoming decade, space weather will become more and more relevant. Today, we are more vulnerable to space weather hazards than in the past, and in the future, our modern, technological society is going to be more vulnerable than it is today. To address this challenge, researchers at the Department of Atmospheric and Oceanic Sciences at McGill University are currently undertaking interdisciplinary research in which the various dimensions of natural hazards are used to develop new approaches and risk communications to support better decisions using experience from other cutting-edge research in the literature, through a multi-methodological and innovative scientific-technological approach.

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About the Authors

Amaury Caruzzo *is a Postdoctoral Researcher at the Department of Atmospheric and Oceanic Sciences at McGill University. Dr. Caruzzo received his B.Sc. (Atmospheric Science) at the University of Sao Paulo and Ph.D (Aeronautical Engineering) at the Aeronautics Institute of Technology (ITA, Brazil). His research interests include Atmospheric/Space Science and Operations Research with an emphasis on natural hazards, critical infrastructure protection, risk analysis, and decision under uncertainty.*

John Gyakum *is a Full Professor and Chair of the Department of Atmospheric and Oceanic Sciences at McGill University. Dr. Gyakum received his B.Sc. (Atmospheric Science) at The Pennsylvania State University and Ph.D. at the Massachusetts Institute of Technology (MIT). His research interests include synoptic and dynamic meteorology and natural disasters.*

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