Space Weather

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Key Points:

- Space weather forecasters identified 19 needed improvements to data, tools, and understanding the research community could provide
- Criteria for a good operational resource are a data stream with high resolution and time cadence with few technical issues
- Space weather forecasters want to be included in tool development more often and earlier so that tools more effectively meet their needs

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R2O2R Improvements Identified by United States Space Weather Forecasters

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Abstract A communication deficit exists between the space weather research and forecast communities in the research-to-operations-to-research (R2O2R) pipeline. No formal, citable space exists for forecasters to communicate needs and lessons learned to the research community (O2R). This deficit was termed the "valleys of death and lost opportunities" (NRC, 2003, https://doi.org/10.17226/10658) and has resulted in advancements taking up to 20 years or more to become forecast operational. To provide this communication space, we surveyed a group of US civilian space weather forecasters on their needed improvements, use of available resources, and interactions with researchers, via a combination of questionnaire and focus group discussions. Nineteen needed improvements were identified, clustering into four categories: scientific understanding, access to data, forecast office tools, and instrumentation. Participants appeared to prefer resources with a robust data stream of high-resolution and high-time cadence data which suffer few technical issues. Participants want to be included in tool development more often and earlier in the process as they felt they were "seldom listened to when it comes to what [they] actually need."

Plain Language Summary There is no formal space for space weather forecasters to communicate needs and lessons learned to the research community; that is, operations-to-research (O2R) feedback. Because of this, the transition of space weather research into forecast operations (R2O) is inefficient and can take up to 20 years. To provide this communication space, we surveyed a group of US civilian space weather forecasters on their needed improvements, use of available forecasting resources, and interactions with researchers, via a combination of questionnaire and focus group discussions. Nineteen needed improvements were identified, clustering into four categories: scientific understanding, access to data, forecast office tools, and instrumentation. Participants tended to prefer to use resources that provide detailed data on short time intervals, while suffering few technical difficulties. Participants want to be included in tool development more often and earlier in the process as they felt they were "seldom listened to when it comes to what [they] actually need."

1. Introduction

Space weather is an integral part of modern society. Solar-driven geomagnetic storms have disrupted power grids and damaged transformers. Induced ground currents can corrode oil pipelines (Eastwood et al., 2017). Space weather is well-known to interfere with telecommunications and GPS, disrupting services and industries that rely on those networks (such as the Hurricane Katrina relief efforts, Young, 2005). It can severely affect the health and safety of astronauts (Whitman, 2017). Polar flights have been delayed, rerouted, or cancelled due to space weather conditions (Eastwood et al., 2017). Military action was almost been taken due to a solar flare event (Knipp et al., 2016). The Sun has even managed to open garage doors in California (McFarling, 2000). It is estimated that even a moderate event could cost billions globally and take a year or more to recover (Eastwood et al., 2017; Schrijver, 2015).

In response to these impacts, many resources have been invested into space weather. The research community has invested many hours and dollars into understanding the cause, workings, and effect of space weather phenomena. With more governments recognizing its importance (e.g., Ambrose, 2016; Boffey, 2012; Denardini et al., 2016), more funds are being allocated and infrastructure built. As part of this investment, much effort has been made to identify research gaps, both at a high level (e.g., NRC, 2013; Schrijver et al., 2015; and the various activities conducted by the US SWORM Working Group) and at the individual level (e.g., Pulkkinen et al., 2017). However, in the majority of cases, this effort is made by consulting researchers and, increasingly, end-users, the people and organizations who make decisions based on space weather forecasts (e.g., "user requirements"). Space weather forecasters rarely appear to be consulted. As a participant of this paper's study noted, they are "seldom listened to when it comes to what [they] need," which implies that there is either little communication or what exists is ineffective.

Communication between forecasters and the research community (that is not focused on a specific application) tends to be via informal conversations, word-of-mouth, or as a tangential topic (e.g., Merceret et al., 2013; Shprits et al., 2018), and most of that communication tends to focus on what a given space weather forecast office does and how it does so (Murray et al., 2017; Steenburgh et al., 2014). Steenburgh et al. (2014) is a good example of formal, citable communication of specific forecaster needs. They dedicate a portion of their paper's findings to "An Operator's Wish List," where they note that "a discussion of [research-to-operations (R2O)] and [operations-to-research (O2R)] would not be complete without the inclusion of a wish list from the operators' side of the house." Yet, as of November 2020, only one research paper cites the study for the wish list and not for the description of how a forecast office operates.

This dearth of forecaster consultation represents an imbalance of the "push-pull" dynamic identified by the National Research Council (originally reported on in the R2O process of terrestrial weather) (NRC, 2003): there is a great deal of attention given first to the research question ("push") and very little to operational needs ("pull"). This makes it easy to stumble into the valleys of death and lost opportunities, where R2O transition efforts sputter out or never begin in the first place, leading to a transition process that can take decades to make research operational (NRC, 2003).

The inclusion of forecasters in the R2O2R process has known benefits. Consulting them as part of the R2O process increases the efficiency of the transition, as efforts are more targeted, and can result in more effective operational tools (e.g., Steenburgh et al., 2014). Forecast operations monitors and synthesizes multiple disparate data sources and could provide the research community with a wealth of data and a long-term baseline (Denardini et al., 2016). It is also recognized that operations can help pinpoint gaps in our understanding of space weather (Schrijver et al., 2015), as they monitor and use the data constantly and from a different perspective.

In order to explicitly begin filling this O2R communication gap in the research-to-operations-to-research (R2O2R) process, we formally surveyed a group of space weather forecasters on their needs or wishes for improvement, which are presented here in a formal, citable communication. The hope is that by communicating these needs ("pull"), researchers can better target their R2O efforts or identify operational applications of research or datasets they have already performed or acquired, leading to bridged valleys and a more streamlined R2O2R process. In Section 2, we discuss how we conducted the survey and analyzed the data gathered. Section 3 presents our findings, broken down by research question, with discussion in Section 4. Section 5 summarizes our findings.

1.1. A Word on Definitions and Scope

While conducting this study, we noticed ambiguities in the use of the terms "O2R" (e.g., Austin & Savani, 2018; Cranmer et al., 2017; NASA ROSES NNH19ZDA001N-SWO2R; NRC, 2010) and "user"/"end-user" (e.g., Cid et al., 2019; Halford et al., 2019; NRC, 00, 2010; NSTC, 2015; Schrijver et al., 2015) in the literature that we wish to discuss to clarify the scope of this study before continuing. For this study, we use the following definitions:

- O2R: the communication of knowledge and experience from people conducting operations activities to the research community, with the further specification of "operations" to mean "forecasting."
- User: a person who uses space weather knowledge that the research community has produced to make nowcasts and forecasts, with the further specification that the person is currently employed in a semi-regular capacity to do forecasting, not to manage or administer a forecast office. In this study, "user" is another term for forecaster.
- End-user: a person who uses space weather nowcasts and forecasts provided by forecasters to aid in decisionmaking around the protection of life and assets; another term for customer.

This study is an O2R study; we aim to communicate information and experience from a link in the R2O2R chain "upstream" to the research community. Where most R2O papers focus on a narrow content slice with links from all along the chain (basic researcher through to end-user), this study focuses on a narrow link and includes all content areas as thought relevant to the act of forecasting space weather by the forecaster participants. From this aim and the above definitions, the following is outside the scope of this study and will not be discussed.

- End-user needs stemming from space weather impacts. It is assumed that the forecaster participants are aware of these and are taking them into account for what they need from the research community, and it is also assumed that improving their forecasting ability will address most current needs. To that end, customer or end-user need surveys were not collected and are not discussed.
- The current state of knowledge of the gaps and challenges in space weather research from other identification efforts. This study is focused on communicating the needs of forecasters, not interpreting or assessing (see Section 4) as that would mean coloring the reporting of forecaster experience and needs with the authors' perceptions (who are not themselves forecasters). Additionally, this activity would require a full systematic review of the literature and, given the breadth of space weather research, would not be a small task; thus we leave this to future investigators. For the larger identification efforts headed by the US SWORM Working Group, we will note that while many of their recommendations have been used in proposal calls (e.g., NASA ROSES NNH19ZDA001N-SWO2R), they have not yet had time to be implemented at an operational level.
- How the communicated improvement needs might be fulfilled or may already be being fulfilled. We see this as an R2O activity that happens in response to O2R communication and thus outside this study's scope.

2. Materials and Methods

This study posed three broad questions: what do forecasters need or wish would be improved (see Section 3.1); what makes a forecasting resource useful in an operational context (see Section 3.2); and how and how frequently do forecasters interact with researchers (see Section 3.3). Since this study was motivated by a shortfall in communication lines, this last question was included to understand where the shortfalls are for future efforts to address them. Data was collected with an electronic questionnaire and focus group discussions from June 29, 2020 to July 31, 2020. Participants did not have to participate in both activities, and they could choose to answer or not answer any question. Of the 11 civilian US space weather forecasters we initially queried, seven chose to participate in at least one activity, for a response rate of 63%.

2.1. Data Collection

The 1-hour focus group discussions were conducted virtually due to the COVID-19 pandemic. To address the first research question, participants were asked to brainstorm a list of improvements they wished to see in the forecast office. The improvements were then discussed and elaborated. Additionally, participants were asked which forecast area they felt should be prioritized for improvement and what made a forecasting resource useful or valuable.

The electronic questionnaire addressed the second two research questions. The first part of the questionnaire asked participants about their utilization of various forecasting resources. For each resource, participants were asked to assess its effectiveness, availability, and frequency of use. For this study, "effectiveness" was defined as "the [resource's] ability to contribute to an accurate forecast when the resource is available for use." "Availability" was specified as "how often a resource is available, regardless of [the forecaster's] desire to use it"; "frequency of use" is considered separately (see Appendix). The assessments used a five-step unipolar Likert-type scale (e.g., Chyung, Roberts, et al., 2017, 2018, 2020). Effectiveness and availability had an option for "unsure/don't know," in the event the participant had not yet utilized a given resource. The scale anchors are presented in Section 3.2. Table 1 describes the resources discussed.

The second part of the questionnaire asked participants to assess and describe their interaction with researchers. This was divided into two sections: (1) interactions within the context of constructing a forecast, and (2) during the development of a new forecasting tool. For the former, participants were asked to rank

Table 1
Table of the Discussed Resources, Listing Name, Conventional Acronym, Type of Resource, Area of Study as is Relevant to the Participants, and What Type of Data It is Used For

Resource				
Full name	Acronym	Type	Area	Data
Solar Dynamics Observatory	SDO	Spacecraft	Solar disk	Extreme ultra-violet and white light imagery; magnetograms
Solar and Heliospheric Observatory	SOHO	Spacecraft	CMEs and solar atmosphere	Coronagraph and extreme ultra-violet imagery
Solar Terrestrial Relations Observatory	STEREO	Spacecraft(s)	CMEs and solar wind	Coronagraph and extreme ultra-violet imagery; particle data
Advanced Composition Explorer	ACE	Spacecraft	Solar wind	Particle data/in-situ particle data
Deep Space Climate Observatory*	DSCOVR	Spacecraft	Solar wind	Particle data
Geostationary Operational Environmental Satellite*	GOES (series)	Spacecraft(s)	Flares and solar wind	Particle data and X-ray
Global Oscillation Network Group	GONG	Ground	Solar disk	Helioseismology
Solar Electro-Optical Network—Radio Solar Telescope Network	SEON RSTN	Ground	Solar radio bursts/radio flux	Radio (MHz)
Solar Electro-Optical Network—Solar Optical Observing Network	SEON SOON	Ground	Solar disk	Optical
Learmonth Solar Observatory	—	Ground, part of SEON	CHECK	CHECK
Ground magnetometers	—	Ground	Earth surface magnetic field	Local magnetic field data
Wang-Sheeley-Arge-Enlil	WSA-Enlil	Model	Solar wind + CMEs in interplanetary space	Inputs from GONG, SOHO, etc.
Relativistic Electron Forecast Model	REFM	Model	Near Earth electron environment	Inputs from GOES and ACE
Synoptic drawings	—	Forecast Office Tool	Solar disk	Synthesis
Audible alerts	—	Forecast Office Tool	Various	—
Alert programs	—	Forecast Office Tool	Various	—

All ground resources have international locations. The ground magnetometers considered here are those used to calculate Kp-index. SEON locations have one or both components. Resources that look at the solar disk are used in multiple sub-areas. Items with an asterisk were not on the administered questionnaire but were added due to their mention by participants.

the usefulness of a list of interactions from 1 (most useful) to 8 (least useful). This section used reverse coding to avoid patterned responses (see Section 3.3.1). For the latter section, participants were asked to assess the frequency of their inclusion on a five-step unipolar Likert-type scale (see Section 3.3.2).

Open-response questions were included throughout the questionnaire to gather qualitative data on the nuances of the resource assessments (e.g., why a particular resource was most effective, if a given resource's use depended on the solar cycle, etc.) and on the nature of an interaction (e.g., why those interactions were useful, how participants were being included in the development process, how they wanted to be, etc.).

All data (questionnaire and transcripts), along with interviewer notes, were de-identified. Focus group questions and a questionnaire sample are available in the Appendix.

2.2. Data Processing and Analysis

Given the small sample size, we note that this study is similar to a case study and that thus we did not look for statistically significant results in our analysis. Instead, we focused on general group consensus or leanings.

The questionnaire scales assess the participants' opinions and result in ordinal data (Stevens, 1946). This has two consequences. First, the mean does not hold any physical meaning; the median (middle quantile) and mode (most frequent value) are more appropriate measures of central tendency (Chyung, Roberts, et al., 2017). Second, statements of “greater than” or “less than” can be made, but not by how much, that is, the distance between ranks is either not measurable or holds no absolute meaning (Stevens, 1946). This is especially true, and most visible, for the frequency of use scale, which gives a ballpark sense of how often a resource is utilized and whose distance between steps is not uniform. Because of this and the case-study level of the data, we restricted ourselves to analysis of the median, mode, and distribution for the quantitative data, searching for consensus or overall tendencies.

When analyzing the questionnaire data, a validity issue with the items “in-situ observations” and “Learmonth Solar Observatory” became apparent, so they were removed from the analysis. This decision is discussed in Section 4. As such, they are not listed in Table 1. The original question wording is retained in the Appendix.

DSCOVR and GOES were not on the administered questionnaire; however, they were brought up multiple times by participants in both the questionnaire and focus group discussions, so they have been included in Table 1 for reference. Because they were not in the administered questionnaire, we do not have quantitative data on them and they are not included in the quantitative analysis. Their absence is also discussed in Section 4.

The qualitative data from the focus group transcripts and questionnaire open-response questions were analyzed thematically using a combination of deductive and inductive methods (Fereday & Muir-Cochrane, 2006; Labra et al., 2019). The a priori category of “wished for improvement” was applied to all qualitative data. The data was manually coded using variations of the following phrases: “would like to have”; “would be helpful”; “we're lacking/have no capability”; “we need”; “could improve.” Repeated or similar improvements were merged. We then searched for common themes among the identified improvements for use as an organizational structure. As this is on the level of a case-study, we did not conduct any content analysis for this theme: a single comment was enough for something to be coded as an improvement. We also provided space for inductive codings describing new themes observed in the data.

The open-response questions on forecasting resources also had a priori categories stemming from the question wording (e.g., “very effective” and “very ineffective”). The responses were analyzed for phrases describing why a resource fell under a given category. These phrases were then assessed for common themes or clustering. The portion of the transcripts pertaining to resources was analyzed similarly. Themes from the questionnaire data were compared to those found in the transcripts to look for commonalities.

The open-response questions on forecaster-researcher interactions were analyzed more inductively. Repeated or variations of phrases were flagged and organized into common themes, which were then organized into broader categories. These were used to provide insight and nuance to the complementary quantitative data.

To ensure our interpretations of the data most accurately represented the participants' reality and experience, we conducted a member-check (Lincoln & Guba, 1985; Walker & Litchman, 2021). We sent a manuscript draft to the participants for feedback, which was used to adjust findings, their interpretation, and the overall manuscript. Reflexive journals were also kept to check researcher biases and preconceptions (Ortlipp, 2008; Walker & Litchman, 2021).

3. Findings

Here, we discuss the findings of the survey. Findings are broken down by question area. Section 3.1 will discuss the identified improvements, Section 3.2 discusses the attributes that make a forecast resource useful in an operational context and some current pitfalls, and Section 3.3 discusses how forecasters view interactions and communication with researchers.

3.1. Identified Improvements

The participants identified 19 improvements and needs. These were grouped into four broad categories: Scientific Understanding (5 items); Access to Data (4 items); Forecast Office Tools (6 items); and Instrumentation (4 items). These categories and their improvements are displayed in Figure 1.

Scientific Understanding	Access to Data
Imminent prediction of events	Historical database of space weather events
$-B_z$ prediction upstream of L1	Database of flare active regions
Radio bursts and blackouts prediction	Real-time magnetograms and shear maps
Proton event timing	Ionospheric measurements
Additional CME warning signs	

Instrumentation	Forecast Office Tools
More and better coronagraphs	Improvement of operational tools
Instruments on east limb or L5	Consolidation of tools into one interface
ACE EPAM and/or SIS on more spacecraft	Ability to overlay models in interplanetary space
More ground magnetometers	Synthesis of multiple data sets into movies
	Model output statistics
	Proton event timing tool

Figure 1. The improvements identified by the participants, grouped by category. The order of the categories as well as the order of their items has no significance. See text for further description of individual items.

Which category, or which item within a category, were considered “top priority” was difficult for participants to determine as they felt strongly that “they're all things we need [and] what it boils down to is at this point, we'll take whatever we can get.” Instead, in a process they said was performed periodically, participants identified which were “critical” or “crucial,” as in without that resource, they would not have any capability to forecast a given event or the robustness of their results would drop dramatically. This was nearly all the improvements identified. Within a category, therefore, order does not represent strict priority ranking. Figure 1 is also not in any particular order, and the following discussion will go through the categories clockwise.

We also refer the reader to the forecaster wish list presented in Steenburgh et al. (2014) as a complement to the one presented below. Schrijver et al. (2015) also present a set of research recommendations, where they approach the question from the “push” side of the R2O2R process. There are a few overlaps, which are noted below.

3.1.1. Scientific Understanding

These are the improvements or needs that pertain to physical understanding of the phenomena being forecast (e.g., observational signatures, or how a specific emission affects the ionosphere, etc.).

Imminent prediction of events: For all three of the major solar events (coronal mass ejections [CMEs], flares, and particle events), participants said that they “really have no capacity whatsoever to predict an imminent [occurrence]. We can predict the probability...but we have no means of telling whether or not it's imminent, and therefore we have no warning capability ...We can only alert that it's happening.” In the case of flares, participants highlighted imminent forecasts on minute timescales: “we haven't been able to tease out [any] kind of *short-term* predictive capability” [emphasis ours] that would “[allow] us to predict that a flare is likely to occur somewhere within the next 10 min...” They mentioned the tornado warning system as a reference.

-B_z prediction upstream of L1: Prediction of the -B_z component of the magnetic field in CMEs or solar wind allows forecasters to predict whether or not the Earth's magnetosphere will be disturbed. This capability was identified as "well-known to be severely lacking." Currently, -B_z can only be determined with DSCOVR or ACE, which sit at the L1 point and thus limit the time available to accurately model and send out warnings and alerts, in turn limiting what can be done to protect vulnerable technologies. Schrijver et al. (2015) also noted this.

Radio bursts and blackout prediction: One participant said that "we don't really know anything about predicting radio emissions...so it's hard to say 'oh, there'll be a radio burst affecting GPS'..." This can be related to the previous item.

Proton event timing: Currently, the ability to nowcast energetic proton events is "pretty good, but forecasting the event before there's any sign of it...we're really lacking on that capability." Schrijver et al. (2015), Murray et al. (2017), and Shprits et al. (2018) also note this lack, particularly in determining intensity, duration, and arrival.

Additional CME warning signs: Signs that can be obtained ahead of coronagraph imagery increase the lead time on CME forecasts. Currently, forecasters use categorizations of impulsive versus long duration flares as a probability diagnostic. "Anything else that could clue us in, that could help bolster that...would be helpful..."

3.1.2. Access to Data

These are the improvements that pertain to data the participants wish to have access to or to be generated.

Historical database of space weather events: Participants said a database of this nature would "pay big dividends in a couple of areas." Foremost was the forecasting aspect: forecasters would be able to search for previous events that were "most like that set of issues [for] some idea of what may be possible. Say 'okay, the last time we had this particular set of conditions, or something close to it, here's what we saw in terms of severe weather.'" The participants cited the database of severe thunderstorms used by the Storm Prediction Center in Norman, OK, as a terrestrial weather example. Additionally, participants mentioned such a database would be useful for communicating with the press and forecast customers.

Database of flare active regions: Participants said that flare probabilities are assigned to active regions after examining the region's magnetic complexity and comparing it to a baseline compiled from previous data. This process could be bolstered and enhanced by "obtain[ing] data on the complexity of the region at the time of the flare, amount of magnetic shear observable, growth rate/decay rate, where the actual flaring occurred and any other pertinent data into a database over several solar cycles." One participant also mentioned that any way to tell if an active region "was more prone to pumping out a CME...would be helpful because [they] would have that information...in advance of the coronagraph imagery..." This item was also noted by Steenburgh et al. (2014).

Real-time magnetograms and shear maps: Both of these data products were mentioned as ways to improve flare forecasting, but one participant emphasized the real-time aspect: "if you can [observe] on a real-time basis, I think you can dramatically improve the forecasting time. Instead of coming up with probabilities for a daily, you could probably come up with probabilities on the hourly." The participant also mentioned that the forecast office used to be provided shear maps in the early 2000s, but "that kind of went away...And I think that needs to be revisited." The participant was unsure why the maps were no longer provided but speculated it had to do with computational cost.

Ionospheric measurements: Participants stated that they "currently do not have access to real-time ionospheric measurements" and that it "would be helpful in model verification" when forecasting ionospheric conditions and structures. Schrijver et al. (2015) also note a lack of observational data.

3.1.3. Forecast Office Tools

These are the improvements that pertain to software, models, or other techniques that would be used in the forecast office during the forecasting process.

Improvement of operational tools: Several participants agreed that what they would like "to see improved most are the operational tools that we use to put the forecast together. There's a lot of emphasis right now on introducing models into the forecast office...but the actual tools that we use to assemble the forecast and integrate all this information range anywhere from [10 to 20] years old." One participant mentioned that there has been some movement in this direction but the pace has been slow.

Consolidation of tools into one interface: Moving available operational tools into one interface or one programming scaffold would reduce the number of webpages needed to create a forecast. Each aspect of the forecast comes from a different tool, which is developed on a separate platform, so time is lost in simply navigating to and around the data and tools. This is related to the previous item.

Ability to overlay models in interplanetary space: One participant said that having a tool showing large regions of space "where you can zoom in, you can overlay weather, you can overlay various models, see how they're all working together and also have your ground-based truthing" would be useful, as it would allow forecasters to see the whole picture and be better able to determine which models more closely reproduce observations. The CAVE application for the Advanced Weather Interactive Processing System (AWIPS) in terrestrial weather and Jhelioviewer for solar data were cited as examples. This is related to the previous item. Something similar was noted by Steenburgh et al. (2014).

Synthesis of multiple data sets into movies: Examining movies instead of still images allows forecasters to "find out a lot more [about] what's going on and what gives you more potential for flaring [for example], if you look at things as they progress." Specifically, participants mentioned solar magnetogram data with white light imagery, along with SDO AIA 171 and 193 imagery and possibly vector magnetograms and free energy models.

Model output statistics: This is a product developed for numerical prediction models in terrestrial weather. The statistics help translate the model output into a forecast, e.g., "when the model tells you [X], the most likely set of variables is [Y]." This "would help the forecaster better exploit all the model data [and] more wisely integrate that into the forecast."

Proton event timing tool: A "good display or model or something [that would give] us an indicator that a solar proton event is likely to happen" and help predict the start time, intensity, and duration would be helpful in forecasting proton events (see Section 3.1.1).

3.1.4. Instrumentation

These are the improvements that pertain to instruments or spacecraft that forecasters felt would improve their current abilities. Except for *ACE EPAM and/or SIS*, all items here have also been noted by Schrijver et al. (2015).

More and better coronagraphs: Currently SOHO is considered the "only source" of coronagraph imagery. A participant said that "if [SOHO] died today...we'd have no capability whatsoever of looking for [CMEs]... which is our primary means of forecasting these major geomagnetic storms," which is the "top area of concern, especially for government agencies." SOHO is "extremely old [and] we don't get the best coronagraph imagery from it anymore." There are coronagraphs on STEREO, "but the data's availability varies" and STEREO's orbit makes interpretation complex. Another participant mentioned that combining coronagraphs on the Sun-Earth line with ones off-axis make CME characterization and modeling more effective.

Instruments on east limb or L5: "Anything to see off the east limb would be extremely helpful" in increasing forecast lead times.

ACE EPAM and/or SIS on more spacecraft: One participant said they would like a version of ACE's Electron Proton & Alpha Monitor (EPAM) instrument on future spacecraft and a version of ACE's Solar Isotope Spectrometer (SIS) instrument "on all the spacecraft, potentially at the L5 point." EPAM helps forecasters get "a really good rough guess" of the geomagnetic response to CMEs, and SIS does similar for proton events.

More ground magnetometers: Ground magnetometers provide data for ground truthing that forecasters use to both verify models and adjust forecasts. "[We] need more stations...[we] got to make sure the models are accurate, and [we] can trust the models."

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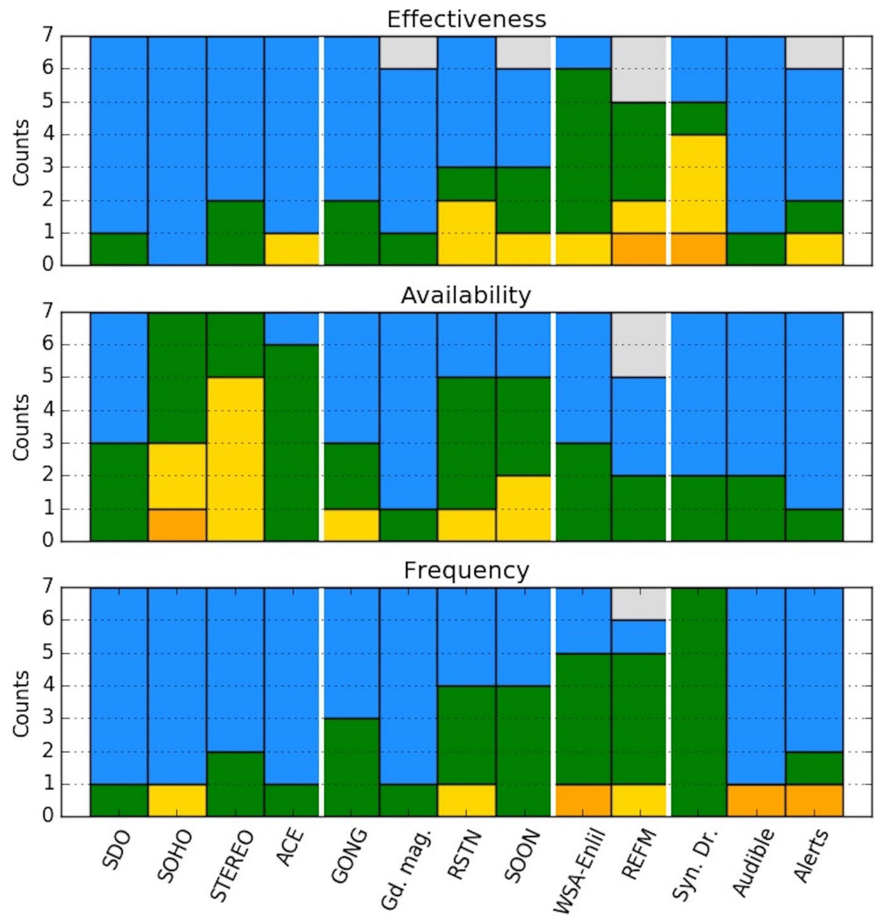

SCALE	1	2	3	4	5	Unsure/ Don't Know
Effectiveness	Not at all	-	Somewhat	-	Extremely	Y
Availability	Extremely unavailable	-	50/50 chance	-	Extremely available	Y
Frequency	Never	Monthly	Weekly	Daily	Hourly	N

Figure 2. The stacked raw scores of effectiveness (top), availability (middle), and frequency of use (bottom) for the resources discussed in the questionnaire (see Table 1). Vertical white lines separate the "spacecrafts," "ground instruments," "models," and "forecast office tools" groups. The table shows the scales' verbal anchors and the color-code used for visualization. The "unsure" response in frequency is an assessment that was left blank. A few general leanings can be seen between the groups (see text).

3.2. Characterization of Existing Resources

Here we turn our attention to the resources utilized by forecasters, the second question area. Figure 2 illustrates the distribution of assessments across the three scales (see Section 2.1). Participants were not restricted to only one option, and four resources did receive multiple frequency assessments: RSTN, SOON, WSA-Enlil, and alert programs. The first three were assessed at both "Daily" and "Hourly"; these were coded as "Hourly," the most frequent option, for the purpose of data visualization. The last was assessed at "Weekly," "Daily," and "Hourly"; these were coded as "Daily," the "average" option, for visualization. There were no multiple assessments for any resource in the effectiveness and availability scales.

The assessments show a few general leanings among participants. First, spacecraft resources are considered the most effective, followed by ground resources, while the effectiveness of the models and forecast office tools discussed in the questionnaire is considered to vary. Second, availability has an inverse relationship to effectiveness: models and forecast office tools are the most available, while spacecrafts have more variable availability. Third, when they are available, how often participants use a resource follows how effective they think it is. Lastly, all resources are used (nothing was assessed as 1/Never), and they tend to be used on a roughly daily basis.

As was mentioned in the previous section, forecasters will use whatever resource they can. This means that even low-effectiveness or low-availability resources are used with some frequency and at all points of the solar cycle (i.e., no resource is assessed at a 1 on any scale, and assessments of 2 are rare). Another consequence of this is, again as above, that participants had a difficult time specifying a "top" resource because "so many come in small formats that are critical to what we do." Instead, they specified which resources were "critical" or "crucial" within a given space weather domain. The given example was coronagraphs, specifically SOHO. SOHO is "extremely old" and "not an operational satellite" so forecasters are not always high in the queue. However, it is the main source of coronagraph imagery used in CME detection and forecasting. Without SOHO, "we don't have that capability." In other domains, the following resources were identified as crucial: SDO's AIA and HMI for the heliosphere; ACE and DSCOVR for solar wind; GOES for near-Earth; and ground magnetometers for geomagnetic storm monitoring.

From the assessments, open-response questions, and comments in the focus groups, we were able to identify some general leanings on what makes a resource useful in an operational context and what can be a hinderance:

- Seeing data from the source instrument is considered more effective in creating a robust forecast than models that work off that data (It should be noted that there are more data sources than models in Table 1.)
- SDO and GONG were repeatedly identified favorably for their (1) real-time data, (2) visual resolution/clarity, and (3) robustness.
- There are three obstacles that hinder the effectiveness and/or availability of resources: (1) technical issues that either make the resource unavailable or affect the data such that it is unusable (DSCOVR was brought up often for this, along with SOHO, SEON, and STEREO); (2) the location of the instrument can lower the data's usefulness or makes getting it in a timely manner or at all difficult (STEREO's orbit was mentioned, along with weather and atmosphere issues for ground resources, and lag-time for data delivery from international resources); (3) the fact that these are generally science-designed or science-oriented resources that have been applied to operations, so they are not always available on an operational timetable.

Participants were also asked what other resources they utilized that were not named on the questionnaire. DSCOVR and GOES had the most mentions. Other mentions were geospace Kp; NASA/SPoRT Mag four; the models WAM, CTIPe, ROTI, MUF, CARI7, and GLOTEC; Jhelioviewer; and conferring with other forecast offices. This last was described as being an "invaluable resource."

3.3. Rating of Interactions and Communications

Since the motivation for this study was a shortfall in communication lines, we also investigated how and how often forecasters interact with researchers (1) in general and (2) as part of the tool development process in particular.

3.3.1. General Interactions

In general, "interactions between forecasters and researchers seem to be pretty isolated," with "not a lot of cross-talk." It was noted that there is a large cultural difference, particularly when it comes to the day-to-day operations of the forecast office, as researchers tend to focus very narrowly on a subject field "when the forecaster needs the whole picture."

Figure 3 illustrates how useful forecasters find the various ways they interact with researchers (see Section 2.2) and shows that, when there is interaction, participants find researchers to be most helpful when the interaction and/or communication is part of the daily functioning of the forecast office or project collaboration. Of the latter, projects within the participants' organization are considered more useful than those originating outside. In these interactions, researchers are most helpful as "sounding boards," particularly during "unusual or high-stakes forecasts," due to the insight and different point of view they can provide.

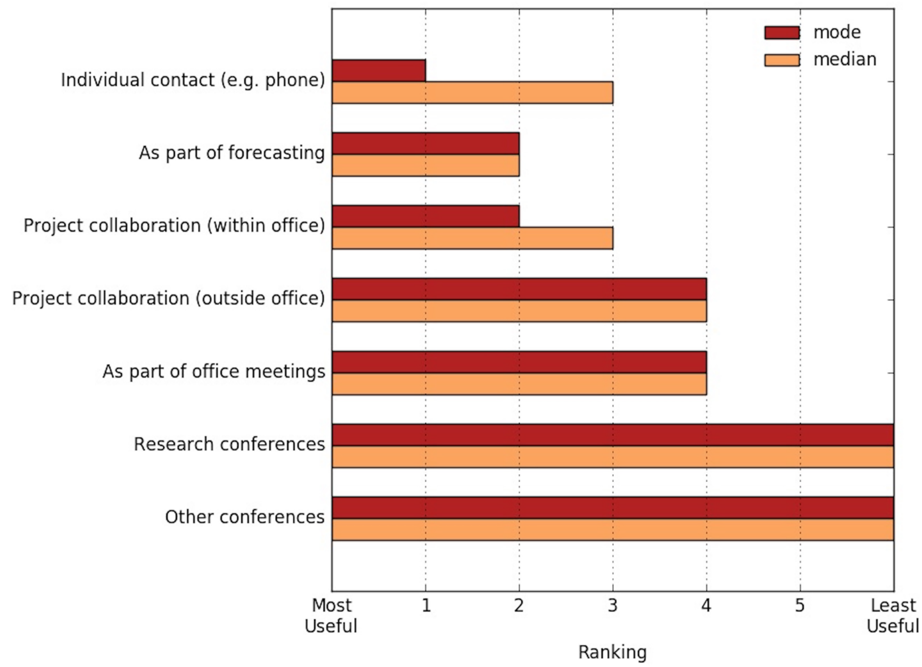

Figure 3. The ranking of various ways forecasters interact with researchers as determined by the mode. For most of the interactions, the mode is equal to the median, indicating a clustering around the median; however, two interactions have modes less than their median, so both measures of central tendency have been plotted. Note this scale is read inversely to those used in Figure 2: a larger number here means the interaction is considered to be less useful (see Section 2.1).

With regards to daily operations and forecasting, the most helpful thing researchers do is primarily "be available to answer questions." Additionally, assisting with model construction, providing insight interpreting model outputs, and determining if the data is physical or instrument noise were listed as helpful contributions.

Conferences in general were not considered useful for the participants, but they were mentioned as useful for "management and IT to make and develop new tools" and as an avenue to "provide 'lessons learned' from operations and to directly address the research community." Some considerations that were not covered in the study protocol were the small number of forecasters, the need to cover a 24/7 schedule, and available travel funds (personal communication). It is unclear whether or not this affected the rankings in Figure 3 and is worth further investigation.

3.3.2. Within Tool Development

Figure 4 presents the participants' assessments of how often forecasters are currently included within the development process of a new forecast office tool (top panel) and how often they would prefer to be included (bottom panel).

Currently, forecasters are involved in tool development on an infrequent or variable basis. When they are involved, it tends to be at the end of the development process and focused on how the information is displayed. It was noted that "often a person is chosen to represent the interests of the forecast office although the individual may or may not have any relevant forecasting experience." This is likely related to the fact that "forecasters are usually not able to go to these meetings often because of the 24/7 schedule we maintain [thus] our needs may not be the priority based on funding, availability of developers, or bureaucratic goals." Another participant noted that it "has improved in recent years… (to a certain extent)" but that what usually happens is forecasters are "presented with a tool that the researchers/developers had developed, based on what *they* thought the best parameters were or what *they* thought [forecasters] needed/wanted" (emphasis original).

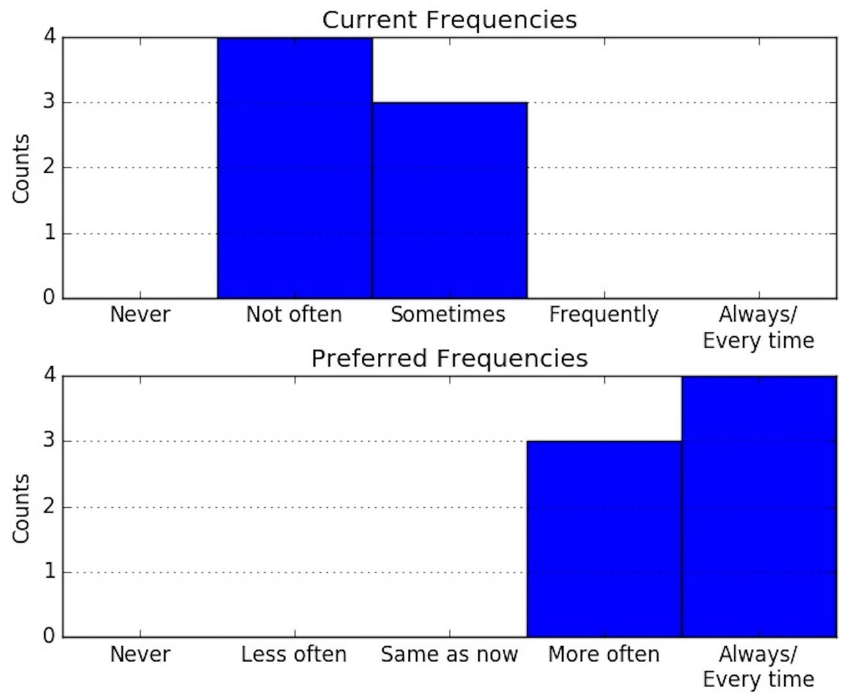

Figure 4. Responses to the questions of how often forecasters are included in the development of a new tool for their use (top panel) and how often they would prefer to be included (bottom panel). All participants agree that forecasters should be included more often.

The participants consider this level of involvement to not be enough and would prefer to be involved more often, with half of the participants saying that they should be included every time a tool is being developed for their use. Participants said they would prefer to be included earlier and in more aspects than how the information is displayed (though they do find that aspect useful), such as how the information would be used in an operational context and the initial selection of projects. It was noted that this would "reduce the amount of refinement a new tool or product requires once it is introduced into operations," instead of, as one participant noted, "here's the next greatest thing which doesn't get used" and that "the best models that we have came from direct collaboration between a forecaster and a developer."

A need for greater forecaster and/or "end user" participation in the R2O process for the ease it imparts to the transition has also been stated by numerous others (e.g., Merceret et al., 2013; NRC, 2003; Robinson, 2012). Steenburgh et al. (2014) describe an example of what tool development can look like when forecasters are included throughout the process.

4. Discussion

The transferability of this study's findings, its "external validity" or the extent to which its findings can be applied outside of the study's context, is difficult to assess with such a small sample size, so we instead do as recommended by Lincoln and Guba (1985) and provide a description of the study's context such that the reader can determine the degree of transferability to their own contexts.

Space weather forecasters do not make forecasts in isolation. They confer with forecasters from other organizations and countries routinely, in some cases daily (Denardini et al., 2016; Murray et al., 2017). Additionally, while local variations in geology and the Earth's magnetosphere can influence how an event will affect a given region, space weather can and does impact large regions of the Earth's hemispheres (Schwenn, 2006) and comes from a single source, making it a global phenomenon. Thus, this study's findings have potential to be generalized to more than just the current participants. In particular, the improvement items listed under Scientific Understanding, Access to Data, and Instrumentation have the potential to be useful to all space weather forecasters. Conversely, Forecast Office Tools and researcher interactions are more context-dependent, so they have a higher probability of pertaining primarily to the population of forecasters surveyed.

As mentioned in Section 2.2, two resource items were removed from the questionnaire data for analysis: in-situ observations and Learmonth Solar Observatory. These items were removed due to overlap with other resources in Table 1, which captured the targeted assessment. The findings in Section 3.2 were not affected by their removal. On a related note, the resources DSCOVR and GOES were not in the questionnaire administered to participants. DSCOVR is the primary solar wind resource, with ACE serving as back-up. The GOES series is responsible for determining the strength of solar flares and also contributes important particle flux and magnetometer data. The absence of these resources on the questionnaire and thus from Figure 2 is a shortcoming of this study. However, both resources were brought up multiple times in open-response and focus group questions, so we are still able to include some qualitative data on their effectiveness, availability, and frequency of use. DSCOVR is a critical operational resource for solar wind data, but it has had technical issues that affect its availability and effectiveness. GOES is a critical operational resource for solar flares and has been termed "pretty reliable" and "a great tool that is readily available." Both are also spacecraft and data sources, further supporting the interpretation that participants appear to prefer those.

There is the possibility that the data illustrated in Figure 2 suffers from ceiling effects. Scales that measure participants' perceptions of a subject are well-known to have ceiling effects (Chyung, Hutchinson, & Shamsy, 2020), and the data distribution is definitively skewed towards higher (more positive) values for all three assessment scales. It is possible that the scales used in the questionnaire were not granular enough to realistically capture the participants' experience, though Chyung, Hutchinson, and Shamsy (2020) note that research into the ability of scales with more than five points to reduce ceiling effects is currently inconclusive. They also note that while a fully anchored scale performs best at reducing ceiling effects, partially anchored scales also perform well compared to completely unanchored scales. For the purpose of a preliminary overview study, we conclude that the scales used here likely have minimal risk of ceiling effects. As stated in Section 3.2, we have interpreted this lack of low-value assessments (e.g., 1 or 2) as meaning that no forecasting resource is completely ignored. The open-response answers and focus group discussions appear to support this interpretation ("It all matters.").

Our aim was to improve R2O2R communications by gathering O2R feedback directly from forecasters. To avoid coloring the communication with our own perceptions, we used direct quotes where possible. Discussing which improvement items are feasible or the steps required to make them so is outside the study's scope (see Section 1.1). Feasibility would be better determined by the research community.

5. Conclusions and Recommendations

In this study, we set out to explicitly fill an O2R communication gap that can lead to well-known delays and complications in the R2O transition process. We did this by formally surveying a group of US space weather forecasters on their needs, resources, and the nature and frequency of their interactions with the research community.

The participants identified 19 items for improvement, which can be organized into four categories: Scientific Understanding, Access to Data, Forecast Office Tools, and Instrumentation. These improvements are summarized in Figure 1. The participants mentioned that a list of needed improvements "would be evolutionary, and always be changing" as new discoveries are made and transitioned into operations.

Participants appear to find seeing the data from the instrument source to be the most effective, with preferences for real-time and robust data with high resolution. However, they currently have so few resources that they will use whatever they can, if it has proven even a little bit effective. The low number of resources means that within an individual subject area (e.g., CMEs), one instrument or spacecraft has become critical to the participants' ability to detect or forecast within that arena. Common hinderances to a resource's usefulness are technical issues, location, and not being an operational resource.

Participants currently do not interact much with researchers outside of forecast construction or project collaboration. When they do interact, they find researchers are most helpful when they can answer questions and provide feedback, particularly during high-activity episodes, and insight and assistance with models and data verification.

The participants do not think they are being included enough in tool development and wish to be included more often and earlier, with half of the participants saying that they should be included every time. They want to be included in the selection process of new tools, determining how that tool could or would be used in an operational context, and how the information is displayed and analyzed.

There are two avenues that would benefit from further investigation. The first is the use of models in forecasting. Only two models were named in the questionnaire, but in comments elsewhere the participants only discussed models as a category and not any one in particular. This seems to be at odds with some of the current R2O conversations which focus on developing or transitioning many new models into operations. It would be prudent to investigate forecaster experience and utilization of models to better direct that R2O effort. The second is the breakdown in forecaster-research communication lines. This study indicates that the breakdown occurs because forecasters and researchers are rarely in the same space at any critical mass for effective communication. Why this is the case is not data that this study was able to acquire. Solutions would be made more effective by further investigation into the challenges around getting forecasters and researchers into the same space. In regards to communication that is not in-person, there are some avenues being developed (e.g., Halford et al., 2019). However, those tend to be project-based; when it comes to general communication, there are few options that are not conferences. One possible solution is to conduct a survey similar to this one at regular intervals. This would provide regular and formal communication, as well as capture changing priorities. If these surveys also include a wider population of forecasters, the findings would be more generalizable and likely sample a wider range of needs.

Appendix A: Questionnaire Sample

The following is a sample of the distributed electronic questionnaire:

Current Resources:

This section asks about the overall usefulness of the resources currently available to construct a forecast.

1. Please rate the following resources on their effectiveness.

"Effectiveness" is defined here as the ability to contribute to an accurate forecast when the resource is available for use.

	1 (not at all)	2	**3 (somewhat)**	4	5 (extremely)	Unsure/Do not know
SDO	☐	☐	☐	☐	☐	☐
SOHO	☐	☐	☐	☐	☐	☐
STEREO	☐	☐	☐	☐	☐	☐
ACE	☐	☐	☐	☐	☐	☐
GONG	☐	☐	☐	☐	☐	☐
Ground magnetometers	☐	☐	☐	☐	☐	☐
Learmonth Solar Observatory	☐	☐	☐	☐	☐	☐
RSTN	☐	☐	☐	☐	☐	☐
SOON	☐	☐	☐	☐	☐	☐
In-situ observations	☐	☐	☐	☐	☐	☐
WSA-Enlil	☐	☐	☐	☐	☐	☐
REFM	☐	☐	☐	☐	☐	☐
Synoptic drawings	☐	☐	☐	☐	☐	☐
Audible alerts	☐	☐	☐	☐	☐	☐
Alert programs	☐	☐	☐	☐	☐	☐

Are there any instruments in particular you would like to highlight (e.g., an instrument that does an especially stellar job and/or which does an especially poor job)? List as many as you like.

2. Please rate the following resources on their availability.

"Availability" is defined here as how often a resource is available, regardless of your desire to use it.

	1 (extremely unavailable)	2	**3 (50/50 chance)**	4	5 (extremely available)	Unsure/Do not know
SDO	☐	☐	☐	☐	☐	☐
SOHO	☐	☐	☐	☐	☐	☐
STEREO	☐	☐	☐	☐	☐	☐
ACE	☐	☐	☐	☐	☐	☐
GONG	☐	☐	☐	☐	☐	☐
Ground magnetometers	☐	☐	☐	☐	☐	☐
Learmonth Solar Observatory	☐	☐	☐	☐	☐	☐
RSTN	☐	☐	☐	☐	☐	☐
SOON	☐	☐	☐	☐	☐	☐
In-situ observations	☐	☐	☐	☐	☐	☐
WSA-Enlil	☐	☐	☐	☐	☐	☐
REFM	☐	☐	☐	☐	☐	☐
Synoptic drawings	☐	☐	☐	☐	☐	☐
Audible alerts	☐	☐	☐	☐	☐	☐
Alert programs	☐	☐	☐	☐	☐	☐

Are there any instruments in particular you would like to highlight (e.g., an instrument that is available all the time and/or which is never available)? List as many as you like.

3. Please rate the following resources on how often they are used when they are available.

	Never	Monthly	Weekly	Daily	Hourly
SDO	☐	☐	☐	☐	☐
SOHO	☐	☐	☐	☐	☐
STEREO	☐	☐	☐	☐	☐
ACE	☐	☐	☐	☐	☐
GONG	☐	☐	☐	☐	☐
Ground magnetometers	☐	☐	☐	☐	☐
Learmonth Solar Observatory	☐	☐	☐	☐	☐
RSTN	☐	☐	☐	☐	☐
SOON	☐	☐	☐	☐	☐
In-situ observations	☐	☐	☐	☐	☐
WSA-Enlil	☐	☐	☐	☐	☐
REFM	☐	☐	☐	☐	☐
Synoptic drawings	☐	☐	☐	☐	☐
Audible alerts	☐	☐	☐	☐	☐
Alert programs	☐	☐	☐	☐	☐

Are there any spacecraft and/or instruments that are only used during particular points of the solar cycle (e.g., only used during solar maximum)? Please describe why that is the case.

4. Are there any resources that were not listed above that are considered essential?

Research Connections:

This section asks about the interaction between the forecast office and the research side of space weather.

1. Please rank the following potential interactions from "most useful" (1) to "least useful" (8).
— As part of constructing a forecast
— As part of meetings at [the office]
— Project collaboration ([within office])
— Project collaboration ([outside office])
— Research conferences
— Other conferences
— Individual contact (email, phone, etc.)
— Other (please specify)

What are the aspects of your top-ranked interaction that make it so useful? What are the aspects of your bottom-ranked that makes it not useful?

2. In your experience, how often are forecasters (either you or colleagues) invited to work on the development of a new tool or the improvement of a current one?

1 = never 2 = not often 3 = sometimes 4 = frequently 5 = always/every time

At this frequency, how are forecasters being asked to contribute?

3. How often do you think should forecasters be included in the development of a new tool or the improvement of a current one, as compared to how often they are included currently?

1 = never 2 = less often 3 = same as now 4 = more often 5 = always

How should forecasters be asked to contribute?

4. In regard to daily operations and/or constructing forecasts, what is the most helpful thing that researchers do or provide?

Appendix B: Focus Group Questions

The following is the list of focus group questions:

1. Which of [your organization's] products should be prioritized for improvement and why?
2. What are some examples of good resources? What makes a resource valuable?
3. Individually, brainstorm for 2–3 min what pieces of information (e.g., "direction of a halo CME") that would improve [your organization's] forecasts of geomagnetic storms.
   a) As a group, come to a consensus on the top 3 to 5.
4. Individually, brainstorm for 2–3 min what pieces of information that would improve [your organization's] forecasts of particle events.
   a) As a group, come to a consensus on the top 3 to 5.
5. Individually, brainstorm for 2–3 min what pieces of information that would improve [your organization's] forecasts of radiation events (e.g., solar flares).
   a) As a group, come to a consensus on the top 3 to 5.

Data Availability Statement

The gathered data are stored in Butler (2021). The quantitative data are publicly available. The qualitative data and focus group transcripts are not publicly available due to the University of Colorado Boulder IRB protocol.

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