Future Needs for Space Weather Forecasting

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Abstract

As space weather forecasting continues to mature, our goal should be to produce accurate and actionable forecasts that provide value to end users. Here, we advocate for four focus areas to help achieve that goal: 1) A shift to probabilistic forecasting, 2) Continued development of applied tools to link space environment drivers with impacts on satellite systems, 3) Providing historical and contextual information, 4) Providing measurements and tools for satellites in non-GEO orbits.
1. Introduction
The space sciences have continued to advance, and although there has been significant progress in some domains, such as solar wind-driven physics-based modeling, substantial challenges remain in producing accurate, actionable space weather forecasts. Just as in the evolution of terrestrial weather forecasting, additional information on the uncertainty in these predictions can and should be included to help inform users of the most likely outcomes. The inclusion of probabilistic information presents additional challenges in the interpretation of this information by users, so the uncertainty in these forecasts must be communicated appropriately so that the intended outcome or message is realized.

Additionally, as the connection between the environmental drivers or parameters and actual impacts on systems and technology is challenging to determine, a shift toward impact-based forecasting is critical for space weather forecasts to reach their full value. While the myriad of systems, impact mechanisms, and stochastic nature of some effects make this incredibly challenging, the space sciences community must continue to pursue applied research in this area to improve the usefulness of space weather products and services.

The space weather community can continue to evolve and improve to address these challenges with continued investment in this area. The application of new tools and techniques, such as AI/ML, as well as the improvement of underlying models presents opportunities and new approaches to solving these problems. Finally, moving forward, special attention must be paid to putting measurements and forecasts into historical context and tailoring outputs to different orbit regimes.

2. Need for Probabilistic vs. Deterministic Forecasts
While there is a long history of deterministic forecasting in space weather, there are inherent limitations in the skill of space weather forecasting which are not appropriately conveyed in deterministic forecasts. For example, one common approach in geomagnetic storm forecasting is to provide a deterministic forecast for each 3-hourly synoptic period for the next several days in Kp. While this method does have benefits in allowing the expected storm intensity to be communicated simply and clearly, such as describing the peak storm intensity on a given UT day, it fails to provide a mechanism to describe the uncertainty associated with that forecast. This uncertainty presents itself in several ways including the intensity, evolution, timing, and overall confidence in a prediction.

Conveying confidence in a forecast parameter allows users to make better informed decisions about the possible actions they may take or better interpret or attribute space weather impacts to their systems, such as in satellite hazards and the correct association between an environmental driver and anomaly. As one example, Figure 1 shows a comparison of 2 models of the GEO electron environment: A deterministic model (REFM; https://www.spaceweather.gov/products/relativistic-electron-forecast-model) and a probabilistic model (LEEF-GEO; (Boyd & O’Brien, 2021)). As shown in the figure, the probabilistic
model offers considerably more information by giving a range of percentiles rather than a single value. Also, the forecast horizon can be extended considerably up to 28 days rather than 3 days. This enables such a model to provide more utility to end users – allowing for long term planning and giving an estimate of the model uncertainties.

Figure 1: Comparison of a deterministic model (Relativistic Electron Flux Model; REFM) with a probabilistic model (Long-Term Energetic Electron Forecast at GEO; LEEF-GEO) of the GEO >2 MeV electron fluence. The forecast shown here was made on 22 Jun 2022.

While there are challenges associated with producing and evaluating a probabilistic forecast, recent developments have made that transition more tractable. ML/AI forecasts can utilize quantile regression (Zhang et al., 2020) or can be run as a model ensemble (Guerra et al., 2020). Additionally recent work has shown how probabilistic forecasts can be evaluated using different metrics (Camporeale et al., 2019). The transition to make probabilistic forecasting the norm, as it is for terrestrial weather, will be a key step for future efforts.

3. Impact-based Forecasts and Decision Support
3.1 Impact-based Forecasts
Space weather forecasts have traditionally focused on specific environmental parameters such as X-ray flux intensity in the case of solar flares, proton fluxes at specific particle energies or integral energies in the case of solar particle events, or in terms of the maximum deviation of magnetic fields on the surface of the Earth in the case of geomagnetic storms. While these quantities are useful in studying and describing the physical intensity of the phenomena, they generally fall well short in describing the likely impacts from space weather events. While generalizations are possible on what technologies are impacted by these phenomena, the lack of certainty limits the usefulness of these forecasts or event descriptions. In some cases, this can even create perceived risks, when the actual risks are small or even negligible.

These problems are exacerbated by the fact that space weather is intangible to many users and difficult to put in context as they are units/phenomena that most do not use or cannot relate to in day-to-day applications. Furthermore, the relationship between environment and impact evolves over time as technology matures and vulnerabilities are mitigated or now realized in applications where they were not before. Nonetheless, there are many cases in which sufficient information between cause and effect exists to provide better information to users on space weather hazards and their likelihood.
To bridge this gap, an operational tool is needed to translate the measured quantities (like particle flux) into useful quantities for satellite operators. One example of such a tool is the Space Environment Anomalies Expert System (SEAES). The version of this tool for GEO (called SEAES-RT) has been running at NOAA/SWPC for the last several years. As described in O’Brien (2009), SEAES outputs a quantity known as the hazard quotient. This normalized parameter gives the ratio of the current probability of an anomaly to the mission averaged probability of an anomaly. These hazard quotients are computed using real historical anomaly datasets for each of the four major hazards: Event Total Dose, Single Event Effects, Surface Charging and Internal Charging. This enables a more accurate, applicable, and tailorable measure of the hazard that the space environment poses.

The conventional view holds that scientists deliver environmental forecasts and specifications, and users or third-party developers develop decision aides to consume those outputs. However, experience has shown that the space weather user and developer base is often not sophisticated to bridge the gap from environmental outputs to impacts. Therefore, the scientific community must push further into the application development domain until the user community’s size and sophistication allow them to assume that responsibility.

Therefore, continued development by the scientific community of similar tools to better describe space weather impacts is of critical importance. These developments are often complex and challenging as impact associations can be hard to develop in the absence of robust impact databases. There are many challenges in creating and maintaining impact or anomaly databases, including the generally proprietary nature of much of this data. A “ground truth” of the driving space environment can also be challenging to ascertain given the expanse of the environment and its generally limited characterization.

### 3.2 Providing Contextual/Historical Information

Challenges also arise in presenting space weather information in the appropriate historical context. While some space weather activity is correlated with the solar cycle, there are other aspects that are not, with some that are even anti-correlated such as the galactic cosmic ray background. While generally well understood by the scientific community, these variabilities are not always fully appreciated across the space weather customer base. For some phenomena, events associated with significant impacts are quite rare (e.g., extreme geomagnetic storms or solar particle events). The challenge of putting space weather events in context is complicated by the fact that events that are interesting but not incredibly impactful can be misconstrued in the media, particularly given the absence of truly impactful events for long periods of time given the natural cycles of solar activity. For these reasons, presenting the historical context is incredibly important.
Figure 2 shows a hypothetical scenario for two satellites: one launched in February 2019, the other in May 2020. A small storm in early Aug 2020 (highlighted in red) produced a modest increase in the electron flux observed by GOES, just above the SWPC alert threshold. For satellite 1, this level of flux had been observed numerous times before and would therefore likely not be a cause for concern. However, for satellite 2, this is the highest flux this spacecraft had ever observed, and operators would likely need to carefully monitor for any anomalies.

That is why it is vital to be able to put space weather observations into context: Is this the worst flux we’ve seen in the last week/month/year? What percentile day is today? This context is important not only for observations like those from GOES, but also for applied results from tools like SEAES-RT. To enable this, a critical first step is to make an archive of historical real-time observations and model results easily available. This is presently not the case for many of the NOAA/SWPC offerings. The most recent generation of GOES observations (GOES-16/17) from SWPC only go back 7 days and while the GOES observations are archived at NCEI, these files have a different format (netcdf vs json), calibration factors, and content (e.g. there are no integral proton measurements in the netcdfs) than the real-time SWPC data. Additionally, tools such as SEAES-RT do not have any historical results available, severely limiting their utility. Providing this archive is critical for operators and users to get the most out of space weather data.

3.3 Extrapolation to Data Sparse Regions
While some space weather impacts affect the space environment uniformly or predictably, such as X-ray effects on the D-region of the ionosphere affecting the sunlit side of Earth and being strongest at the sub-solar point, describing space weather impacts for most phenomena requires complex temporal and spatial information. Examples include describing the evolution of ionospheric disturbances or the evolution of Earth’s trapped radiation environment. In the case of the latter, there are practical limitations to flying and maintaining large numbers of sensors to provide sufficient monitoring of the radiation environment everywhere it is needed to support satellite operations.
Given the data-sparse nature of the space environment, the development of techniques to extrapolate from where environmental monitoring is available to places where it is required. For the satellite radiation environment, there is a longstanding history of exquisite measurements of the radiation environment at a finite number of local times in GEO. However, with the increasing utilization of LEO and MEO orbits, understanding and measuring the different radiation environments at these orbits is critical.

Figure 4: Comparison of the energetic electron environment at GEO (top panel; from GOES) and LEO (bottom panel; from POES). The dashed red line shows the NOAA/SWPC Alert Threshold, and the red points on the POES plot show times when the GOES flux was above that threshold.

Figure 3 shows a comparison of the daily average >2 MeV flux from GOES with the normalized >300 keV Outer Belt Index from LEO as measured by POES. While they both generally follow the same trends, there are key differences. First, the increase at LEO can occur sooner (as in Event 1,2) and the response at LEO can be very different, either larger (as in Event 2) or smaller (as in Event 3). Therefore, a LEO operator relying solely on GEO data has a strong possibility to mischaracterize their radiation environment. In terrestrial weather terms, this is similar to forecasting the weather in Chicago using a measurement from Washington D.C. As LEO and MEO orbits become more popular, it is vital to have both quality LEO and MEO measurements and tools that can map available measurements to under-sampled orbital regimes.

4. Conclusions

As space weather forecasting continues to mature, we need to continue to strive to produce accurate and actionable forecasts that provide value to end users. To this end, we advocate for four aspects that need to be a focus for future modeling efforts: 1) A shift to probabilistic forecasting, 2) Continued development of tools linking space environment drivers with impact
on satellite systems, 3) Providing historical and contextual information, 4) Providing measurements and tools for satellites in non-GEO orbits.

5. References


