Revisions to NOAA's Space Weather Scales

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Cover image: An illustration of the Sun interacting with Earth’s magnetosphere.
Credits: NASA’s Goddard Space Flight Center/Mary Pat Hrybyk-Keith

Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) introduced three Space Weather Scales (SWS) in 1999 as a way to communicate current and future space weather conditions and their possible effects on people and systems. The space weather users base, space weather measurement and forecasting capabilities, and user needs have grown and changed over the past 25 years. As a result, the SWS audience has grown, so NOAA embarked on a process to review and potentially revise the SWS to better serve all users. The NOAA Space Weather Prediction Center (SWPC) tasked the Science and Technology Policy Institute (STPI) to assist in the revision and eventual deployment of the revised SWS. The three scales under consideration for revision are the Geomagnetic Storm Scale (G-scale), the Solar Radiation Storm Scale (S-scale), and the Radio Blackouts Scale (R-scale). The G-scale is a measure of global geomagnetic activity due to solar wind activity and coronal mass ejections. The S-scale is a measure of energetic proton flux associated with the immensity of a solar radiation storm. The R-scale is a measure of x-ray flux from solar flares that corresponds to the strength of radio interference on the sunlit side of the Earth. The SWS are used worldwide to initiate hazard preparedness and mitigation operations, as well as to inform anomaly attribution and research activities.

The study focused on answering the following research questions:

1. What scales are currently being used and how are they being used? (Current state)
2. What is the value (benefits) of the current scales? (Usefulness of the scales)
3. What are the challenges (gaps) of the current scales? (Challenges of the scales)
4. How should the scales change, if at all, to meet the needs of stakeholders? (Proposed changes to address challenges)
5. What phenomena should be captured by potential new scales? (New scales)

STPI engaged with multiple U.S. and international stakeholder groups including the end-user community sectors, U.S. Government decision-makers, space weather service providers, and the public. Over a 10-month period, we facilitated input from nearly 500 people through over 170 engagements including interviews, group engagements or discussions, a request for information via the Federal Register, and a targeted survey. The goal of the engagements was to identify user needs and interests, and to ensure that user views are incorporated into any revision of the SWS. We also reviewed academic literature, government reports, and other relevant materials. STPI analyzed qualitative inputs from the engagements through a coding framework and identified common themes addressing each study question.

What scales are currently being used and how are they being used?

Most participants indicated they use the SWS in some capacity (about 60 percent); however, the degree to which participants use the SWS varies by scale. Most participants use the G-scale (75 percent) while slightly fewer report using the S- and R-scales (50 percent and 46 percent, respectively). Beyond the scales, many users reported using other SWPC products and services that describe space weather events.

Participants predominantly use the scales in five ways: (1) taking action or executing operational procedures for systems; (2) monitoring space weather for current or post-event anomaly attribution; (3) sharing information by communicating space weather activity and its possible effects to their company, community, or colleagues; (4) triggering action to brief leadership or producing briefings to other sector stakeholders; and (5) seeking additional information about the event itself using other data products.

What is the value (benefits) of the current scales?

Participants identified five categories of usefulness of the scales: (1) the scales are simple, easy to follow and understand; (2) user familiarity with the SWS makes them useful; (3) the scales are useful for forecasting and understanding predicted space weather impacts on their systems and to their customers' operations; (4) the SWS are useful for staying abreast of space weather conditions and for understanding general information on space weather; and (5) the historical record that goes along with the scales helps users understand the frequency of space weather events.

What are the challenges (gaps) of the current scales?

This study identified multiple challenges with the current formulation of the SWS. The most common challenge was the shortcoming in the communication of the SWS. Many users expressed that the scales do not provide impact information in a way that allows them to make operational decisions. Space weather is global in nature but the effects are experienced at a localized level and the actual impacts of space weather events depend on external factors that are hard to track. Another challenge is that user communities use the scales differently, and the one-size-fits-all approach (that includes the general public) hampers SWPC's ability to provide high-quality detailed information to audiences that need this level of detail. Users identified a lack of geographic specificity, varied impacts of space weather events across sectors, and insufficient warning time as major challenges. There are also scale-specific challenges including forecasts for the G-scale reflecting a level of precision that is incommensurate with current science. Many users identified issues with the basis of the G-scale, which is bounded at Kp=9 and only updated every 3 hours—

limiting SWPC's ability to accurately communicate the intensity of a geomagnetic storm, particularly at the upper end of the scale, in a timely manner. There was also widespread concern about the radiation dose effects on aviation passengers and crews, and the unsuitability of the S-scale for communicating the risk. While the description of the S-scale mentions human health effects, the S-scale is not an accurate proxy for radiation health risk and the description causes confusion among the public.

How should the scales change, if at all, to meet the needs of stakeholders?

Improving Communication

Participants recommended SWPC improve how they transmit and describe space weather information so it is easier to receive and understand. SWPC could also improve the navigability of the SWPC website, or improve users' ability to find requested products that already exist. The text describing the SWS could also be updated to include more up-to-date effects, convey more information on sectoral impacts, and to use more plain, accessible language. Communication surrounding the scales could also be reformulated to follow best practices in risk communication, which may include providing sector-specific risk-informed action statements.

SWPC could rename the S- and R-scales to better align with the measured phenomenology, lessening confusion on what both scales are conveying. Participants noted that users confuse the S- and R-scales because they commonly associate the letter R with radiation. Furthermore, participants expressed confusion that the Radio Blackouts Scale does not reflect radio blackouts at all frequencies. Members of the aviation stakeholder community were also frequently alarmed by the name Solar Radiation Storm Scale, despite it not having a significant impact on human health.

Incorporating geographic specificity

Participants—especially operational end-users—want geographic specificity with scales, forecasts, and products. Users discussed this change most frequently for the G-scale, but also for the S-scale and associated products that describe impacts on the aviation sector. Geographic specificity could be added to the G-scale through the development of regional K or Ho indices for the United States. Users also discussed that while the global Kp index is still useful, having a regional K index would benefit many G-scale users, particularly the power grid and emergency management sectors.

Expanding the upper end of the G-scale

There was consensus that modifying the G-scale could make it more actionable for users and improve SWPC's Impact-Based Decision Support services. Participants recommended changing the basis of the G-scale from Kp, a bounded index, to Hpo, an unbounded index. Making this change would allow SWPC to expand the upper end of the G-scale and solve the problem of G-5 being used to describe storms of very different intensity. This would allow SWPC to expand the upper end of the G-scale and differentiate catastrophic and non-catastrophic G-5 storms, such as Carrington-like events and the recent Gannon storm.

Improving G-scale forecasting

In addition, SWPC could consider modifying their G-scale forecast to fewer levels, to be more commensurate with their forecasting accuracy. The current levels of the scale reflect a degree of confidence and precision that is not reflected by the forecasting science. Ensuring SWS users have a more accurate understanding of the probability of a forecast may allow them to make better risk-informed decisions.

Clarifying the S-scale

Participants indicated that users frequently misinterpret what the S-scale means for health effects on aviation passengers and crews. SWPC could provide more clarity on the uses of the S-scale while simultaneously striving to release information relevant to the radiation dose exposure of those flying at aviation altitudes.

Maintaining Phenomenon- versus Impact-based scales

Participants expressed support for SWPC to continue basing the scales on measures of phenomenology rather than on impacts, though some end-users expressed an interest in changing the basis of the scales to impacts. Space weather experts suggested that impact-based scales would be too challenging because of the paucity of information about space weather effects across the various user communities operating in geographically diverse locations. However, to address the needs of end-users, SWPC could consider providing sector-specific communication with risk-informed action statements to aid users in decision-making.

What phenomena should be captured by potential new scales?

Participants suggested new scales for SWPC to consider. They expressed interest in a new aviation scale or product, with many participants suggesting a dosimetry index. Participants from the grid sector requested a geoelectric field scale. SWPC already has a nowcast geoelectric field product, with localized geoelectric field data. Many end-users seemed unaware of the geoelectric field product, so more promotion and education of the product could address the user community's interest in a geoelectric field scale. Some participants also suggested ionospheric scintillation and neutral density scales or products to quantify (1) ionospheric-induced disruptions to radio signals passing through the atmosphere and (2) atmospheric changes that affect satellite orbits, respectively. Finally, a few participants suggested SWPC transition to a single space weather scale that would provide a general indication of the space weather environment, rather than multiple individual scales.

Contents

1. Introduction

A. Purpose

The National Oceanic and Atmospheric Administration (NOAA) introduced three Space Weather Scales (SWS) in 1999 as a way to communicate current and future space weather conditions and their possible effects on people and systems. The Geomagnetic Storm Scale (G-scale) is a measure of global geomagnetic activity due to solar wind activity and coronal mass ejections (CME). The Solar Radiation Storm Scale (S-scale) is a measure of energetic proton flux associated with the immensity of a solar radiation storm. The Radio Blackouts Scale (R-scale) is a measure of x-ray flux from solar flares that corresponds to the strength of High Frequency (HF) interference on the sunlit side of the Earth. The SWS are used worldwide to initiate hazard preparedness and mitigation operations, as well as to inform anomaly attribution and research activities.

Space weather measurement and forecasting capabilities, user base, and user needs have grown and changed over the past 25 years. As a result, the SWS audience has grown to include government leadership and various end-user communities, including aviation, emergency management, human space flight, power grid, radio frequency applications (e.g., communications, Global Navigation Satellite Systems [GNSS], radar, radio astronomy), rail, satellites, space domain awareness, and tourism (Aurora). Therefore, NOAA embarked on a process to review and potentially revise the SWS for use by decision-makers and users around the world. The NOAA Space Weather Prediction Center (SWPC) tasked the Science and Technology Policy Institute (STPI) to assist in the revision and eventual deployment of the revised SWS. STPI engaged with a broad range of stakeholders to identify their needs, interests, and to ensure their views are incorporated into any revision of the SWS.

B. Study Questions

The goal of this study is to provide NOAA with a set of proposed revisions to the SWS. Through discussions with the NOAA sponsor, STPI focused efforts on answering the following study questions:

1. What scales are currently being used and how are they being used? (Current state)
2. What is the value (benefits) of the current scales? (Usefulness of the scales)
3. What are the challenges (gaps) of the current scales? (Challenges of the scales)

4. How should the scales change, if at all, to meet the needs of stakeholders? (Proposed changes to address challenges)
5. What phenomena should be captured by potential new scales? (New scales)

Chapter 3 addresses study questions 1 and 2; Chapter 4 focuses on study questions 3 through 5.

C. Stakeholders

To answer the study questions, STPI engaged multiple U.S. and international stakeholder groups: (1) end-user community sectors, (2) U.S. Government decision-makers, (3) space weather service providers, and (4) the public. We identified participants from STPI contacts, NOAA referrals, and participants' suggestions.

1. End-User Community Sectors

STPI reached out to end-users who rely on the SWS to inform preparation, mitigation, research, and anomaly attribution activities within the following sectors:

- Agriculture
- Aviation
- Communications
- Education
- Emergency Management
- GNSS
- Human Space Flight
- Meteorology
- Power Grid
- Precision Drilling
- Rail
- Research
- Satellites
- Space Domain Awareness
- Surveying
- Tourism (Aurora)

We directly engaged members of each sector, except for the rail, agriculture, and precision drilling sectors—whom we were unable to reach. However, our dialogues did include people who work with those communities. Public, private, academic, NGO, and national security sector engagement examples included representatives from the Federal Aviation Administration's Air Traffic Control System Command Center and the National Aeronautics and Space Administration's (NASA) Space Radiation Analysis Group, grid operators and airlines, universities, the International Civil Aviation Organization (ICAO), and U.S. Space Command.

In addition to contacting representatives from each sector, STPI relied on discussions with space weather expert groups, including the Space Weather Advisory Group (SWAG), whose mission includes understanding space weather user needs as directed by the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act of 2020 (Public Law 116-181). We relied heavily on SWAG's 2024 User Needs Survey to identify relevant sectors and understand the space weather challenges faced by the user community (SWAG 2024).

2. U.S. Government Decision-Makers

STPI spoke to government decision-makers by engaging with the White House Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee.[1] The SWORM established a Fast-Track Action Committee (FTAC) composed of SWORM subcommittee members and other nominated representatives. STPI worked with the FTAC to engage government officials so SWS revisions would reflect the desires of U.S. Government decision-makers. The FTAC focused on input from policy offices within the agencies, rather than government "customers" of NOAA data. These customers are considered part of the end-user community described in the previous section, with whom STPI met directly. We gathered FTAC input from the following agencies: Department of Energy, Department of Homeland Security (DHS)/Cyber and Information Security Administration, DHS/Federal Emergency Management Administration, Federal Energy Regulatory Commission, Department of Agriculture, U.S. Geological Survey, and NASA.

3. Space Weather Service Providers

STPI communicated with space weather service providers to understand their capabilities, end-user needs, and how changes to the SWS would affect their operations. These organizations monitor, forecast, and provide timely information regarding space weather events and their possible effects. Non-NOAA providers have adopted and incorporated the NOAA SWS to varying degrees into their customer products and have significant interest in how the SWS might be revised. We spoke to representatives from the following space weather service providers:

- America Latina League for Space Weather
- Bureau of Meteorology - Australian Space Weather Forecasting Centre
- European Space Agency Space Weather Office
- ICAO
- International Space Environment Service
- Natural Resources Canada
- NOAA SWPC
- South African National Space Agency Space Weather Centre
- The Weather Company[2]
- United Kingdom Meteorological Office Space Weather Operations Centre
- U.S. Air Force 557th Weather Wing

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[1] The SWORM is the interagency working group representing the collective interests and capabilities of the Federal Government related to space weather.

[2] Private weather service provider

4. Public

NOAA issued a Request for Information (RFI) seeking feedback from the general public on the SWS and how they should change.[3] Some RFI responses came from end-users, but many also came from the public. Additionally, STPI contacted broadcast meteorologists and science journalists to understand how they communicate space weather events. These engagements helped ensure input related to SWS revisions is accessible to everyone.

5. International Community

STPI collected input from individuals from Africa, the Americas, Europe, and the Asia-Pacific region during planned conferences and meetings. We spoke to people from academia, the commercial industry, and the government, and also engaged with transnational organizations, such as the World Meteorological Organization (WMO) and Committee on Space Research (COSPAR), which coordinate international cooperation and research on space weather and its effects. Through the various engagements, representatives from the following countries and international organizations had the opportunity to provide input and feedback on the NOAA SWS:

- Argentina
- Australia
- Brazil
- Belgium
- Canada
- Chile
- Finland
- France
- Germany
- Ireland
- Japan
- Mexico
- NATO
- Netherlands
- New Zealand
- Norway
- Poland
- South Africa
- South Korea
- Spain
- Sweden
- Taiwan
- United Kingdom

D. Approach

STPI reviewed academic literature, government reports, and other materials shared by stakeholders and experts that had relevance to the SWS. Throughout the course of the study, interviewees shared documents or procedures with the team to illustrate how they use the scales or to recommend changes to the scales. International partners also shared reports and documentation on how they developed their own SWS.

To gather input from the various communities and stakeholders, STPI relied heavily on interviews, group engagements, the RFI, and a targeted survey for those who could not participate in the outreach activities. Engagements were guided by the study questions, but

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[3] NOAA SWS RFI: https://www.federalregister.gov/documents/2024/05/28/2024-11565/request-for-information-on-the-noaa-space-weather-scales-sws

tailored to the specific approach. The results of each engagement were collected and organized by study question and coded into themes, the method for which is discussed in Section E.

1. Interviews

STPI selected stakeholders from our contacts, NOAA referrals, and participant suggestions to gather input from across the sectors. NOAA's introductions enabled us to gather useful feedback from known users of SWPC information. We conducted each interview using a protocol developed from the study questions (see Appendix A for the interview protocol). The team captured high-level takeaways from each interview based on the questions, but also kept recorded transcripts or notes for subsequent review. About three-quarters of the interviews took place virtually; the remaining individuals were interviewed in-person at the space weather events STPI attended. In total, we conducted 63 interviews with 157 individuals. Over half of the interviews were with a single person, and the remaining interviews had, on average, three to four participants.

2. Group Engagements

STPI facilitated four international group engagements in the Americas, Europe, and the Asia-Pacific region to solicit input from leading space weather researchers, policymakers, and users regarding their unique needs and ideas for improving the SWS. One engagement for Europe was hosted in Ireland, two for the Asia-Pacific region were hosted in Australia and South Korea, and one for the Americas was hosted at the Brazilian embassy in Washington, DC. Each engagement had 12–25 space weather experts and users and lasted between a half-day to 2 days, depending on the group's size and expertise.

A STPI team member facilitated discussions with occasional input from NOAA representatives, who were present at all international engagements. A STPI team member took transcript-style notes, then generated high-level takeaways for each of the study questions that were subsequently coded. The discussion topics were closely related to the study questions; however, the agenda was arranged to discuss each scale specifically (G-, S-, and R-scales) and concluded with a discussion on possible new scales.

During the Annual Space Weather Workshop event in Boulder, CO in April 2024, STPI hosted a 3-hour SWS revision event. The event was attended by nearly 100 domestic and international conference attendees from government, academia, and industry. STPI moderated a discussion on the scales, which included four panels with three to four space weather experts and user-community representatives each. STPI developed panel questions based on the study questions and interview protocol. The STPI moderator asked tailored questions to panelists based on their space weather expertise and the sector they represented.

3. RFI

NOAA collected public input through an RFI published in the Federal Register from May 28, 2024 to August 2, 2024.[4] The RFI provided an opportunity for interested parties, including the public, to inform the SWS revision process through a uniform data collection format.

Eighty-one comments[5] were received during the open comment period. Twelve participants submitted comments anonymously, with the remaining 67 participants representing perspectives from 21 U.S. States and 7 countries. Fourteen submissions contained attachments in addition to the comments. STPI identified 5 stakeholder categories represented within the RFI submissions: private citizens (65 submissions), industry (7 submissions), foreign government (5 submissions), nonprofit (3 submissions), and U.S. Government (1 submission). Sixteen of the 81 respondents indicated an affiliation with an organization. Of those 16, 11 were submissions on behalf of an organization and 5 were submissions by individuals affiliated with an organization.

4. Survey

After the RFI closed, STPI fielded a survey that aligned closely with the interview questions to allow unreached participants to provide input to the SWS revision process. The survey was pre-tested with U.S. and international SWS stakeholders. The survey was developed using validated survey instruments to measure the perceived usability and usefulness of the SWS, as well as a series of Likert questions to gauge reaction to possible changes to the SWS. Appendix B contains additional information regarding the survey.

5. Literature

We also reviewed academic literature and government documents on science communication, risk perception, risk communication, and space weather-specific hazard communication. These resources included information from the Centers for Disease Control and Prevention, NASA, and the National Academies of Science, Engineering, and Medicine. The literature search began by exploring canonical authors from the field and also drew on keyword searches as well as adjacent literature either cited by or based on the initial set of results. High-level takeaways were integrated into our analysis of suggested improvements to the scales, with special attention to communication improvements.

In addition, we reviewed a combination of peer-reviewed documents and gray literature, including presentation materials from stakeholders, operating procedures, and websites describing user needs. This information helped us understand how the SWS are

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[4] "Notice; Request for Information on the NOAA Space Weather Scales:" https://www.regulations.gov/docket/NOAA-NWS-2024-0069

[5] Four participants submitted comments twice, and one participant submitted comments three times.

currently used by and useful to stakeholders. Some of these documents also included details on specific proposed improvements to the SWS; such information was included in our analysis and informed the rationale of the proposed new scales.

E. Engagements

STPI began its outreach by organizing an event at the 2024 American Meteorological Society Meeting to introduce the SWS revision project and gather input from conference attendees on our project plan and study questions. This was followed by other large events, including the April 2024 Space Weather Workshop, as well as the Asia-Pacific, European, and Americas meetings. In between these events we held virtual group interviews with attendees from several organizations, such as the SWAG and the North American Electric Reliability Corporation, a not-for-profit international regulatory authority whose mission is to ensure the effective and efficient reduction of risks to the reliability and security of the grid. Table 1 lists the major events and activities undertaken during the study.

Table 1. Major Events and Activities Undertaken During This Study
January to October 2024

Events and Activities	Dates (2024)	Locations
Project Kickoff	January 10	Washington, DC
American Meteorological Society Annual Meeting	January 28 – February 1	Baltimore, MD
Individual and Group Interviews	February 5 – September 30	Virtual
Space Weather Week	April 15 – 19	Boulder, CO
RFI	May 28 – August 2	Virtual
Asia-Pacific Region	May 20 – 24	Adelaide, Australia
European Region	June 24 – 25	Dublin, Ireland
Asia-Pacific Region	July 13 –16	Busan, Korea
Survey	August 7 to October 23	Virtual
Americas Region	October 9	Washington, DC
SWAG Discussion	October 22	Virtual

Over the course of 11 months, STPI gathered input from approximately 480 individuals. Not all individuals provided input at the larger group discussions, but they had the opportunity to learn about the NOAA scales revision activity and were provided opportunities to contribute input. Most interviews involved multiple people who all had the chance to share their thoughts on the SWS. Table 2 describes the type of engagements, as well as the total number of people who participated, responded, or were present.

Table 2. Number of Engagements and Outreach for SWS

Type of Engagements	Number of Engagements	Number of Participants
Interviews	60	171
Sector-specific interviews	58	149
SWAG Meeting	1	12
FTAC participants	1	10
Request for Information	81	81
Survey	25	25
Domestic Group Engagements	2	130
American Meteorologic Society Meeting	1	30
Space Weather Week Panel Discussion	1	100
International Group Engagements	4	76
Asia-Pacific Region (Australia)	1	19
Asia-Pacific Region (Korea/COSPAR)	1	20
European Region (Ireland)	1	25
Americas Region (Brazilian Embassy in Washington, DC)	1	12
TOTALS	**172**	**483**

Note: About 10 individuals were present at multiple events and have been double counted in the totals.

F. Methods

STPI developed a framework to organize, code, and analyze information collected from the interviews, group engagements, and the RFI. While the engagements were structured differently, we qualitatively coded statements and key takeaways that were relevant to the study questions and identified key themes for each question. The input from the interviews, RFI, and group engagements was coded using the same framework. We used a hybrid coding approach called abductive coding[6] that allowed us to develop a new theory about the data based on existing theories and concepts. Survey findings and feedback were analyzed separately (see Appendix C) and were used as supplemental information when discussing individual findings. Themes and ideas discussed five or more times were included in the findings presented in Chapters 3 and 4.

When analyzing the RFI responses, STPI determined the relevancy of the comment to the study questions and only coded those responses deemed relevant. STPI coded 1,037 comments across its interviews, group engagements, and the RFI. Information shared by participants relevant to the main study questions was recorded and transferred into an Excel

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[6] Abductive coding is a hybrid of inductive and deductive qualitative analysis.

spreadsheet where all information relevant to each question was collected. The codebook can be found in Appendix C.

G. Limitations

Several limitations and caveats to the study need to be acknowledged. First, STPI contacted individuals who were known or suggested to us. Consequently, it is possible that our results are not applicable to the entire stakeholder population since this convenience sampling was not a representative sample from the entire space weather stakeholder population. We attempted to contact representatives and key experts from each of the sectors described in Section C. Secondly, not all industries and sectors responded with equal enthusiasm, resulting in more opportunities to engage with people from the aviation, satellite, power grid, and emergency management sectors. We were less successful in gathering feedback from the rail, agriculture, or precision drilling sectors.

Finally, the global reach and diversity of effects of space weather means that stakeholders are from a wide-ranging group, with a variety of technical knowledge and understanding of the SWS and space weather phenomena. When possible, we have clarified remarks by users who indicated a flawed understanding of the scales to more accurately represent their needs. Also, our mission was to understand how people use the scales and what they would like to see changed, irrespective of the feasibility of their solutions.

H. Report Organization

The report is laid out as follows: Chapter 2 provides an SWS overview and background information on space weather phenomena. Chapter 3 summarizes participant input on what scales are most used, how they are used, and how they are useful. Chapter 4 discusses the challenges and options for NOAA to consider when revising the scales. Finally, Chapter 5 offers some key takeaways and next steps.

2. Space Weather Scales Overview

A. Background

The G-, S-, and R-scales are based on measurements of space weather phenomena and have corresponding forecasts (predictions) and nowcasts (current observations). See Appendix A for more information on space weather phenomena, how they induce effects on Earth's environment, and the consequences those effects can have on technology and human health.

The three NOAA SWS use 5-point scales, modeled after the Saffir-Simson scale (i.e., the Hurricane scale), which is likely familiar to U.S. users. The "effects" column of the NOAA SWS tables describes potential ramifications of space weather events on technology and human health.[7] Predicting the effects of space weather is challenging as each event and set of circumstances is unique and could lead to different consequences, especially since effects also depend on non-space weather factors that are hard to characterize. The effects column thus provides cautionary warnings as to what problems *may* happen during space weather events, but does not claim that specific events *will* occur.

B. Characterizing Geomagnetic Storms with the G-Scale

NOAA SWPC, other space weather service providers, and space weather researchers monitor magnetometer data to track the onset of and changes in geomagnetic storms. The magnetometer data are often given in the form of a 3-hour index, called the K-index, which provides a quantitative measure of the changes in local magnetic activity (Combs and Viereck 1996).

The K-index value ranges from 0 to 9 and is directly related to the amount of fluctuation (relative to a quiet day) in the Earth's magnetic field over a 3-hour interval. The higher the K-index value, the larger the change in the Earth's magnetic field, and the greater chance the effects of geomagnetic storms will be experienced. A K-index value is also tied to a specific magnetometer and geographic location. For locations without observatories, researchers need to extrapolate what the local K-index would be by looking at data from the nearest magnetometers. K-index values from multiple locations are averaged to create a global geomagnetic storm index called Kp that quantifies the Earth's magnetic activity

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[7] NOAA SWS tables: https://www.swpc.noaa.gov/noaa-scales-explanation

on a planetary scale.[8] Kp provides the maximum possible intensity of a changing magnetic field that a system can experience at a given location. This index is the basis for the NOAA G-Scale, which quantifies variations to the Earth's magnetic field (Combs and Viereck 1996; NOAA 2024; Matzka et al. 2021). The G-Scale projects Kp index values, with a Kp of 5 as the threshold to designate a G1 event (weakest), and a Kp value of 9 and above to designate a G5 event (strongest; Figure 1).

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[8] Kp is derived from 13 global magnetometer observatories located in the mid-latitudes (45–61.2 degrees) above and below the equator. Predictions of Kp are usually based on solar wind parameters measured by satellites like Advanced Composition Explorer or Deep Space Climate Observatory, which are located at the "L1" region 1.5 million kilometers from the Earth along the Sun-Earth line.

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

Figure 1. Geomagnetic Storm Scale (G-Scale) Description

C. Characterizing Solar Radiation Storms with the S-Scale

Solar radiation (proton) storm intensities are quantified by proton flux measurements on the NOAA Geostationary Operational Environmental Satellites (GOES). The GOES satellite detector measures the arrival of protons with a variety of energies equal to or greater than 10, 50, 100, and 500 million electron volts (MeV). Solar proton storms are classified using the NOAA S-Scale. The S-Scale is determined by the number of high-energy protons reaching Earth per second, per unit area, per unit solid angle, and relates different magnitudes of particle flux units (pfu) to each of its 5 levels.[9] A proton event of 10 pfu is an S1 (weakest) and one of 100,000 pfu is an S5 (strongest). The higher the S-Scale value, the greater the chance that systems will be affected to a greater degree (Australian Government Bureau of Meteorology 2024; NOAA 2024a; Figure 2).

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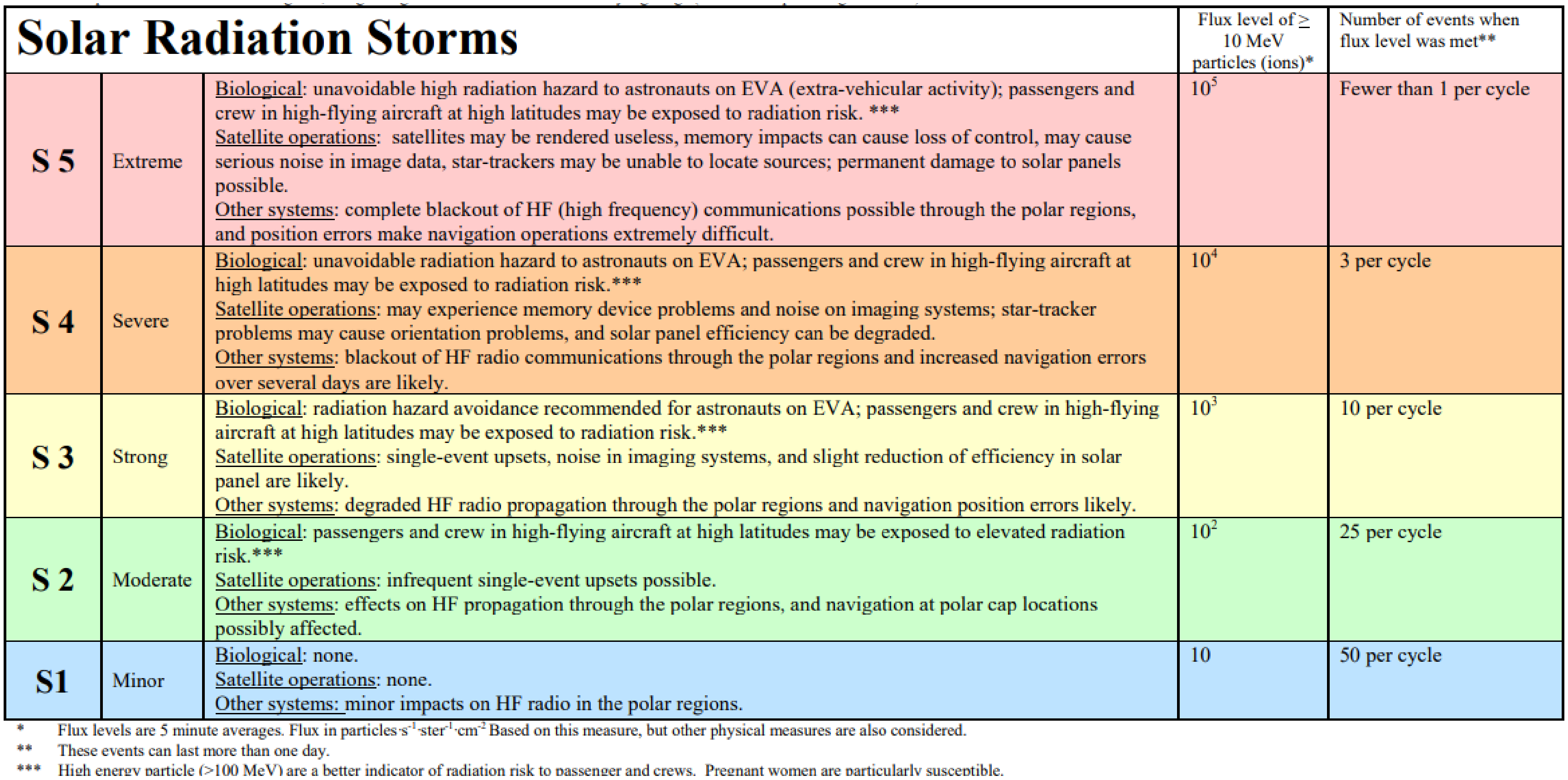
[9] One pfu is equal to 1 proton with an energy of 10 MeV or greater reaching Earth per second, per unit area, per unit solid angle.



Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles$\cdot s^{-1} \cdot ster^{-1} \cdot cm^{-2}$ Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Figure 2. Solar Radiation Storm Scale (S-Scale) Description

D. Monitoring and Characterizing Solar Flares and Radio Blackouts with the R-Scale

Solar flare intensities are quantified by x-ray radiation from the Sun arriving at the Earth as measured by the NOAA GOES satellites. The measured x-ray energy corresponds to the strength of shortwave HF radio interference on the sunlit side of the Earth. The x-ray intensities are classified in terms of peak emission in the 0.1–0.8 nm spectral band and described by a sequence of classes—A, B, C, M, and X—with X-class flares being the most powerful eruptions. Each letter represents a ten-fold increase in energy output. Each letter category below X is further divided into nine subdivisions; for example, M1 to M9, where an M9 flare is nine times more powerful than an M1 flare. Notably, the X class of intensities continues past 10 as there is currently no higher letter category.

The NOAA R-Scale classifies the additional radio interference effects of HF radio blackouts over five levels, with an x-ray event of the weakest intensity (M1) being R1 and the strongest (X20+) being R5 (Figure 3). The higher the R-Scale value, the greater the chance that systems will be affected to a larger degree (NOAA 2024b; Australian Government Bureau of Meteorology 2024).

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2x10^{-3})	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 (5x10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in W·m^{-2}. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

Figure 3. Radio Blackouts Scale (R-Scale) Description

The R-Scale does not capture the effects of solar radio bursts, which are intense emissions of radio waves across a wide range of frequencies that can interfere with radio signals, such as GNSS, communications, and radars. Solar radio bursts may or may not be associated with solar flares (Ishii et al. 2024; Knipp et al. 2016; Cerruti et al. 2008; Marqué et al. 2018).

E. Watches, Warnings, and Alerts

SWPC issues watches, warnings, and alerts when (1) there is the potential for an event, (2) an event is imminent, or (3) an event is detected, respectively. They disseminate watches, warnings, and alerts for geomagnetic storms; warnings and alerts for solar radiation (proton) storms; and alerts for x-ray induced HF radio blackouts (Table 3).

Table 3. Notifications Based on Space Weather Scales

Storm Type	Associated Scale	Watch	Warning	Alert
Geomagnetic	G-Scale	X	X	X
Solar Radiation	S-Scale		X	X
Radio Blackout	R-Scale			X

A geomagnetic storm watch is issued when there is a risk of a G1 event or greater, even if its occurrence or timing is uncertain. Watches provide advance notice (typically 1–3 days) to organizations whose mission or equipment is affected by geomagnetic activity so they can execute contingency plans. SWPC uses coronagraph imagery from the GOES-19 Compact Coronagraph and the NASA SOHO satellite to observe and characterize CME attributes, including velocity, angular width, and origin. This information is then entered into a model that estimates the CME arrival time. Geomagnetic storm watch intensity is not based on model output, as the model only provides arrival time information. Predicted intensities are based on forecaster intuition and experience of observing similar events. The model's uncertainties and subjective decision-making involved limit SWPC's predictive ability on an event-by-event basis. Geomagnetic storm watches are provided at the G1, G2, G3, and "G4 or greater" levels. The Space Weather Follow-On Lagrange 1 (SWFO-L1) will provide such capability when it becomes operational, within the next year (Steenburgh 2024; National Environmental Satellite, Data, and Information Service 2025).

Geomagnetic and solar radiation storm warnings are issued when a significant geomagnetic or solar radiation storm is imminent or likely. A warning is a short-term, high confidence prediction of imminent activity. Measurements of low energy electron flux received from NASA's Advanced Composition Explorer (ACE) spacecraft can provide early indication and insight into the intensity of an approaching CME and solar proton event. In addition, ion measurements from ACE can be used to predict geomagnetic storm intensity. Geomagnetic storm warnings are based on DSCOVR and ACE measurements. DSCOVR and ACE measure the magnetic field and the velocity distribution functions of solar protons, electrons, and ions. These observations occur about 30 minutes before CMEs interact with the Earth's magnetic field and surrounding environment. When DSCOVR or ACE detect a CME, SWPC issues a Sudden Impulse Warning to notify customers of the CME's imminent arrival at Earth. SWPC may issue geomagnetic storm warnings based on the initial measurements of the CME magnetic field. Geomagnetic storm warnings are provided at the G1, G2, and "G3 or greater" levels. SWPC issues solar radiation storm warnings for an expected S1 or higher event at geosynchronous orbit using a statistical model that suggests whether a proton event is possible and if so, when it will occur and how strong it might be. The radiation warnings are also based on measurements of the environment taken by the GOES spacecraft (Steenburgh 2024).

Alerts, unlike watches and warnings, indicate that the applicable geomagnetic, space radiation, or solar x-ray flux thresholds have been exceeded. SWPC issues alerts when the NOAA geomagnetic or solar radiation storm level is reached (G1 through G5 or S1 through S5). They will also issue a solar radiation alert when the 100 MeV proton flux is expected to reach 1 proton flux unit or a radio blackout alert when a solar flare occurs (R2 through R5; Steenburgh 2024).

While SWPC does not issue solar radiation watches or radio blackout watches or warnings, they do provide probabilistic forecasts for each phenomenon. They provide 3-day forecasts on the probabilities of S1 radiation storms as well as R1, R2, and "R3 or greater" radio blackout events occurring (Steenburgh 2024). Details on other SWPC products and alerts can be found in the National Weather Service Instruction 10-1101 (NOAA 2024i).

3. Space Weather Scales Usage

STPI developed a framework to qualitatively code responses and systematically categorize excerpts from the interviews, group engagements, and RFI into themes. Each theme captures recurring concepts within the textual data, allowing us to organize unstructured data for analysis and interpretation. In this chapter, we discuss the results from this approach along with our survey findings (where applicable) to provide insight into what SWS respondents use, how they use the SWS, and how useful they perceive them to be. See Appendices B and D for a detailed discussion of the coding and survey analyses, respectively.

A. What Scales Are Used?

Most participants said they use the SWS in some capacity. However, the degree to which participants use the SWS varies by scale; most participants use the G-scale and slightly fewer report using the S- and R-scales. SWPC produces a host of products describing space weather events, beyond the SWS, and many users reported using products other than the SWS or conflated other related SWPC products with the scales.

Of the more than 200 people who participated in the group engagements and interviews, 60 percent reported using the SWS. Seventy-five percent reported using the G-scale, 50 percent reported using the S-scale, and 46 percent reported using the R-scale. In contrast, of the 25 people who responded to the survey 92 percent reported using the G-scale, 96 percent reported using the S-scale, and 79 percent reported using the R-scale. More than one-third of survey respondents reported having SWS-based procedures (see Appendix D for more details). The surveyed population may have been skewed towards SWS users, given they were a subset of a captive user base who wanted to provide more input to the study.

Users in every sector we engaged said they use the G-scale, but there were also respondents across the sectors that rely on other space weather indices and products, such as Kp, instead of the G-scale. Users in all but one sector (i.e., tourism) said they use S-scale. Most S-scale users we engaged with came from the aviation, GNSS, and satellite operations communities. In regard to the R-scale, most users came from the aviation community—with some users identifying as the general public, or from the human space flight, research, or tourism sectors. We cannot definitively say users from a specific sector do not use a particular scale since we do not know if our participants reflect the uses and opinions of the entire space weather stakeholder population.

B. How Are the Scales Used?

STPI categorized participant use of the scales into five different themes: (1) Taking action: create procedures to dictate their response based on different SWS values; (2) Monitoring: monitor space weather for current or post-event anomaly attribution; (3) Sharing information: communicate space weather activity and its possible effects; (4) Trigger to brief leadership: produce and deliver briefings to stakeholders; and (5) Seeking additional information: prompt the search for additional information about the event. The following section describes a definition for each theme ordered by its frequency. A few respondents mentioned that they did not directly use the scale, but monitored other SWPC products or services during space weather events.

Many international space weather operations centers that were queried in this study either track the SWS or have their own variation of the SWS. These organizations monitor the NOAA website and SWS levels; if the SWS status changes, the international operations centers either utilize the SWS in their own forecasts or as a point of comparison to their own information, especially when determining if actions need to be taken.

1. Taking Action

The SWS are used by some participants to trigger action, such as posturing systems, employing mitigations, or altering activities. This category includes any action that is not communication or seeking more information. For example, the aviation sector uses the scales to restrict operations on different routes and the power grid sector may delay maintenance activities and switch operating procedures from cost-saving measures to continuity assurances ones.

Power Grid

One power grid operator uses the G-scale to monitor the global geomagnetic activity. This information is combined with local magnetometer and measured geomagnetically induced current (GIC) data to determine likely system effects. When G4 is reached, they alert their operational staff to prepare for an event that may affect the operation of their power system. At G5, they may start executing mitigating actions outlined in their operational procedures, including:

- Recalling all available transmission and generation plants from outage,
- Reconfiguring the grid to minimize the total GIC,
- Running industry coordination meetings, managing real and reactive power flows,
- Restoring the power system if outages occur, and

Responding to and providing advice to local and national emergency managers on the likely extent and effect of the storm as it unfolds.

2. Monitoring

Participants described how they use the scales to watch the level of space weather activity and categorize it. In some cases, monitoring could include being aware of the space weather situation, and in other cases it may simply be categorizing current space weather conditions. This includes planning for possible changes. Participants that use the scale for monitoring do not execute operational procedures based on specific SWS values. Participants indicated a need for awareness so they can identify or eliminate space weather as a possible cause of anomalies or degraded functionality of their systems. For example, military users need to distinguish hostile satellite communications or radar jamming from space weather-induced scintillation effects, as these behaviors can look similar.

3. Sharing Information

Some participants used the scales as a tool to help communicate the current status of space weather conditions and their possible effects with internal and external stakeholders. This includes broadcast meteorologists informing the general public that a space weather event may be occurring, releasing public warnings, and communicating preparedness information. These participants indicated this type of communication was to educate and inform stakeholders by making them aware of the current space weather conditions. Those receiving this information may not have to take action as they do not operate systems that would be affected by a severe space weather event.

National Security

One international military respondent told us their organization uses the SWS to estimate space weather effects on different technologies as follows:

- G-Scale for estimating effects on HF skywave communications, satellite communications (SATCOM), and GNSS. When G3 and above is achieved, they send dedicated messages to units, informing them of possible effects.
- S-Scale for estimating effects on satellite systems, high altitude radiation as well as polar region HF Skywave communications and SATCOM interference.
- R-Scale for estimating effect on HF skywave communications, SATCOM, and radar interference. When R3 and above is achieved, they send dedicated messages to units, informing them of possible effects.

4. Briefing Leadership or Other Stakeholders

Another way in which the scales were used was to trigger briefings to leadership and targeted groups who would need to be aware about possible impacts to systems. Participants expressed that action would not necessarily be taken, but a change in level to the scale would prompt a briefing to system operators and, in particular, to leadership in potentially affected sectors. In contrast to taking action, the use of this scale is to provide a level of awareness to operators. In one case, a respondent stated, "for anything beyond G3, we send a dedicated message to units, informing them of possible impacts. However, we have no control of courses of action, only recommendations."

Aviation

The airline and air-freight companies STPI interacted with have documented pre- and in-flight polar operational procedures based on the SWS. Each company reacts to space weather events differently, but in general they will *at least*:

- Confer with space weather service providers, management, and long-distance operational control and air navigation service providers for G2, S2, and above events;
- Consider rerouting to ensure SATCOM availability and adding fuel reserve for lower altitude flying when G3, S3, and above events occur (some start at G2, S2);
- Plan flights at normal altitudes, but ensure planes contain fuel reserve for lower altitude flying when conditions are S3 or below but forecasts are expected to meet or exceed S4 (some will not plan polar routes when S4 is forecast or R3 occurs);
- Plan flights at a lower altitude for S4 and S5 events;
- Advise departed flights of the S-scale conditions and recommend they descend to a lower altitude when S4 conditions are reached; and
- Coordinate with long distance operational control and air navigation service providers and consider changing to a route that ensures SATCOM coverage if the blackout area is anticipated to affect planned routings for any R-level.

5. Seeking Additional Information

Participants used the scales as a trigger to seek additional information on space weather depending on the scale level. These stakeholders gather additional data by reviewing different SWPC products and transition from a passive to active space weather monitoring posture. In these instances, participants sought out details about the event timing and regional consequences, or increased monitoring based on a scale level. This is different from other responses, as participants utilize the scales to indicate when to have a heightened awareness of space weather activity or their effects.

Many international space weather operations centers that were queried in this study either track the SWS or have their own variation of the SWS. These organizations monitor the NOAA website and SWS levels; if their status changes, the international operations centers either utilize the SWS in their own forecasts or as a point of comparison to their own information, especially when determining if actions need to be taken.

C. How Are the Scales Useful?

While some participants answered this question, a majority of those with whom STPI engaged were more focused on ways the scales could be improved rather than ways in which the scales are useful. For those that responded to the question, STPI categorized responses into six categories: simplicity, user familiarity, forecasting, space weather general knowledge, standardization, and historical information. Some users indicated that the scales were not useful in response to this question. Survey respondents concurred with the interview findings and perceived, on average, the SWS to be slightly useful.

Responses to this question frequently described the scales as simple or easy to follow, and their simplicity makes them easy to understand. Participants' familiarity with the SWS was also frequently highlighted as a factor that makes them easy to use. Participants identified them as an uncomplicated and recognizable tool for capturing and communicating space weather conditions at a high level. Participants noted that the SWS provide a standard, common-language description of space weather that facilitates the exchange of space weather information between interested parties. STPI notes that most of the participants who highlighted standardization for this question were international stakeholders.

Aside from the simplicity and user familiarity associated with the scales, participants noted that the forecasts provided through the scales are useful for stakeholders. Participants who indicated usefulness through forecasting used the scales to understand predicted space weather impacts on their data and to their customers. Some participants also noted the usefulness of the SWS for staying abreast of space weather conditions and for understanding general information on space weather. Finally, participants also discussed the usefulness of the historical information log of the scales, which helps users understand the frequency of space weather events.

Several participants responded to this question by indicating that the scales are not useful. For example, one participant from the satellite sector specified that the S-scale is not useful for ground-level enhancement hazard information. Another participant described that while space weather predictions are useful, the scales themselves are not useful. Other participants also discussed only using the data associated with the scales for their operations, rather than the SWS. One participant noted that a lack of understanding of the scales and their nuances make the scales "not very useful for the public."

4. Space Weather Scale Challenges and Revisions

Through our qualitative analysis of comments from interviews, group engagements with stakeholders, and RFI responses, the STPI team identified common themes around challenges to using the current SWS. Some of the challenges reflect expert opinions, and some reflect common misconceptions we heard from stakeholders who are less familiar with space weather. Based on information analyzed, the major challenges reported fell into four categories: communication of scales information was challenging to understand or interpret; the measurements underpinning the scales are not ideal for describing the space weather phenomenon; effects to systems due to severe space weather events are in many cases not well understood and vary greatly by sector and geography; and scales are sometimes being used incorrectly or not as intended.

These challenges are discussed in the following sections along with potential revisions to the SWS as suggested by the stakeholders who participated in this study. We included proposed changes from coded engagements if they were mentioned five or more times. Each suggested improvement is motivated by a challenge followed by a description of how this challenge can be addressed. Where possible, we provided additional context and detailed suggestions on how to address the challenge and provided NOAA a suggested timeframe to pursue these revisions. The timeframe for potential revisions is structured as follows:

- **Short-term options** are those actions that should be executable in 1 to 3 years and should cause minimal disruption to the community or stakeholders. These options are the "quick wins" of what we heard, and if implemented, could go a long way toward addressing some of the challenges, particularly related to communication, mentioned by the community;
- **Medium-term options** are those that we estimate can be implemented in 3 to 5 years, and will require more discussion, consideration, and buy-in from the community. NOAA would need to embark on these options with an understanding that some current scales users could be negatively impacted by these changes, and they would have to assess the implications for these communities; and
- **Long-term options** are those that are more visionary in nature and could take place in the next 5 to 10 years. These options will all require more research, community engagements, and further refinement.

STPI notes that some of the potential revisions identified by the space weather community contradict one another. While this section offers potential revisions to the scales, it does not fully address the feasibility of implementation of these changes.

A. Improve the Written Communication of the Space Weather Scales

Though several participants described the scales as helpful in assessing the severity of a space weather event, some participants disagreed and discussed how the language of the scales is complex and difficult for some users to understand. These participants mentioned that jargon, acronyms, and probabilistic language within the scales create a barrier of understanding for general users. Despite the findings from the previous section where some participants indicated the scales were "easy to use," more participants indicated that the text used in the scales is not written in plain language and is not accessible for many users. It takes some users significant time and effort to understand the scales as they are currently written. Users also mentioned difficulties finding impact advisories on space weather.

Participants also highlighted that the current description of the scales is not up-to-date, and the scale names—particularly the S-scale and R-scale—were misleading. Within this broader category of improving the written communication of the scales, we identified 11 unique suggestions for revisions, all of which can be implemented in the short-term.

1. Improve the User Experience of the SWPC Website Related to Scales Information (Short-Term)

Many RFI respondents suggested improving the accessibility of SWPC's website, in ways such as updating the time zone of SWPC notifications to include all U.S. time zones, making historical data easier to access, and making the definitions of the scales simpler.

Based on stakeholder engagements, we suggest that a more intuitive website with clearly displayed information would avoid confusion and allow stakeholders to take advantage of all of SWPC's work. STPI notes that throughout its engagements with the space weather community, participants asked for products or services that SWPC already provides, which may imply that these products or services are not easily accessible for those seeking related information.

2. Change the Text of the Scales

a. Use Plain, Accessible Language in the Scales (Short-Term)

RFI participants and information from other stakeholder engagements suggested the scales be written in simple language that is more understandable by non-space weather experts. They suggested that improving the language in the effects and the likelihood of occurrence sections could be beneficial to users. While many space weather experts can easily decipher the language in the scales, some non-scientist scale users may struggle to understand and can sometimes misinterpret how space weather affects their systems, which influences how they do their jobs or execute their missions. Two opportunities for improvement include the preamble introduction to the SWS on the NOAA SWPC website and the terminology used in the SWS effects column. For the preamble section, SWPC may consider adding improved definitions or descriptions of geomagnetic storms, solar radiation storms, or radio blackouts; their measures of intensity or frequency of occurrence; or the scale limitations.

Regarding the effects column, participants highlighted how some terminology describing SWS effects is confusing to non-scientists, which can lead to misunderstandings of what systems can be affected during space weather events. For example, not all participants realize (1) *high frequency (hf)* and *low frequency* have specific definitions and applications, resulting in them interpreting that the scales indicate other frequency bands and their uses are affected; and (2) low frequency navigation is not GNSS navigation, making people believe GNSS might have issues when the SWS refer to low frequency navigation.

Furthermore, STPI suggests defining terms that have technical definitions and explaining how to use them. For example, SWPC could make clear that HF radio is used for a selected set of over-the-horizon applications and the effects associated with that HF band are separate from other frequency bands, such as those used for satellite communications or cell phones. Some participants suggested providing examples in parentheticals after each technology type is introduced. For example, *satellite navigation* and *low-frequency radio navigation* could become *satellite navigation* (e.g., *GPS and Galileo*) and *low-frequency radio navigation* (e.g*., Loran land-based radio navigation*) the first time each term appears.

Finally, some participants pointed to the *Australian Space Weather Alert System* document (Australian Government Bureau of Meteorology 2024) and the *Space Weather Effects on Technology* video (Australian Government Bureau of Meteorology 2024a) as illustrative examples of conveying space weather information and the SWS well. These exemplars pair written and verbal explanations with graphics, making space weather and its effects more accessible to non-scientists.

b. Update SWS to Describe How Space Weather Affects Modern Technology (Short-Term)

The scales, which were written in 1999, describe the impacts of space weather on then-common technologies. However, since then, newer technologies—such as cell phones, satellite broadband internet, satellite voice, line-of-sight very high frequency (VHF), and GNSS—have become essential parts of modern life that can also be affected by space weather disturbances. Nevertheless, impacts on older technology, like HF radio, remain important for emergency response and aviation applications. Some participants, like new Low-Earth Orbit (LEO) operators, believe that space weather only affects outdated technology and not the systems most commonly used today. LEO satellite operators want to know how SWS satellite effects apply in LEO since they were written at a time when most satellites were in geosynchronous orbit (GEO).

STPI suggests that SWPC update the descriptions of how the space weather disturbances captured by SWS can affect commonly used modern technologies. For example, SWPC could clearly state that HF communication refers to a limited set of uses, including backup communications for emergency managers and the aviation community. SWPC could also explain that references to HF interference do not necessarily mean that systems commonly used by people—such as satellite phones, internet, TV, and cell phones—will experience noticeable issues. One participant suggested that SWPC explicitly state that modern communication technology can be impacted by space weather, but that effects will be more limited than on shortwave HF radio.

c. Provide Scale Average Frequency Information on Day, Week, Month, and Year Timelines (Short-Term)

Some participants found it hard to understand how often specific types of space weather events occurred over a specified time period. They described two main issues. The first is that it is unclear what is meant by "Average Frequency." The second challenge is understanding and interpreting the implication of the 11-year solar cycle in the SWS left-most column header as well as the relationship between "X per cycle" and "Y days per cycle" in that column's entries. They suggested that converting the SWS "Average Frequency" information from events per solar cycle into a more common frequency measure would improve understandability. One possibility is to provide a range of frequencies depending on the time horizon to solar maximum.

d. Provide Risk-Informed Action Statements (Short-Term)

Some participants discussed how the lack of information around impacts makes the scales not actionable. They highlighted how the scales do not provide sufficient impact risk information for some users to understand what action is required of them or their system. While the scales are based on space weather phenomenology, many users expressed a need for nuanced and specific information related to effects on their sector.

Users suggested SWPC consider replacing the list of possible effects with action statements, such as: "Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid" or "Energy networks may need active management or monitoring." Using action statements aligns with the theory of risk communication that states that preparedness is strongly correlated with the belief that one can take effective actions to mitigate the risk (i.e., that you can prepare and that your preparation will mitigate risks; Wachinger et al. 2013). Providing examples of effective actions to mitigate space weather risk would likely help stakeholders prepare for space weather events. However, providing information on the risks of space weather so that users can make informed decisions is complicated because space weather and its effects are still not well understood.

e. Provide Information on S-scale Effects for Aviation (Short-Term)

Aviation space weather stakeholders expressed confusion regarding the S-scale and adverse impacts of space weather radiation on human crew and passengers. SWPC may consider clarifying to SWS users that 10 MeV protons are not a threat to airline passengers and crews flying at commercial cruising altitudes. Many stakeholders suggested updating the descriptions of the scales to reflect the current scientific understanding of which proton energies put commercial airline crews and passengers at risk. Some participants suggested removing the biological aviation effects language for the S-scale entirely; 10 MeV protons, on which the S-scale is based, are unable to penetrate the atmosphere into commercial aircraft.

Because the S-scale is often misunderstood and misused, many experts suggested educating users about the appropriate uses and real meaning of the scale. SWPC could consider adding a plain-language disclaimer above the S-scale informing the reader of the S-scale's limitations and how the scale should be interpreted. This could help stakeholders understand that the S-scale is not a good proxy for human health effects of radiation at aviation altitudes. The disclaimer could let people know that the S-scale is a hazard warning proxy for possible effects experienced by systems and humans due to their interactions with solar protons.

3. Rename the Scales

a. Rename R-Scale (Short-Term)

Participants discussed how the name of the R-scale, "Radio Blackouts Scale," is misleading because it falsely implies the scale is for radio blackouts across *all* radio communication frequency bands. However, the R-scale predominantly reflects the effects to skywave HF signals, which is a small portion of the radio spectrum, leaving line-of-sight communication and other portions of the spectrum unaltered.[10,11] Emergency managers, in

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[10] The Radio Blackouts Scale captures the interrelationship between solar flare x-rays and absorption of electromagnetic waves as they traverse the D-layer of the ionosphere. HF radio waves, primarily in the 3 to 30 MHz Band, suffer complete absorption, or blackouts, from interaction with the ionospheric D-layer.

[11] See Appendix A for more details.

particular, may incorrectly expect a total radio blackout across all radio frequencies based on the R-scale. Users have suggested not referring to the R-scale as a "Radio Blackouts Scale" and proposed instead calling it a "High Frequency Radio Blackouts Scale" or something similar to indicate the specific range on which the scale is focused. If such a change is made, the R-scale description should explain that the D-layer absorption may be accompanied by other frequencies experiencing interference effects due to scintillation.

International group engagement participants noted that both the G-scale and S-scale names are associated with environmental disturbances—while the R-scale's name is tied to the effects people observe rather than the disturbances that cause it. If having a name commensurate with the other scales is important, the R-scale's name could be changed to "X-ray Flux Scale" or something similar.

b. Rename S-Scale (Short-Term)

Participants, especially from our international engagements, suggested the name of the S-scale be changed. Participants indicated that the name "Solar Radiation Storm" is misleading because the phenomenon measured is solar protons, not radiation as the name implies. The name "Solar Radiation Storm" is interpreted as being inclusive of all forms of radiation, which creates unnecessary alarm among the public. Many non-scientists have a negative perception of radiation, which contributes to public alarm. STPI also notes the scale does not include all types of solar radiation as both X-rays and visible light are forms of radiation not covered by the "Solar Radiation Storm" scale. Therefore, more closely tying the scale name to the metric the scale is based on (i.e., proton flux measurements) would help scale users focus on the information the scale coneys. Some participants suggested renaming the S-scale to "Solar Energetic Particle Scale," "Solar Proton Scale," or "Solar 10 MeV Proton Scale."

Some users also confused the S- and R-scales, as they associate the letter "R" with radiation. It is unclear how or if the letters associated with the R- and S-scales should change, if the names change—but careful consideration should be given before an "R" or "S" change because some users have incorporated the scale letters into their operational procedures. SWPC may consider giving advance notice that the name and/or letter associated with the scale is changing long before such a change is implemented.

B. Increase Outreach and Education on Space Weather Scales (Medium-Term)

Participants highlighted the need to educate non-space weather experts and the public on the scales and how to interpret or use the scales. Non-scientist users and the public need to understand how space weather may affect them and how best to react to anticipated space weather. One illustrative RFI response requested SWPC make the public more aware of space weather and its potential impacts: "the agency needs to have an information campaign for the public to learn about space weather and its effect on earth-bound systems."

However, the communication literature notes that simply communicating the science may not be sufficient to inform stakeholders, particularly if it is important for the audience to make specific decisions. According to the National Academies of Sciences, Engineering, and Medicine, the "deficit model" of scientific communication (i.e., where if people simply had access to more information they would make different decisions) is inaccurate. Decision-making depends on a range of personal and societal contexts, taking into account more than scientific information (National Academies of Sciences, Engineering, and Medicine 2017). STPI suggests that SWPC apply effective risk communication strategies in its communication of the scales and space weather events. Interactive communication, for example, is a particularly effective form of risk communication as it empowers the audience and reflects preferred learning styles of adults. This is particularly true if messengers explain an organization's actions, address local concerns, and provide accurate, honest, and timely updates (Steelman and McCaffrey 2013). Adopting best practices in outreach and communication from other parts of the National Weather Service (NWS) and from the academic literature could help SWPC communicate what the SWS mean to a range of users.

C. Provide and Explain Uncertainty of Forecasts so Users Understand the Limitations of the Information (Medium-Term)

There is currently a mismatch between the accuracy users anticipate from SWPC's forecasts and the accuracy the scientific measurements are able to deliver. Participants indicated a degree of uncertainty in forecasting space weather events that is not clearly communicated to users. As one interviewee stated, "Current scales imply a certain level of precision and certainty that we just don't have. We don't have a high level of confidence."

A majority of survey respondents indicated that adding uncertainty or error information about the SWS forecasts or nowcasts would improve the usefulness of the SWS. Researchers and forecasters noted the difficulty of making accurate predictions. The severity of geomagnetic storms, in particular, can only be predicted once the direction of its magnetic field is known and that cannot be measured until a CME, or fast-moving solar wind, reaches the DSCOVR and ACE spacecraft located at L1. Even after a CME reaches those spacecrafts, the magnetic field direction can continue to change. This means that even for a big CME, induced GICs could be negligible if the CME's magnetic field orientation is the same as the Earth's magnetic field orientation.

To address users' concerns about uncertainty, STPI suggests that SWPC explore how to quantify and explain the probability of space weather events occurring and the uncertainty associated with SWPC's forecasts. Multiple studies have indicated that users with access to uncertainty information understand forecasts better than those without and that presenting that information graphically often allows users to understand the information more quickly (Marimo et al. 2015; Roulston and Kaplan 2009). Additionally, appropriately presented probability information can allow users to make better decisions (Ripberger et al. 2022). However, probability and severity can be misunderstood or used interchangeably, so it is important to specify which is being discussed (Ripberger et al. 2022).

Some forecasters at SWPC already add some information on the likely impacts of a geomagnetic storm, but this could become a required part of the forecast information. SWPC could adopt best practices in communicating probability information from other parts of the NWS that have the benefit of lessons learned from terrestrial weather communication. Working with NOAA social scientists and communication experts could also help SWPC determine the optimal way to communicate about uncertainty and probability in space weather forecasting. Additionally, as sophisticated space weather end-users have expressed a desire for more information about the uncertainty in SWPC's space weather models, providing that information could be an easy win.

Additionally, many stakeholders have the misconception that impacts associated with a particular scale level will *always* occur when a space weather event reaches a particular scale level. This misunderstanding leads to confusion among some stakeholders and has led to "reaction fatigue" for some users because the stated effects often do not match end-user experience. This is a particular challenge with space weather events that are low probability but high impact. Helping users understand the likelihood of the event occurring and the range of possible impacts would allow them to make decisions according to their own risk tolerance and judgements. At minimum, providing a plain-language description of the variability of space weather phenomena and how this makes forecasting challenging would help manage users' expectations.

D. Differentiate Between Catastrophic and Non-Catastrophic Space Weather Events

Many participants discussed that the SWS levels are not aligned with the effects of space weather they experience. Space weather experts find it challenging to translate G5, S5, and R5 events into impacts users encounter, and SWS users do not find their experiences to match the dire consequences they expect from an "extreme" event. One participant said, "This can have the unfortunate side effect of sensitizing the media, government agencies, and general [public]; reporting can be overblown when an event is at the lower end of the scale and underreported or misinterpreted as being benign when an event is at the upper end of the scale."

Gannon Storm – May 2024

In May 2024, one of the most intense space weather events since the 2003 Halloween storms occurred. For approximately 10 days, the Sun cast a number of intense solar flares and CMEs toward Earth resulting in G5 conditions causing power grid operators and the aviation sector to take actions to mitigate the effects of the intense storm. In addition, the satellite and the GNSS sectors also experienced effects. But the storm's intensity was not as high as the Carrington Event that took place in September 1859 (SWAG 2024).

Respondents discussed this challenge across all the scales, but highlighted it as a specific issue for the G-scale, where power sector users have difficulty connecting the G5, and other G-levels, to effects on their systems. For example, G5 Carrington-class[12] storms could have catastrophic effects, while other G5s, such as the May 2024 Gannon Geomagnetic Storm, have minimal effects. They mentioned that the inability to distinguish between consequential and inconsequential events makes it difficult for them to scope their response based solely on the SWS. Emergency managers and some operational agencies also echoed this sentiment. Notably, the minimal effects to operational systems from the Gannon storm have been influenced by the space weather community's work over the past 10 years to help power grid operators mitigate against severe space weather events (SWAG 2024). As a result of these efforts, G5s near the G4/G5 threshold are now less consequential and perhaps should be distinguished from catastrophic G5s.

Participants recommended the three following options to help SWS users differentiate between catastrophic and non-catastrophic space weather events:

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[12] One study participant observed that the existing G5 category covers all events from approximately 250-350 nanoteslas per minute magnetic field change to beyond 6,000 nT per minute magnetic field change. The Gannon storm magnetic field change was approximately 280-240 nanoteslas per minute and the Carrington-class event between 1,000 and 6,000 nanoteslas per minute.

1. Reframe Scale Description Qualifier “Extreme” for Severe Events That Do Not Imply Dire Consequences (Short-Term)

Some participants recommended NOAA replace “Extreme” as a description qualifier with a word that more closely matches people’s experience so that the description is commensurate with effect. They also suggested only using “Extreme” when referring to a Carrington-class event.[13] One group of respondents suggested the scales could be renamed as follows:

- G/S/R5= “Severe”
- G/S/R4 = “Strong”
- G/S/R3 = “Moderate”
- G/S/R2 = “Minor”
- G/S/R1 = “Nominal”

Another suggestion was to use the terms “Unfavorable, Moderate Impacts, Slight Degradations, and Favorable” to describe the top four levels.

2. Add Qualifier for G5 Storms (Short-Term)

In addition to renaming the SWS description qualifiers, some participants recommended a modifier to G5s. For example, the UK Met Office predicted the Gannon storm as a “low” G5, in an attempt to convey the magnitude of the event compared to a worst-case “high” G5 scenario, such as a Carrington-class storm. Modifiers such as these would help users determine consequences. Other ways to distinguish a truly catastrophic storm from less consequential storms include using a color code for low- and high-G5s, adding a warning symbol or catastrophic tag, or providing a written statement indicating how the current prediction or conditions compare to Gannon- and Carrington-class storms.

3. Expand the Number of Scale Levels (Medium-Term)

Many users suggested adding one or more levels above 5 to help distinguish between high and low consequence storms at the severe level (5). Stakeholders suggested G1–G4 stay the same, G5 encompass extreme events, and higher G-values capture up to and beyond Carrington-class events. One respondent suggested defining G5 to capture geomagnetic field storms with magnetic field changes between 250 and 1,000 nanoteslas per minute (nT/min) and having every additional 1,000 nT/min step be another G-level. This would mean that G6, G7, and G8 would be associated with magnetic field changes of

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[13] The Carrington Event refers to an 1859 geomagnetic event with the most severe storm intensity on record. The storm led to visible auroras around the world and degraded telegraph communications. A similar event today would likely have much wider effects given the modern proliferation of technology.

1,001–2,000 nT/min, 2,001–3,000 nT/min, and 3,001–4,000 nT/min, respectively. Any expansion needs to maintain the historical structure of G1–G4 and not require historical records to be reclassified. Also, because the G-scale is based on Kp and Kp is capped at Kp = 9 (corresponding to G-5), any change to the G-scale would require replacing Kp with another metric.

Although a majority of those who suggested expanding scale levels specifically addressed the G-scale, several participants also suggested adding a level 6 to the S- and R-scales to communicate the difference between large and extreme storms. One participant further suggested adding a level at the bottom of the R-scale (i.e., R0) to communicate the lack of ionization in the atmosphere at solar minimum, which can also cause HF radio communication problems.

In contrast to expanding the scales at the upper end, some stakeholders mentioned they thought it was important that the SWS remain 5-point scales so that they match the more well-known Saffir-Simpson and Enhanced Fujita scales for hurricanes and tornadoes, respectively. While some may consider this superficial similarity to be important, we note that other global weather severity scales (i.e., earthquakes and tsunamis) follow a 12-point scale convention. There is little to no information in the literature that references the value of a 5-point scale over other types. In fact, the 12-point tsunami scale, which was proposed in 2001, was preferred over a 6-point scale because it had fewer problems with saturation at the upper end of the scale (Lekkas et al. 2013).

E. Reduce the Number of Scale Levels

In contrast to expanding the scale levels, some stakeholders suggested reducing the levels in the scales commensurate with the accuracy of what can be forecasted.

1. Simplify the Scales into Fewer Levels to Match Forecasting Precision (Medium-Term)

While many stakeholders expressed a desire for *more* levels, several space weather experts—especially forecasters and members of the space weather scientific community—mentioned that the scales currently imply a level of precision *in forecasting* that the science cannot support. However, survey respondents were evenly split regarding the idea of whether simplifying the SWS into fewer levels would improve their usefulness. As the scales are based on phenomenon measurements, the observational precision can match the scales' specificity and even be enhanced to more levels, but the *forecasting* precision cannot. This criticism is salient for the G-scale, which is the only scale where specific levels are forecast. Currently forecasters use a combination of solar wind data, visual inspections of the Sun, and experience to make predictions for the G-scale. In general, forecasters felt more comfortable forecasting to a 3-point scale where phenomena were classified as minor, moderate, or strong. Some even suggested a simple binary forecast of storm or no storm (watch or no watch) for the G-scale, similar to how the S-scale is currently used for forecasts.

Additionally, some have argued that categorizing natural hazards themselves can cause issues communicating adequately to the public. The Saffir-Simpson scale, which classifies hurricanes as Categories 1–5, has been criticized for doing a poor job communicating the severity of hurricane intensity beyond wind speed to the public. Members of the public sometimes react to Category 1 hurricane forecasts with complacency, despite predictions of dangerous and severe flooding or storm surges, which the scale does not capture (Miller 2019). Other scientists have suggested new scales for hurricanes that are based on physical measurements other than wind speed, and have also proposed 6-point and 10-point scales (Harris 2022). Since the NWS has adopted a policy endorsing Impact-Based Decision Support Services and terrestrial weather communication is moving towards providing more impact and risk information, STPI suggests that SWPC follow the same course of action.

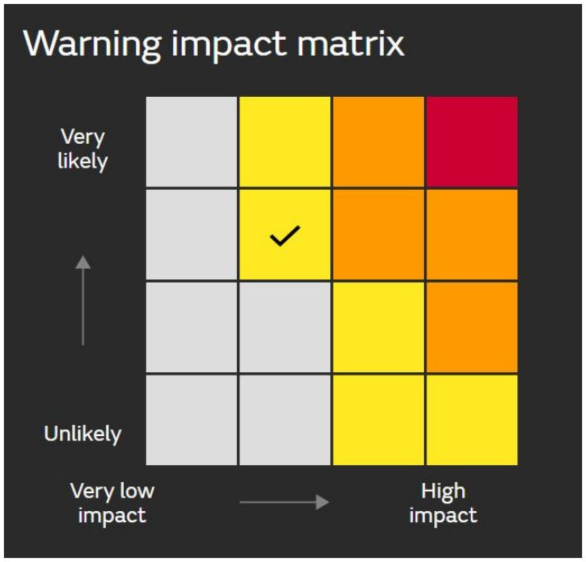
2. Use the Red, Amber, Green Color Scheme Instead of Scale Numbers to Describe the Urgency and Severity Communicated in the Scale (Medium-Term)

The aviation community, in particular, wanted information about space weather and the scales conveyed with color coding. Multiple aviation stakeholders, including from the Federal Aviation Administration and industry, mentioned that aviation information is always color coded and that a similar color-scheme would be helpful in communicating about space weather. While the NOAA SWPC website features the scales in a color-coded format (Figure 4), some participants discussed that the scales do not match their preferred color scheme. Participants indicated that SWPC should consider color coding the space weather products, warnings, watches, and alerts to help the airline industry and other stakeholders with limited knowledge who need easily digestible information.

Possible examples for color-coded space weather information are below, including how SWPC presents the SWS on their home page. Figure 5 explains how the UK Met Office color codes its warning impact matrix, and Figure 6 is an example of the color-coded key for a Met Office Space Weather Operations Centre product.

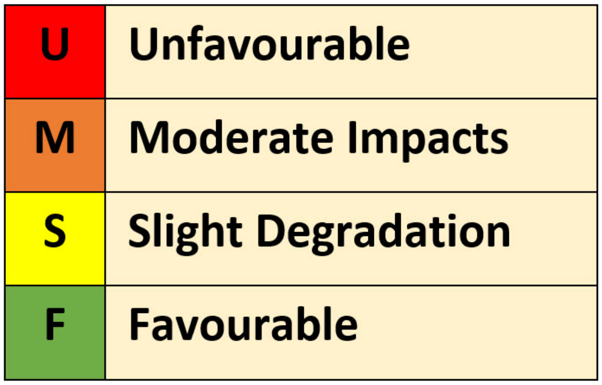
Source: https://www.swpc.noaa.gov/

Figure 4. Example of Current Color Scheme of Scales



Source: https://www.metoffice.gov.uk/weather/guides/warnings

Figure 5. UK Met Office Warning Impact Matrix Color Scheme



U	**Unfavourable**
M	**Moderate Impacts**
S	**Slight Degradation**
F	**Favourable**

Source: Reproduced from email from mark.gibbs@metoffice.gov.uk to dpechkis@ida.org on 7/1/24

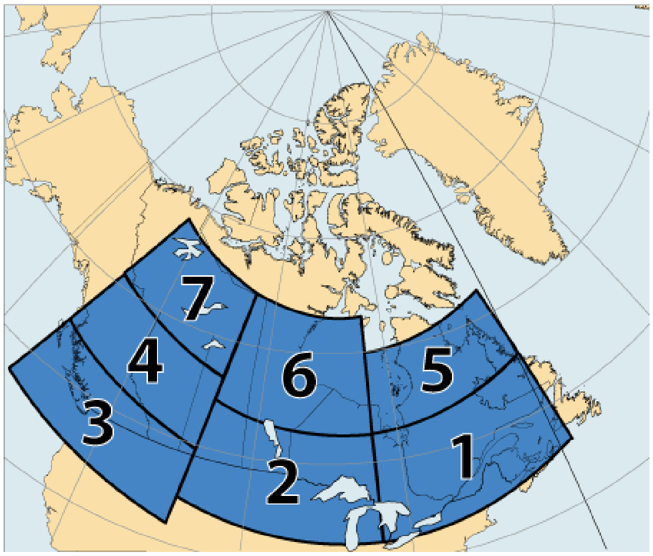
Figure 6. Met Office Space Weather Operations Centre Space Weather Impact Information Example

F. Incorporate Geographic Specificity into the Communication of Space Weather Hazards (Medium-Term)

Environmental conditions, due to solar activity, vary across the United States and around the world; this leads to different geographical regions observing distinct technological effects, which are sometimes inconsistent with the different SWS levels. Participants said the scales would be more useful if they were tailored to geographic regions. The SWS contain indices of planetary activity that capture the different environmental disturbances on a global, not regional, scale. However, participants want to know the "weather" in their "neighborhood."

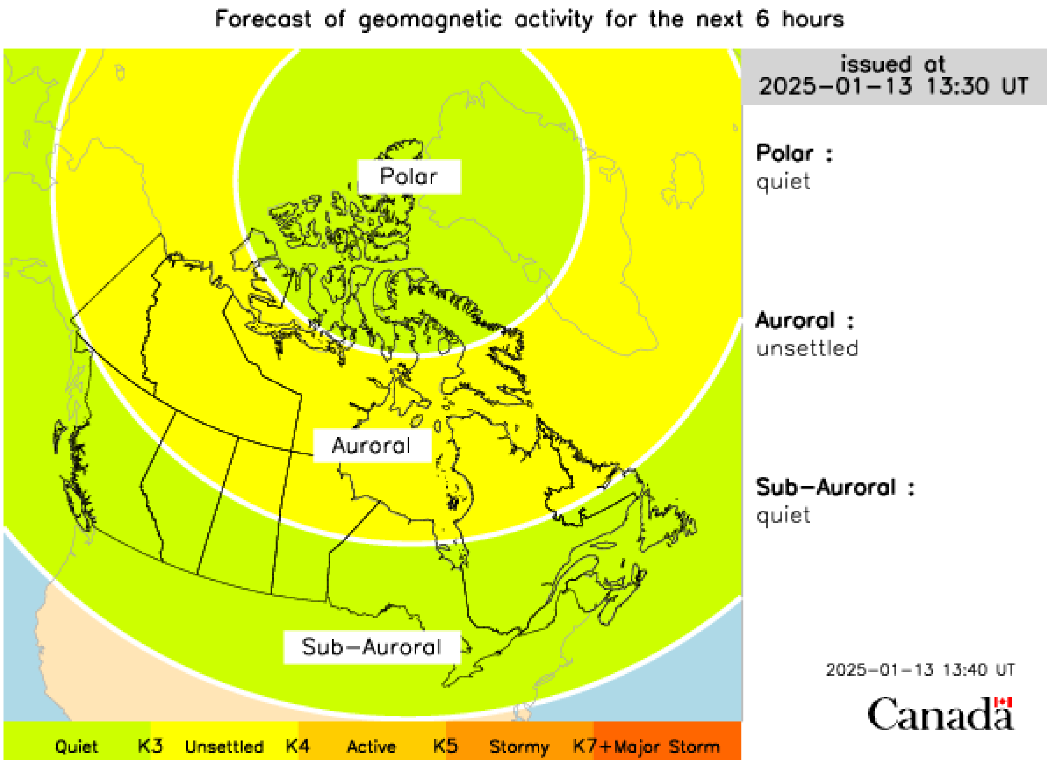
Associating the G-scale with regional information was one of the most requested improvements from the people we interviewed. For example, some U.S. grid participants wanted to know about geomagnetic and geoelectric field activity levels, which vary widely across the United States and in the geographic locations they operate. A localized alert would help grid operators and surveyors know to expect GICs in their systems. Similarly, airline operators desired charged particle information at high resolution for latitude, longitude, and altitude to tell them how the environment may affect cabin crews and passengers across a particular flight path to inform routing decisions. Emergency managers wished to know what radio frequencies are available in disaster zones so they know what communication systems they can rely upon during an event. However, many of those same people acknowledged the benefits of having a planetary scale, such as airline companies that fly all over the world, and like having a sense of the global conditions.

Local geomagnetic variations can be captured by local indices. Participants noted that other countries, such as Australia and Canada, provide regional information akin to the G-scale and Kp index. The Australian Space Weather Forecasting Centre produces K_{Aus}, a regional K index specific to Australia, to communicate the magnitude of geomagnetic storms over Australia (Australian Space Weather Forecasting Centre 2025). National Resources Canada publishes a regional K index, Kr, which is approximately equivalent to the local K indices for each of its seven zones, shown in Figure 7. They also forecast Kr over each of these seven zones, as well as provide K index values and forecasts for three larger regions: polar, auroral, and sub-auroral, as shown in Figure 8 (National Resources Canada 2024).



Source: https://www.spaceweather.gc.ca/forecast-prevision/short-court/regional/sr-en.php

Figure 7. Zones of Canada's Kr Index



Source: https://www.spaceweather.gc.ca/forecast-prevision/short-court/zone-en.php

Figure 8. Canada's Zonal Reporting and Forecasting of Geomagnetic Activity

International participants from the equatorial region expressed a need for localized R indices to differentiate between the stronger HF effects they experience compared to those observed in the northern latitudes and described by the R-scale. They have observed lower classes of solar flares leading to HF radio blackouts that are not expected based on the published R-scale.

STPI suggests NOAA consider developing regional G- and R-scale indices or providing other products that capture regional information. The regional G-scale could follow the G_{Aus} approach and maybe the R-scale effects could be separated by region for the different R-scale values. Additionally, almost all survey respondents indicated that adding geographic specificity to the scales would make them slightly more useful, with the majority saying such an addition would be extremely useful.

G. Change the Basis of the G-Scale from Kp to Hpo (Medium-Term)

Participants identified several limitations to the G-scale based on limitations of the Kp index. Because the upper limit of Kp is 9, any changes in the Earth's magnetic field activity after Kp level 9 are rated the same way, regardless of magnitude or effect. Another limitation to Kp is that it measures variations of the Earth's magnetic field within a predefined 3-hour window. Therefore, because the G-scale is based on the Kp index, its measurements could be off by up to 3 hours (Yamazaki et al. 2022). Furthermore, systems are not only affected by the magnitude of a geomagnetic storm, but also by how quickly the field varies and the duration of the storm. For example, longer duration geomagnetic storms lead to more time for unwanted geomagnetically induced currents to flow through powerlines, potentially leading to transformer overheating and failure.

Participants recommended NOAA replace the Kp index with the Kp-like planetary geomagnetic activity index, Hpo,[14] as the G-scale's physical basis. Hpo's 30-minute resolution would allow the G-scale to capture temporal features within 30 minutes instead of 3 hours. Hpo is an open-ended index that differentiates the strongest geomagnetic storms that get grouped under Kp = 9 and G-scale = 5. Research has shown that variations in Hpo are consistent with that of Kp (Yamazaki et al. 2022). Given that Hpo was designed to behave similarly to Kp, but with higher time resolution and without an upper limit, it mitigates two of Kp's limitations, making Hpo a viable replacement on which to base the G-scale.

Changing the basis of NOAA's G-scale would not impact the Kp index. Several RFI respondents misunderstood the intent and stated they did not want the Kp index changed, which is *not* an SWPC SWS. SWPC is not responsible for the Kp or Hpo index. These indices are maintained and provided by the German Research Centre for Geosciences (GFZ Helmholtz-Zentrum für Geoforschung 2023).

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[14] "H", "p", and "o" stand for half-hourly or hourly, planetary, and open-ended, respectively.

H. Make Improvements to the S-Scale (Long-Term)

Participants discussed specific challenges with the S-scale. The S-scale is based on the flux of 10 MeV protons and used as a proxy for radiation exposure for aircraft passengers and astronauts. However, participants noted research that demonstrates how aircraft passengers and crews are not at risk until proton energies are greater than or equal to 500 MeV because protons with lower energy cannot typically penetrate through the upper atmosphere and into aircraft (Meier and Matthiä 2014; Meier et al. 2020; Bain et al. 2023). Participants described that astronauts receive increased radiation doses if the proton energy is in the 30 to 50 MeV range; at this energy level, protons can penetrate spacesuits and thinly shielded spacecraft or habitats (Chancellor et al. 2014; Reames 2021). Therefore, participants highlighted that the effects listed within S-scale's description do not equate to the likely consequence of interacting with 10 MeV protons.

Converting the S-scale from being based only on the 10 MeV proton energy threshold to a matrix based on multiple thresholds such as 10, 50, 100, 500 MeV would make the S-scale more applicable to other applications such as human space flight, satellite operations, and aviation.

1. Tailor the Communication to Serve Specific Stakeholders and Sectors More Effectively (Long-Term)

Throughout the study, participants expressed interest in understanding the intended audience of the scales. STPI notes there is currently no consensus on who the scales' audience is (i.e., the general public or operational users). However, the scales are *used* by a wide range of people with varying levels of space weather knowledge across diverse sectors. Several participants suggested tailored, audience-specific, or sector-specific information delivered as scales or products because creating scales to satisfy all audiences is a challenge. Successful scientific communication should be tailored to the situation, which makes defining the use cases and audience for the scales important (National Academies of Sciences, Engineering, and Medicine 2017). For example, some participants suggested that space weather information be targeted at only technical sectors and emergency managers because the public does not need to take action based on the scales. Additionally, participants highlighted that for some critical sectors, like national emergency management authorities, it is important that information be communicated clearly when critical infrastructure is at risk and if there are actions to be taken. Alternatively, some participants suggested that it was problematic to alert people about a potential hazard when there was no relevant action for them to take.

STPI recognizes that providing information that is general enough for the public and specific enough to be of use to technical sectors in the same scales is a difficult task. Each sector or domain has unique information and communication needs. SWPC may consider serving the diverse needs of the users of the scales by prioritizing critical communities and providing these audiences with specific language, risk factors, and action steps, while maintaining a scale or alert on general space weather conditions for the public.

2. Move Towards End-User Specific Products and Services (Long-Term)

Some study participants suggested NOAA should move away from the SWS and adapt user-specific products and services. The SWS audience has differing backgrounds, expertise, and use-cases; however, they try to communicate complex phenomena, in simple terms, to U.S. and international stakeholders across multiple sectors, government areas of responsibility, recreational space weather users, and the public. Many participants opined that no single or limited set of communication tools can provide every stakeholder adequate information to understand how their systems, jobs, or missions could be affected by space weather. However, user-specific products and services—including forecasts and nowcasts—could give audience-specific information, such as effects on communications, GNSS, and the power grid in a user's area of operations.

The UK Met Office Space Weather Operations Centre has developed a suite of user-specific, color-coded products that provide information on specific space weather effects geared towards user-specific needs.[15] For example, Figure 9 shows a four-level color-coded chart of space weather effects on communication systems and GNSS over the UK. The chart covers frequency bands from a very low frequency band (3 to 30 KHz) to extremely high frequency (30 to 300 GHz), as well as for single- and dual-band GNSS and GNSS timing. It informs users of the most severe radio interference, up to 2 days in advance, that can be expected from space weather. Based on the color coding, users can anticipate if they are likely to experience issues based on the classification of conditions. Such a product, possibly tailored towards specific sectors, may provide more actionable information than the current SWS without introducing unnecessary complexities. Additionally, the underlying logic driving the color coding can be adapted as new knowledge or information is gained about the space weather impacts on the technologies used by a specific user or user group. In this instance, the output to the user remains unchanged and therefore requires no change to their operating procedures.

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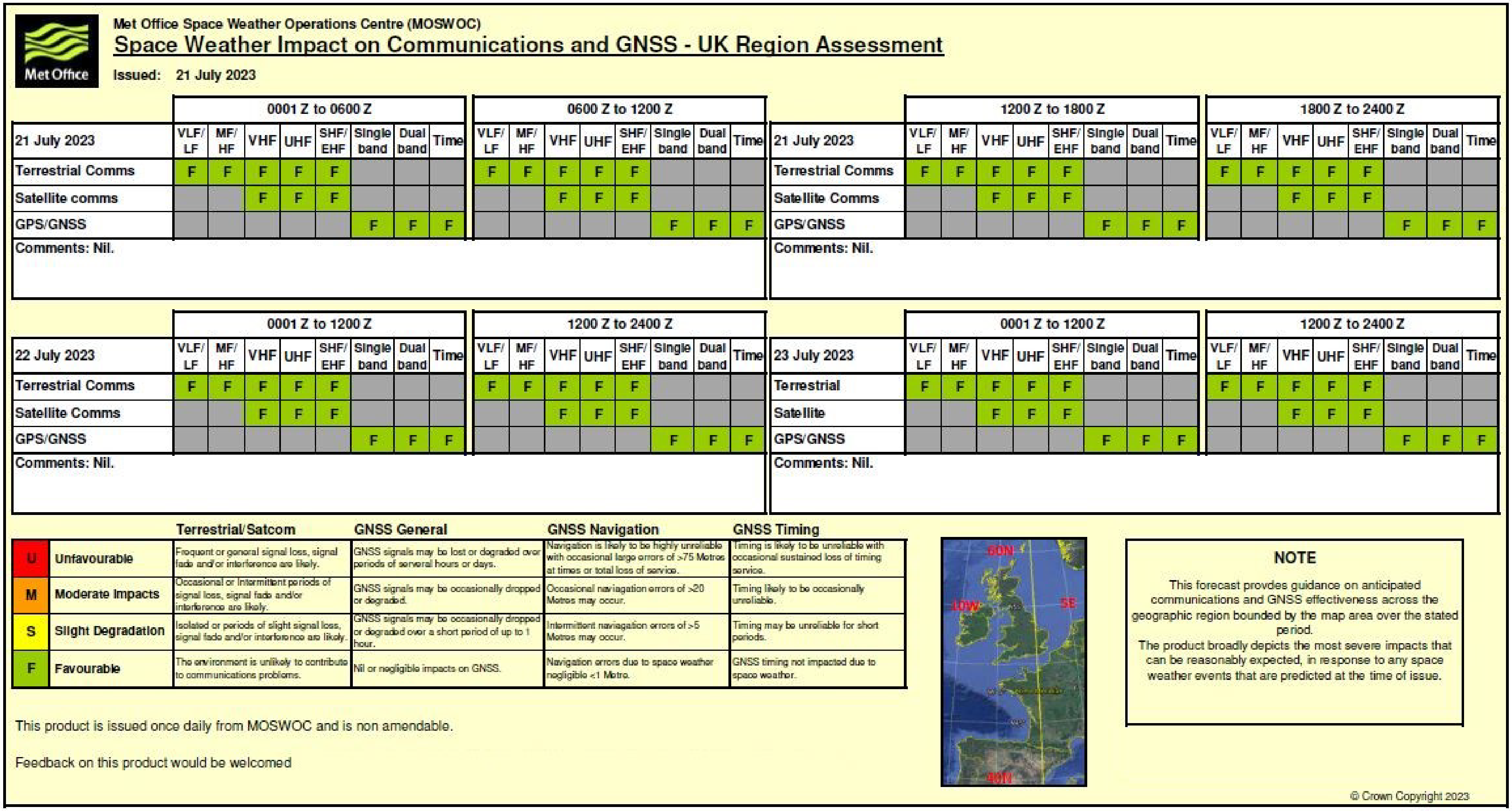
[15] Communication between STPI and UK Met Office



Met Office

Met Office Space Weather Operations Centre (MOSWOC)

Space Weather Impact on Communications and GNSS - UK Region Assessment

Issued: 21 July 2023

0001 Z to 0600 Z

21 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite comms			F	F	F			
GPS/GNSS						F	F	F

0600 Z to 1200 Z

21 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite comms			F	F	F			
GPS/GNSS						F	F	F

Comments: Nil.

1200 Z to 1800 Z

21 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite Comms			F	F	F			
GPS/GNSS						F	F	F

1800 Z to 2400 Z

21 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite Comms			F	F	F			
GPS/GNSS						F	F	F

Comments: Nil.

0001 Z to 1200 Z

22 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite Comms			F	F	F			
GPS/GNSS						F	F	F

1200 Z to 2400 Z

22 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial Comms	F	F	F	F	F			
Satellite Comms			F	F	F			
GPS/GNSS						F	F	F

Comments: Nil.

0001 Z to 1200 Z

23 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial	F	F	F	F	F			
Satellite			F	F	F			
GPS/GNSS						F	F	F

1200 Z to 2400 Z

23 July 2023	VLF/ LF	MF/ HF	VHF	UHF	SHF/ EHF	Single band	Dual band	Time
Terrestrial	F	F	F	F	F			
Satellite			F	F	F			
GPS/GNSS						F	F	F

Comments: Nil.

		Terrestrial/Satcom	GNSS General	GNSS Navigation	GNSS Timing
U	Unfavourable	Frequent or general signal loss, signal fade and/or interference are likely.	GNSS signals may be lost or degraded over periods of serveral hours or days.	Navigation is likely to be highly unreliable with occasional large errors of >75 Metres at times or total loss of service.	Timing is likely to be unreliable with occasional sustained loss of timing service.
M	Moderate Impacts	Occasional or Intermittent periods of signal loss, signal fade and/or interference are likely.	GNSS signals may be occasionally dropped or degraded.	Occasional naviagation errors of >20 Metres may occur.	Timing likely to be occasionally unreliable.
S	Slight Degradation	Isolated or periods of slight signal loss, signal fade and/or interference are likely.	GNSS signals may be occasionally dropped or degraded over a short period of up to 1 hour.	Intermittent naviagation errors of >5 Metres may occur.	Timing may be unreliable for short periods.
F	Favourable	The environment is unlikely to contribute to communications problems.	Nil or negligible impacts on GNSS.	Navigation errors due to space weather negligible <1 Metre.	GNSS timing not impacted due to space weather.

NOTE

This forecast provdes guidance on anticipated communications and GNSS effectiveness across the geographic region bounded by the map area over the stated period.

The product broadly depicts the most severe impacts that can be reasonably expected, in response to any space weather events that are predicted at the time of issue.

This product is issued once daily from MOSWOC and is non amendable.

Feedback on this product would be welcomed

Source: Image provided by email from mark.gibbs@metoffice.gov.uk to dpechkis@ida.org on 7/1/24

Figure 9. UK Met Office User-Specifc Space Weather Product Example

I. Improve Research for Credible Predictions

Participants commonly requested changes to the scales that are more advanced than science currently allows because space weather understanding and predictions are several decades behind terrestrial weather. STPI suggests that more research is needed to improve the lead time of predictions, increase the quantity of real-time data, and understand the diverse array of system impacts from space weather. For example, a radio burst in December of 2023 had unexpectedly severe impacts on aviation communication systems that was not reflected in real-time data or SWPC watches or warnings.

Currently there are monitors for CMEs only at L1—there is no ability to see action on far side of the Sun—and we are only able to provide warnings when a solar proton storm is imminent; there is no advance notice of radio blackout events. Recent technological improvements[16] provide images only every 15 minutes; additional data and observations of the Sun to understand its behavior and the complex impacts of CMEs are needed before accurate forecasts or predictions with advance notice are possible.

J. Provide More Information on the Impacts of Space Weather Events on Systems (Long-Term)

1. Collect Information on the Correlation of Space Weather Effects (Long-Term)

Participants stated a desire for more information on the effects of space weather. However, with increasingly rapid technological advancements, it is unclear how space weather will affect both current and future technologies. Therefore, participants indicated a mechanism or system should be developed for collecting anomalies and operational problems associated with space weather activity. Such data would allow scientists to build evidence-based correlations between effects and space weather events, improving the association between the SWS and expected effects as well as potentially providing an approach for moving towards impact-based scales. The challenge with this approach is that many system owners and operators, especially within the United States, are hesitant to share anomaly information. They fear that public knowledge of their problems potentially provides proprietary information, giving others a competitive advantage. However, international organizations, such a power grid companies (Marshall et al. 2011), are more willing to share relevant and anonymized information. Such efforts could be a good opportunity for NOAA to collaborate with other international space weather prediction centers to improve our understanding of how space weather affects systems. At a minimum, NOAA could update explanations of SWS effects based on journal articles that connect

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[16] The GOES 19 satellite launched with a Compact Coronagraph (CCOR 1) and the Solar Ultraviolet Imager (SUVI) in June 2024.

space weather effects and the events that cause them. Two recent articles worth considering are "Space Weather Effects on Satellites" (Miteva et al. 2023) and "A Preliminary Risk Assessment of the Australian Region Power Network to Space Weather" (Marshall et al. 2011), which respectively present overviews of satellite effects and world-wide power grid anomalies caused by space weather events.

2. Describe the Scales Based on Effects Instead of Phenomena (Long-Term)

Many participants noted that information about impacts within the SWS does not match their experience in how space weather affects them, their ability to do their job, and execute their mission. They suggested changing the basis of the scales to system impacts, instead of physical phenomena, and consequently realigning the thresholds of the scales. For example, a participant mentioned not being concerned about the magnitude of a space weather event itself, but rather if the event would require a change in operational procedures. A majority of survey respondents also indicated that more accurately relating the SWS values to user and system effects would improve the usefulness of the SWS.

There are significant challenges with aligning the scales to system effects, particularly the lack of knowledge of how space weather events correlate to system effects. One international power grid organization provided an illustrative example of how the impacts of space weather can differ from the phenomena. Table 4 features GIC data from five geomagnetic storms between 2021 and 2024 shared by this organization. Maximum GICs for the G3 storms ranged from 12 to 20 Amperes (amps). The G4 storm produced a maximum GIC of 9 amps, which was 3 amps less than the smallest G3 storm in the table. The recent 11 May 2024 G5 storm produced a maximum GIC of 36 amps, but this is 64 amps less than the 100 amp threshold of interest for this particular grid organization.

Table 4. Space Weather Observations from International Power Grid Organization

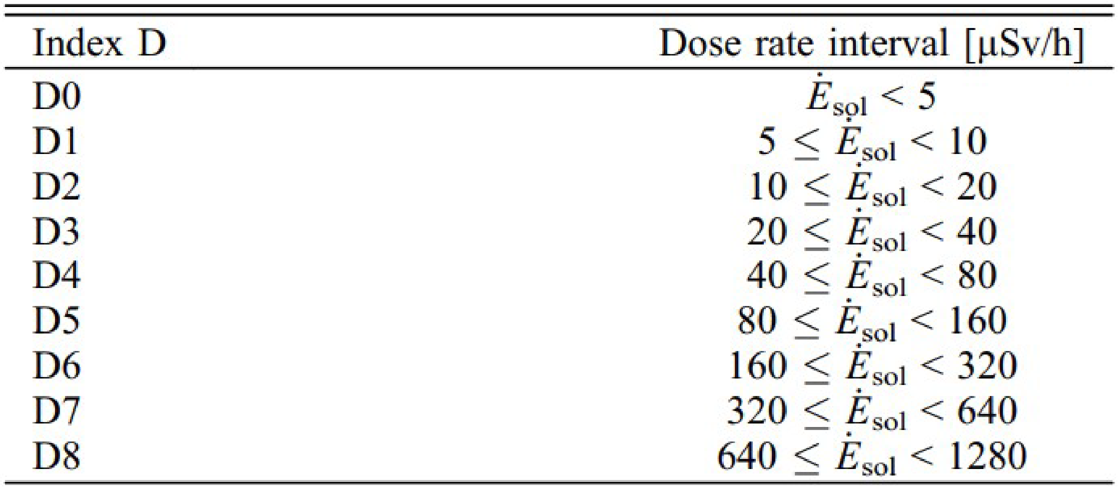
Date	Largest Observed GIC	G-Scale Value
4 November 2021	20 amps	G3
6 November 2023	12 amps	G3
2 December 2023	13 amps	G3
25 March 2024	9 amps	G4
11 May 2024	36 amps	G5

Users and operators have also taken different protective measures against space weather events, further distorting impacts of space weather phenomena on system performance. For example, the U.S. grid has taken protective measures (per TPL-007-2 ([Transmission System Planned Performance for Geomagnetic Disturbance Events]) and is less vulnerable to the effect of space weather than other grids. New systems are continuously fielded and ensuring they are taking protective measures against space weather events would be challenging for SWPC and would require them to have sufficient information of consumers' systems to make impact assessments. Furthermore, there is no standardized way to collect impact-based information on the effects of space weather from operators. Nevertheless, participants across engagements expressed a strong interest in understanding the impacts of space weather on their systems, whether that be through the SWS or another NOAA product or service.

K. Suggestions for New Space Weather Scales

1. New Aviation Scale or D-Scale (Medium-Term)

Participants from the aviation community supported the development of an aviation-focused scale or product. One possibility is to adapt the D-index (Meier and Matthiä 2014) as a new SWPC product or scale (called the D-scale). The D-index, which could represent both local and planetary information, is based on the rate of the effective dose ($E^{\cdot}sol$) estimated from model calculations as well as measurements of the rate of the ambient dose equivalent. Figure 10 shows the D-scale with indices from D0 to D8 and associated dose rate intervals.



Index D	Dose rate interval [μSv/h]
D0	$\dot{E}_{\mathrm{sol}} < 5$
D1	$5 \leq \dot{E}_{\mathrm{sol}} < 10$
D2	$10 \leq \dot{E}_{\mathrm{sol}} < 20$
D3	$20 \leq \dot{E}_{\mathrm{sol}} < 40$
D4	$40 \leq \dot{E}_{\mathrm{sol}} < 80$
D5	$80 \leq \dot{E}_{\mathrm{sol}} < 160$
D6	$160 \leq \dot{E}_{\mathrm{sol}} < 320$
D7	$320 \leq \dot{E}_{\mathrm{sol}} < 640$
D8	$640 \leq \dot{E}_{\mathrm{sol}} < 1280$

Source: Meier et al. (2014)

Figure 10. D-Scale Description

The D-scale can be used to warn aircraft at a specific geographic position and flight altitude, since it is based on the dose rate at a particular point in the Earth's atmosphere. This localized information permits a specific assessment of the effect of a solar energetic particle storm on particular geographic regions. To describe the particle perception in a particular area using a single, generalized local D_L-index, the dose rate is assessed at 41,000 feet (12.5 km), which is typically the upper altitude for civil aviation. A global D_G index can be derived from the local indices and defined by the maximum local D_L index anywhere in the world. Thus, a global warning indicator could be issued letting the airline industry know there is at least one area around the globe with hazardous solar energetic particles. Furthermore, this dose rate-based SWS could be used to assess the radiation exposure of individual flights by examining their routes and flight altitudes. This would provide airlines with maximum exposure data for a particular flight (Meier and Matthiä 2014).

2. Geoelectric Field Scale (Medium-Term)

Many participants in the grid sector suggested the need for a Geoelectric Field Scale, alternatively called an Electric Field Scale or E-scale. While there is a relationship between the G-scale and GICs, GICs are correlated to the geoelectric field. Since GICs directly affect the power grid, a measure of the electric field in volts/kilometer (V/km) is a more helpful metric for the grid than the G-scale or Kp index. SWPC already provides a product indicating the geoelectric field across the continental United States and parts of Canada as shown in Figure 11. Currently, the North American Electric Reliability Corporation (NERC) requires that U.S. power companies prepare for a reference peak geoelectric field amplitude of 8 volts/km, rather than a geomagnetic disturbance (GMD) that is based on the Kp index or G-scale.[17] A few respondents said that an E-scale could be based on the NOAA-U.S. Geological Survey Geoelectric Field Model (NOAA 2024g), with one suggesting the levels could be given as described in Table 5. One researcher thought the E-scale could be unbounded and adapted to provide regional information, but was unclear of the level of resolution needed.

Table 5. Suggested Geoelectric Field (E-Scale) Levels

Scale Level	Volts per Kilometer Range
E1	0.01 – 0.02
E2	0.02 – 0.05
E3	0.05 – 0.10
E4	0.10 – 0.20
E5	0.20 – 0.50
E6	0.50 – 1.00
E7	1.00 – 2.00
E8	2.00 – 5.00
E9	5.00 – 10.0
E10	10.0 – 20.0

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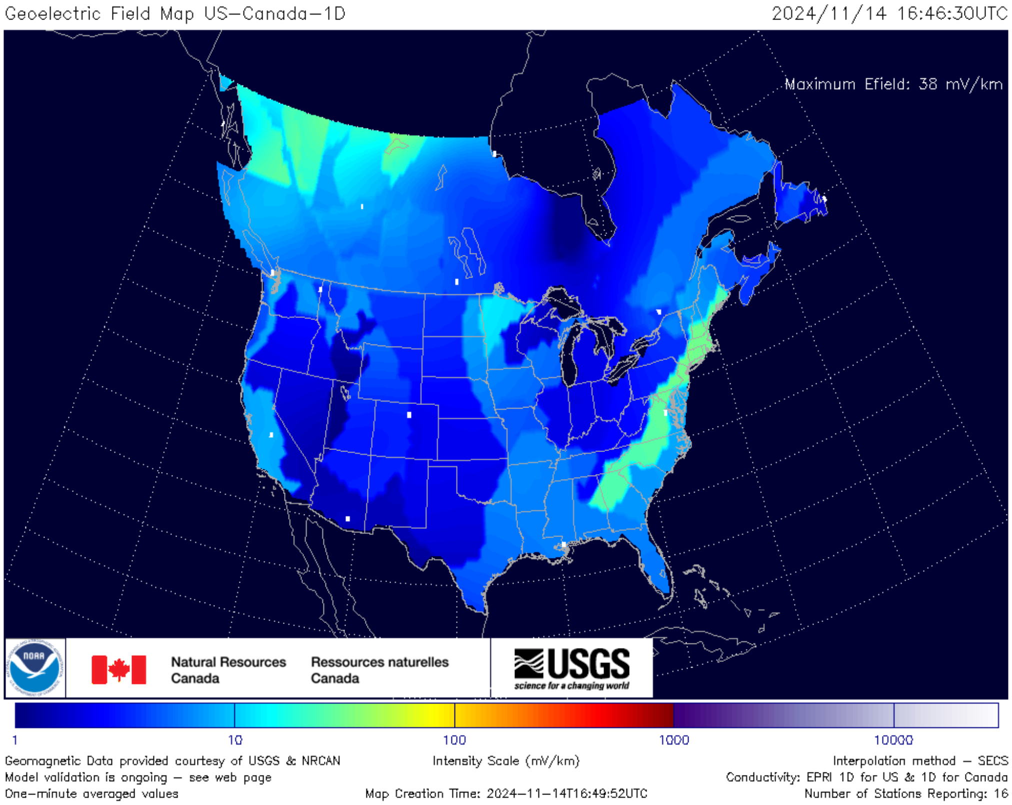
[17] NERC's Transmission System Planned Performance for Geomagnetic Disturbance Events: https://www.nerc.com/pa/Stand/Reliability%20Standards/tpl-007-4.PDF



Source: NOAA SWPC Website

Figure 11. Geoelectric Field Map from which E-field Scale Could Be Based

3. Ionospheric Scintillation Scale or Product (Long-Term)

Participants who rely on GNSS and satellite communications, such as power grid and emergency managers, described the need for a scale quantifying ionospheric-induced disruptions affecting wide area time synchronization and satellite communication services. Ionospheric scintillation affects the amplitude and phase of trans-ionospheric radio wave signals up to a few GHz in frequency, resulting in the loss of signal quality and availability of GNSS, radar signals, and some satellite-based communications systems. The G-, S-, and R-scales do not directly measure these effects and are only weakly connected to scintillation signal degradation. To address this need, SWPC could publish a trans-ionospheric scale, or T-scale, that captures the magnitude of scintillation. The T-scale can be based on the frequency-independent vertical CkL index, which represents the strength of the ionospheric electron density irregularity spectrum, and can be related to other widely used scintillation indices. The CkL index can be derived from ground- and space-based dual-frequency GNSS measurements and augmented by in-situ plasma density measurements. The T-scale would be a planetary index with five levels; users could correlate individual levels to the magnitude of effects they experience. Researchers are working on the details, but an initial prototype may be available in a few years.

4. Neutral Density Scale (Long-Term)

Participants from the satellite sector highlighted a need to better understand neutral density in LEO. Currently there is no measurement data or way to model the atmosphere's neutral density that could be used to develop a neutral density SWS. As satellites have become more numerous in LEO, neutral density has become important for satellite operators. Consequently, space weather's impacts on upper atmospheric expansion have become a concern. This is an area of evolving research. Satellite operators sometimes use the G-scale as a poor proxy for atmospheric expansion. While a product with neutral density or upper atmospheric expansion information would be useful, some users also suggested a scale that indicated percent change in neutral density or drag compared to the day before. It would be particularly challenging to translate information about neutral density into atmospheric drag effect because atmospheric drag effects depend strongly on the size, shape, and location of satellites.

5. Additional Products

Some stakeholders did not suggest SWPC add any scales, but did request additional space weather information from SWPC, which could come in the form of other products. Some space weather data and products of interest to stakeholders are listed below:

- Total Electron Content (TEC) forecast model;
- Interactive tools and simulations to explore GICs;
- Sector-specific or domain-based alerts of some kind (i.e., "space weather alert for spacecraft operating in LEO");
- Maps of solar flare impact and absorption;
- Radio Flux;
- Stop-go Charts; and
- Aviation Radiation Risk products.

6. Single Space Weather Scale

Another solution suggested by participants was to collapse all the scales into a single SWS and transfer the information provided by G-, R- and S-scales into one product. They suggested allowing users to customize which products they want to see and receive updates about. The global scale would provide a general alert that there was something going on with space weather—for example, "Red/Severe Space Weather Event or Risk." This alert would tell users to check SWPC's website for information pertinent to their specific sector, associated operations, and possible effects on technology.

5. Key Takeaways

STPI gained a better understanding of the use, value, and challenges to the scales through interviews, group engagements, RFIs, and other interactions with international stakeholders. We also gathered ideas from SWS user communities, international communities, and Federal Government officials on how the scales should change and reframed that information into actionable, meaningful suggestions. In this final chapter, we provide our key takeaways for NOAA to consider as they revise the SWS—taking into consideration both what was heard and learned through the study as well as our own assessment and observations. We note that the SWS are used differently across the various user communities, and SWPC cannot provide user-specific information for all sectors.

Space weather is global in nature but the effects are experienced at a localized level and the actual impacts of space weather events depend on external factors that are hard to track. Therefore, participants noted that users would have to combine global observations provided by NOAA with their own specific regional research and monitoring systems to determine space weather effects on their systems, health, jobs, and missions.

A. Communicating SWS Information and Providing Education and Outreach

The SWS face the challenge of communicating information to a wide range of audiences, including those not trained as space weather experts and many who do not understand space weather phenomena. Furthermore, the audience for the SWS is diverse, ranging from commercial airlines to satellite companies to power grid operators, all of whom may experience different effects from a space weather event. We heard repeatedly that *what* information is communicated through the scales and *how* that information is provided could be improved. SWPC could consider the following actions:

- Incorporate hazard communication best practices into the scale descriptions through engagement with social scientists, the hazard communications community, and international users;
- Introduce SWS with plain-language descriptions by replacing jargon and acronyms with language understandable by general users;
- Replace the current explanation of effects with risk-informed action statements for key sectors such as aviation, power grid operators, and emergency managers; and

- Improve navigability of the SWPC website and provide a clear web interface for learning about space weather and its effects.

Another challenge is that user communities use the scales differently, and the one-size-fits-all approach (that includes the general public) hampers SWPC's ability to provide high-quality detailed information to audiences that need this level of detail. For example, emergency management, grid operators, and some users in the aviation sectors have operational procedures tied to different levels of the scales—each with a unique impact that varies based on system protections, geography, and infrastructure. Given this, for certain sectors, NOAA could consider the following actions:

- Train users to rely on the scales to communicate the possibility of an event and prompt them to use tailored products for more detailed sector-specific information;
- Rely on the Space Weather Prediction Testbed,[18] a forthcoming facility that will enable collaboration across sectors and the research and operations communities, to interactively engage different key sectors and develop and evolve products as user needs continuously change; and
- Develop audience-specific messaging to translate the potential effects to systems for specific sectors.

Another challenge is the mismatch between the accuracy users anticipate from SWPC's forecasts and the accuracy that current forecasting capabilities deliver. Participants noted a degree of uncertainty in forecasting space weather events that is not clearly communicated to users. To address this, SWPC could:

- Explore how to quantify and communicate the confidence of forecasts;
- Use disclaimers to help manage users' expectations;
- Present uncertainty information graphically; and
- Qualify the extent of measurement and model uncertainty.

B. G-Scale

The G-Scale was the most widely used scale among the participants with whom we spoke. The challenges discussed ranged from nuisances or issues that may be alleviated through improvements in communication, to larger more intractable problems where the science is not well-enough understood. Solving this issue would require more observations, improved modeling, and research progress in space weather predictive capabilities that would take funding and time.

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[18] Space Weather Prediction Testbed: https://testbed.swpc.noaa.gov/

Similarly, most users want more information regarding geographic specificity, more advanced warning of events, and more information on the severity of the potential impacts, particularly as they relate to the G-scale. For example, the power grid sector and emergency managers want more knowledge of localized GICs. Many users also expressed dissatisfaction with the disparate impacts of storms classified as G-5s and sought a way to differentiate a strong geomagnetic storm from a catastrophic one, like a Carrington-level event. However, the desires of many users across sectors are beyond the ability of SWPC to provide given the current state of the science. To summarize, NOAA could consider:

- Changing the basis for the G-scale from kp to the Hpo index, which is unbounded on the upper end;
- Adding geographic specificity through developing regional indices for the United States, which could be regional Kp or Ho indices. The global Kp index could still remain, and should not change, but having a regional index would benefit many G-scale users;
- Expanding the upper end of the G-scale nowcast or communicating to users the variation in effects felt at the top of the G-scale regardless of classification;
- Reducing the granularity of the G-scale forecast to match predictive capabilities and better communicate risk and uncertainty in forecasts to users; and
- Piloting the development of a Geoelectric Field Scale in coordination with the power grid sector and/or promoting the existing geoelectric field products. GICs directly affect the power grid and would be useful to the power grid sector, which currently uses the G-scale or Kp index as a proxy for GICs.

C. S-Scale

The S-scale is based on the 10 MeV protons measured in geostationary orbit, which is appropriate for some sectors but not as helpful to others. One main challenge with the S-scale is that aviation users may be misinterpreting what the S-Scale level means for radiation exposure to the crew and passengers. Another challenge is that the name of the S-scale, “Solar Radiation Storm,” is misleading because some people misconstrue the term “radiation” as harmful and can misinterpret the S-scale as a measure for all types of radiation, not just 10 MeV solar protons. Given these challenges and misconceptions, SWPC could consider the following actions:

- Rename the S-Scale to better align with the underlying phenomenology and prevent public misperceptions of danger;
- Consider revising the S-scale to be based on higher energy levels beyond 10 MeV proton levels that may have biological health impacts at aviation altitudes;

- Rewrite and clarify references to radiation exposure in the current S-scale to accurately reflect the current science of radiation exposure to aviation passengers and crews;
- Consider adding a D-index or D-product to help the aviation sector assess radiation dose exposure; and
- Provide additional geographic specificity information about charged particles at various latitudes, longitudes, and altitudes.

D. R-Scale

The R-scale measures the intensity of solar x-ray radiation and classifies this radiation into interference effects on HF radio only; it does not indicate a total radio blackout effect across all communication frequencies. Notably, the R-scale also does not capture the effects of other types of solar events, such as solar radio bursts, which can interfere with a wide range of radio signals that influence various types of communication technologies. Additionally, as "R" is often associated with radiation, many users mix up the S- and R-scales. SWPC could consider the following actions:

- Rename the R-scale to more accurately reflect the disturbances that cause it, such as the "X-ray Flux Scale" or something similar; and
- Consider using a different letter to represent the scale to eliminate confusion between the S- and R-scales.

E. Final Thoughts

In the interviews and group discussions, stakeholders debated whether the scales should be based on observations of phenomena or on the effects of the phenomenology on users and operations. We concluded that the basis of the scales should continue to be on observed and measured phenomena, but SWPC could work to improve communicating potential impacts and effects for key sectors. In the longer term, SWPC could provide more information on the impacts of space weather events on systems through collaborative data collection and information sharing with sectors and international partners. The eventual goal could be to gather data that would allow scientists to build evidence-based correlations between effects and space weather events, improving the association between the SWS and expected effects, as well as potentially providing more accurate forecasts and predictions of risks to users. In addition, in the long term, NOAA should consider moving towards tailored, audience-specific, or sector-specific products because creating a generalized scale to satisfy all audiences is a major challenge.

Appendix A.
Interview Protocol

The National Oceanic and Atmospheric Administration (NOAA) introduced the Space Weather Scales (SWS) in 1999 as a way to communicate current and future space weather conditions and possible effects on people and systems to the public. Space weather capabilities, user base, and user needs have grown and changed over the past 25 years.

To address these changes, NOAA asked the Science and Technology Policy Institute (STPI) to review and possibly revise, as appropriate, the SWS. The scales are broadcast by NOAA's Space Weather Prediction Center (SWPC), which provides timely and accurate space weather forecasting. The revision will be informed by the needs and interests of stakeholders across the United States and international public, private, academic, and non-governmental organization communities. The following is the interview protocol administered for all sessions:

Can we turn on transcripts and record for notetaking purposes only?

NOAA Scales Revision Interview Protocol

Name(s):

Organization Name:

Organization Type: Industry, Academia, Non-Profit, Government, International

Role:

Interview date:

Interviewer names:

User Type: Government Decisionmaker, User from a sector (what sector?), General public

Interview Questions

1. What sector(s) do you consider yourself a part of?
    a. To what extent is your mission/sector dependent on GNSS and Comms?
2. What space weather scales do you currently use to make decisions?
3. How do you use the space weather scales?

   a. What decisions do you make based on these scales? [probe: is the scale information an input to taking an action?]
   b. What scale values cause you to take a different course of action?
   c. What systems/functions do you have that rely on the scales?
   d. Do you seek further information once the scale changes to the next level? If yes, what information and from whom? Is there any additional processing required?
4. What do you like about the scales? Please provide examples.
   a. In your words, how does your use of the current scales improve your application?
   b. If the scales did not exist, what impact would that have?
   c. Are there examples of how using the space weather scales have helped your mission?
   d. If yes to (b), can you state specific decisions made based off specific scale values?
5. What difficulties have you experienced in leveraging the space weather scales?
   a. Do you feel that you understand the content, context, and information coming from them?
   b. What, if any, technical challenges do you have with the scales?
   c. How could the communications of the scales be improved?
   d. [Probe: Any other challenges?]
6. Do you think the space weather scales should change? If so, how?
   a. If yes, how should the scales change?
      1) The scale thresholds?
      2) What phenomenon is underlying the scales?
      3) Geographic granularity?
      4) Uncertainty?
   b. Are there better ways of communicating space weather predictions and impacts to inform your decision-making?
      1) Is there different language or methods that could improve the communication of the information provided by the scales?
   c. If no, clarify that the interviewee is happy with the scale as is?

        1) Would you recommend any changes to the way the scale information is communicated to help inform your decisions?

    d. Should the scales change, what criteria should be used to evaluate proposed changes to the scales?
    e. If the scales were to change, what would the impact on your mission be?

7. Should there be a new space weather scale? If so, what would you want to see in a new space weather scale?
    a. Why should there be a new scale?
    b. What phenomenon should be captured by potential new scale?
    c. How should thresholds for this new scale be determined?
    d. How would a new scale be used and by whom?
8. What other space weather data do you use to make decisions?
9. How do you use other space weather data to make decisions?
    a. What decisions and actions do you make based on the other space weather data?
    b. Are there specific thresholds that cause you to take different courses of action?
    c. What systems/functions do you have that rely this other space weather information?
10. GPS/Comms
    a. If yes to GPS or Comms, do you rely on any SWPC scales or products to monitor space weather effects on these systems?

Appendix B.
Survey Methodology

The purpose of this survey was to provide key space weather stakeholders—who could not participate in the STPI-sponsored RFI, group engagements, and interviews—an opportunity to contribute input on how the SWS are used and how to improve them. STPI created a survey instrument to gather information on the following:

1. Use of the three SWS by people and organizations;
2. Ease of use;
3. Value of the scales;
4. Potential changes to the scales suggested by people we spoke to during prior engagements; and
5. Survey respondent's ideas for new scales and their possible format.

STPI used these data, combined with the data we collected during our other engagements, to inform this report's findings and identify options that NOAA and the space weather community could implement to improve the SWS as communication tools serving the needs of end-users.

Limitations

This survey measures individual beliefs, perceptions, and opinions of the SWS; however, we used a convenience sampling methodology and responses are not representative of the entire space weather stakeholder community. This survey is intended to supplement the data STPI collected from its literature review, interviews, group engagements, and RFI. It allowed us to gather data from members of STPI's participation list who could not participate in other outreach activities. Our survey data and subsequent statistical analyses should be interpreted as beliefs, perceptions, and opinions from a few members of the space weather community and not a representative perspective of the stakeholder population.

Pretesting the Survey

STPI pretested the survey prior to administering it to our intended audience. This included two internal rounds of review with space weather experts and social scientists. We then asked 14 non-STPI space weather information users who are familiar with the

SWS to take the survey and provide feedback on its understandability, readability, and flow. We received 10 responses. Respondents came from the emergency management (3), research (3), recreational space weather community (2), aviation (1), and satellite operations (1) communities. Two emergency managers were State employees and the third was a Federal employee. Three respondents were from European nations.

Survey Administration

STPI emailed the survey link to 55 people, asking them to complete the survey and share it with others who they thought could provide useful input. The majority (47 of 55) were generated from contacts suggested by the SWPC, European Space Agency, and the Dublin Institute for Advanced Studies. The other eight were representatives from the Space ISAC, Airlines for America, and GPS Innovation Alliance. We sent the link to the 25 European attendees and 3 Australian organizers of the European and Australian Space Weather Scales group engagements, respectively, requesting that they share the survey link with anyone who they thought could provide useful input. STPI sent the email out on August 7, 2024 and we received all responses by October 23, 2024, when the survey data collection period ended.

STPI analyzed all SWS-specific questionnaire responses and did not remove any outliers from our analyses. Two respondents completed some of the demographic questions but did not answer any of the SWS-specific scales. We did not include their demographic information in our demographic analyses.

Demographic Information

STPI's survey instrument collected demographic information to investigate whether demographics affected specific responses. The demographics we collected were:

- Name (open-ended response)
- Organization name (open-ended response)
- Organization type (industry, academia, nonprofit, government)
- Country (open-ended response)
- Job title (open-ended response)
- Job roles and responsibilities (open-ended response)
- Job capacity (government decisionmaker, end-user decisionmakers, space weather service providers, recreational space weather users, general public, or other)
- Level of knowledge with weather (not well at all, slightly well, moderately well, very well, extremely well)

- Years of experience with the SWS (0–5 years, 6–10 years, 11–15 years, 16–20 years, over 20 years)
- Sector(s) they considered themselves apart of
  - Agriculture
  - Aviation
  - Communications
  - Emergency Management
  - Global Navigation Space System (GNSS)
  - Human Space Flight
  - Meteorology
  - Power Grid
  - Precision Drilling
  - Rail
  - Research
  - Satellites
  - Space Domain Awareness
  - Surveying
  - Tourism (Aurora)
  - Other (please describe)

Analyses of demographic data (Figures B-1–4) show that most respondents are European and/or have government positions and consider themselves to understand space weather at least moderately well. Respondents' years of experience with space weather were evenly distributed among early-, mid-, or late-career space weather professions. Figure B-1 shows the survey had 25 respondents, with 20 from 10 European countries and 5 from the United States. Figure B-2 shows respondents work in 3 different organization types, with 18 from government, 4 from industry, and 3 from academia. Of those respondents, 11 identified themselves as space weather service providers, 6 as government decisionmakers, 4 as end-user decisionmakers, or 4 as other. Figures B-3 and B-4 break out the respondents by years of space weather experience and how well they believe they understand space weather. Ten respondents have less than 5 years' experience, 7 have 6 to 10 years' experience, and 8 have greater than 11 years' experience, with everyone feeling they understood space weather at least moderately well. No respondents perceived their understanding of space weather as "Not well at all" or "Slightly well." Every sector was represented except agriculture, with 17 of 25 respondents associating themselves with multiple sectors.

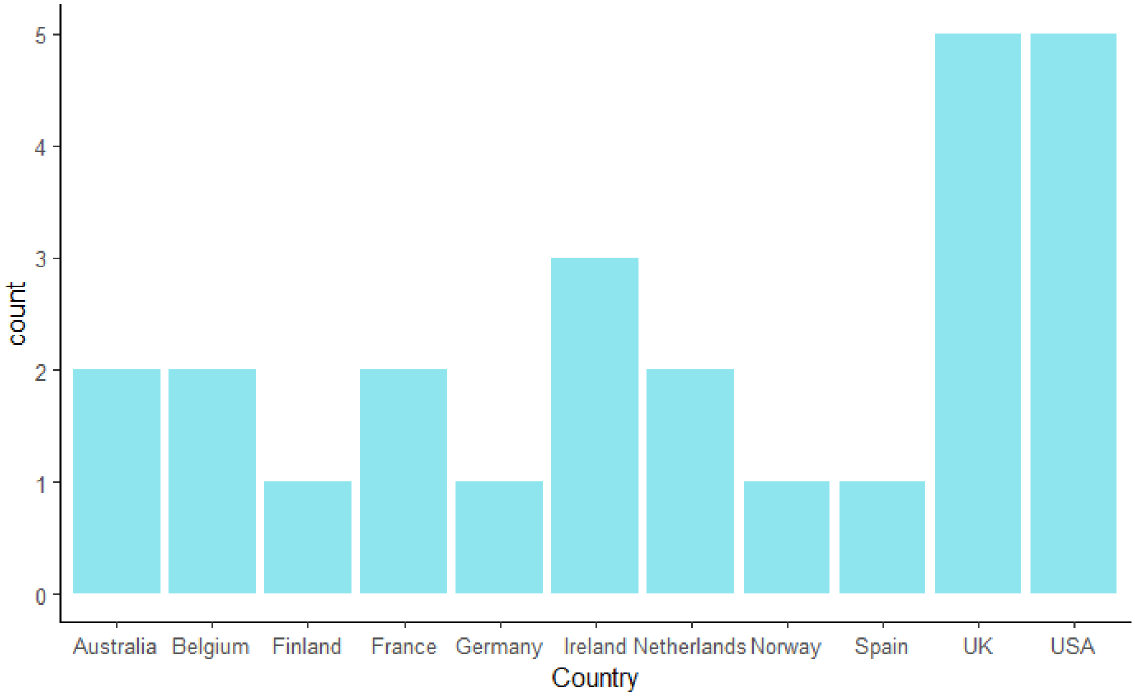

Figure B-1. Number of Respondents from Each Country

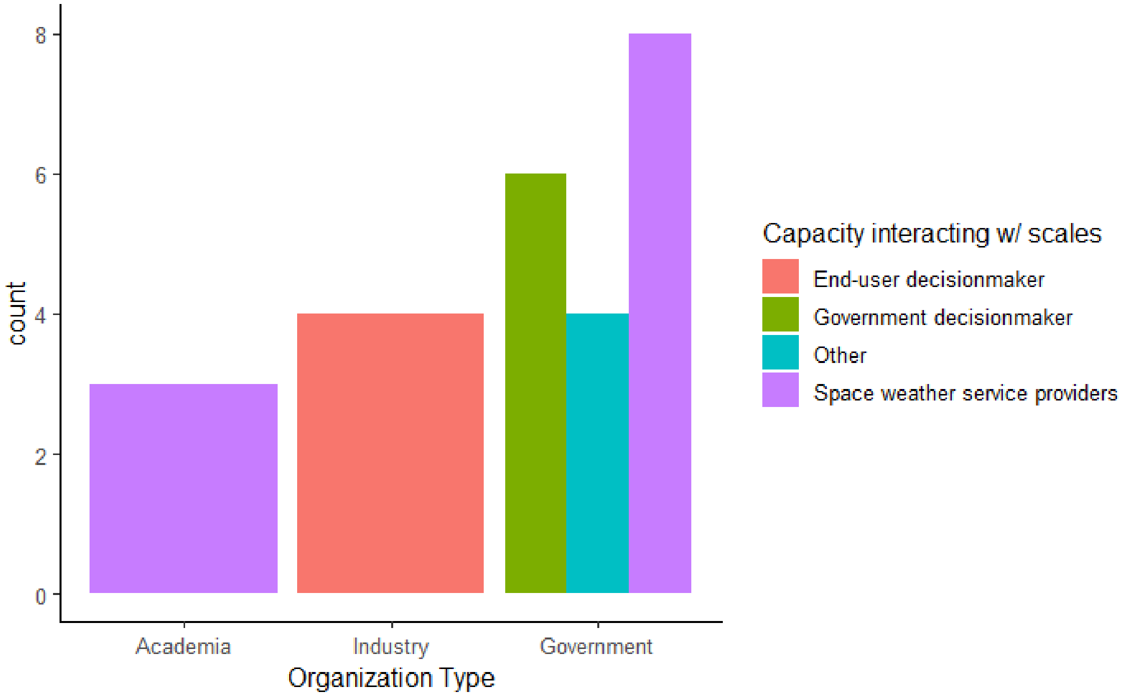

Figure B-2. Number of Respondents Versus Organization Type and Job Capacity

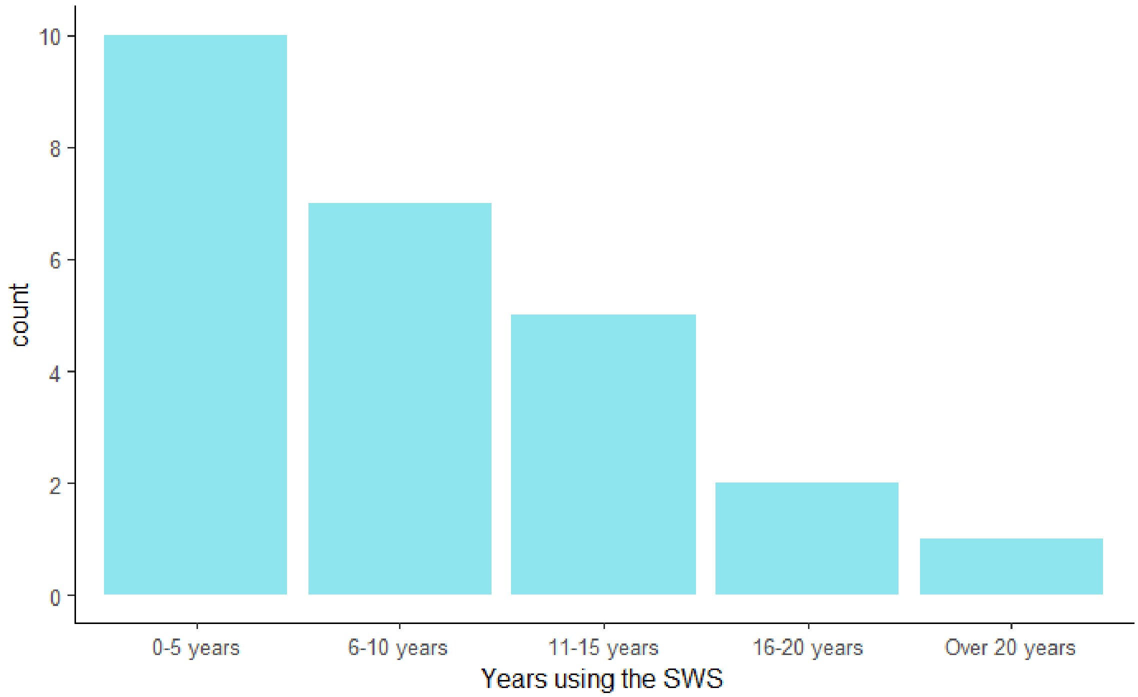

Figure B-3. Number of Respondents Versus Years of Experience

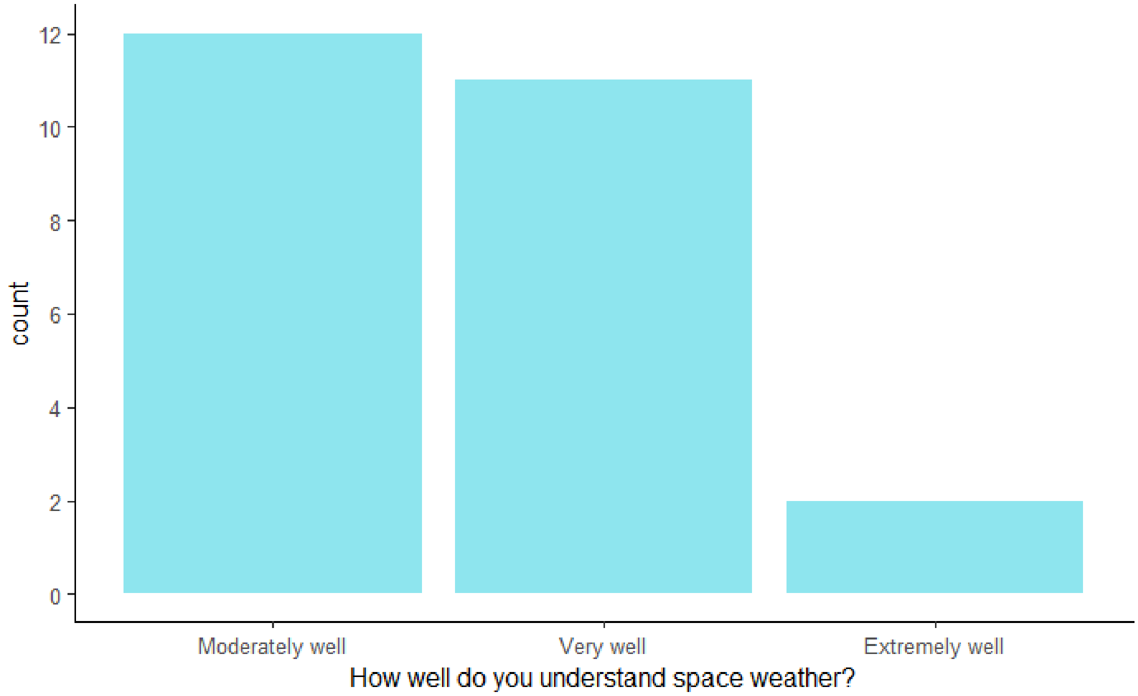

Figure B-4. Number of Respondents Versus Perceived Space Weather Knowledge

How Are the SWS Used?

The survey asked each respondent to select the option that most accurately described how they, or their organization, use each of the space weather scales to support or make decisions. There choices were "*no, we do not use this scale at all*"; "*yes, we use this scale informally, but are not required to either use it or monitor it*"; "*yes, we are required to monitor this scale for situational awareness, but do not have a procedure that uses this scale*"; and "*yes, we have a procedure that uses this scale.*" Figure B-5 shows 23 of 25 (92%) use the G-scale, 22 of 23 (96%) use the S-scale, and 19 of 24 (79%) use the R-scale to at least monitor space weather activity, and more than one-third have a SWS-based procedure.

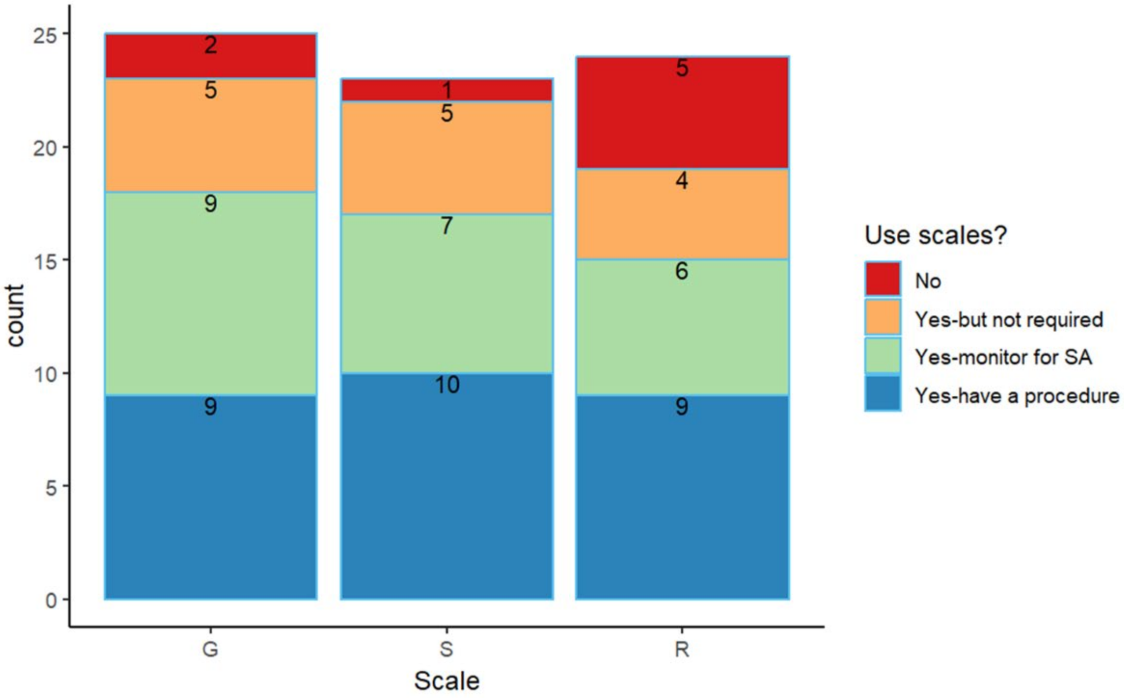

Figure B-5. Stack Bar Chart of How Survey Respondents Use SWS

Measuring Perceived Usability

The survey used the Usability Metric for User Experience LITE (UMUX-LITE) survey instrument to quantify how the SWS affects the ability of respondents or their organizations to complete tasks compared to not having the scales. Tasks included sending out space weather watches or warnings; communicating hazards or risks to leadership, customers, or the general public; taking preparatory or responding actions (e.g., shutting down equipment or changing transportation routes); or deciding to view the aurora. The UMUX-LITE was chosen because it is a validated survey instrument (Lewis, Utesch, and Maher 2013), is quick to take, and has defined analyses methods (Measuring Usability –

Test Science 2024). The questionnaire used validated surveys because they are pre-tested for understandability and designed to minimize measurement error so concepts can be measured as precisely as possible.

Usability is characterized in terms of a composite score, determined by averaging the two response items. Higher composite scores indicate greater usability. The composite scores for each SWS, along with their 80% confidence intervals (Davison and Hinkley 2013), are presented in Table B-1.

Table B-1. UMUX-LITE Usability Scores

Scale	Usability Score (mean)	80% Confidence Interval
G	4.6	(4.2, 5.0)
S	5.1	(4.7, 5.5)
R	4.6	(4.2, 5.1)

Note: Score values range form 1–7 with higher scores indicating greater usability.

Composite usability scores between 4 and 5 do not indicate good usability. The results show that the SWS have marginally acceptable usability on average, with the G- and R-scale less usable than the S-scale. All scales have room for improvement. Our composite usability score interpretation follows an interpretation schema developed by the research community and used by the Department of Defense test and evaluation community (Lewis Utesch, and Maher 2015; Institute for Defense Analyses 2024).

The UMUX-LITE questions and their answers for each SWS are located in Figures B-11–13. They do not add additional information to what STPI learned from the mean Usability Score.

Measuring Perceived Usefulness

The survey measured perceived usefulness using a validated scale developed by Davis (1989). This survey instrument quantified the *perceived usefulness* of the G-, S-, and R-scales for respondents' or their organization's ability to complete tasks, compared to not having the scales. Tasks included issuing space weather watches or warnings; communicating hazards or risks to leadership, customers, or the general public; taking preparatory or responding actions (e.g., shutting down equipment or changing transportation routes); or deciding to view the aurora. The original scale was adapted to a small degree, consisting of rewording changes to be consistent with how the SWS are used. We performed a questionnaire reliability analyses to ensure our changes did not invalidate the survey instrument. To ensure these adaptations did not affect internal consistency of the scale, we calculated Cronbach's alpha, a quantitative measure of reliability. Research finds that Cronbach's alpha being greater than or equal to 0.70 or 0.80 indicates good reliability (Kline 1999). Each of the G-, S-, and R-scales' Cronbach's alpha values are greater than or equal to 0.93, indicating high internal consistency.

Similar to our usability analyses, we determined a composite score by averaging the six response items. The composite scores for each SWS, along with their 80% confidence intervals, are presented in Table B-2.

Table B-2. Perceived Usefulness Composite Scores

Scale	Usefulness Score (mean)	80% Confidence Interval
G	4.5	(4.1, 4.9)
S	4.5	(4.1, 4.9)
R	4.5	(4.1, 4.9)

Note: Score values range form 1–7 with higher scores indicating greater usefulness and value.

Higher composite scores indicate the SWS provide greater usefulness. These results show that all three SWS are slightly useful on average, indicating room for improvement.

The Davis Usefulness questions and their answers for each SWS are located in Figures B-14–16 at the end of this appendix. They do not add additional information to what STPI learned from the mean Usefulness Score.

A Person's Job Affects How a Respondent Perceives the S-scales Usability and Usefulness

We found that a respondent's job capacity (i.e., government decisionmaker, end-user decisionmakers, space weather service providers, recreational space weather users, or general public) affects perception of usability and usefulness of the S-scale with statistical significance at the 80 percent confidence level. We determined this by performing an analysis of variance (Chambers, Freeny, and Heiberger 1992) and Tukey's Honest Significant Difference Test (Miller 1981; Yandell 1997). Plots (Figures B-6 and B-7) of the composite usability and usefulness scores and their associated means suggest that on average, government decisionmakers have a less favorable opinion of the S-scale's usability and usefulness than end-user decisionmakers, space weather service providers, or "other." Given this study's limitations, further investigation is needed to confirm that composite usability and usefulness scores depend on one's job capacity.

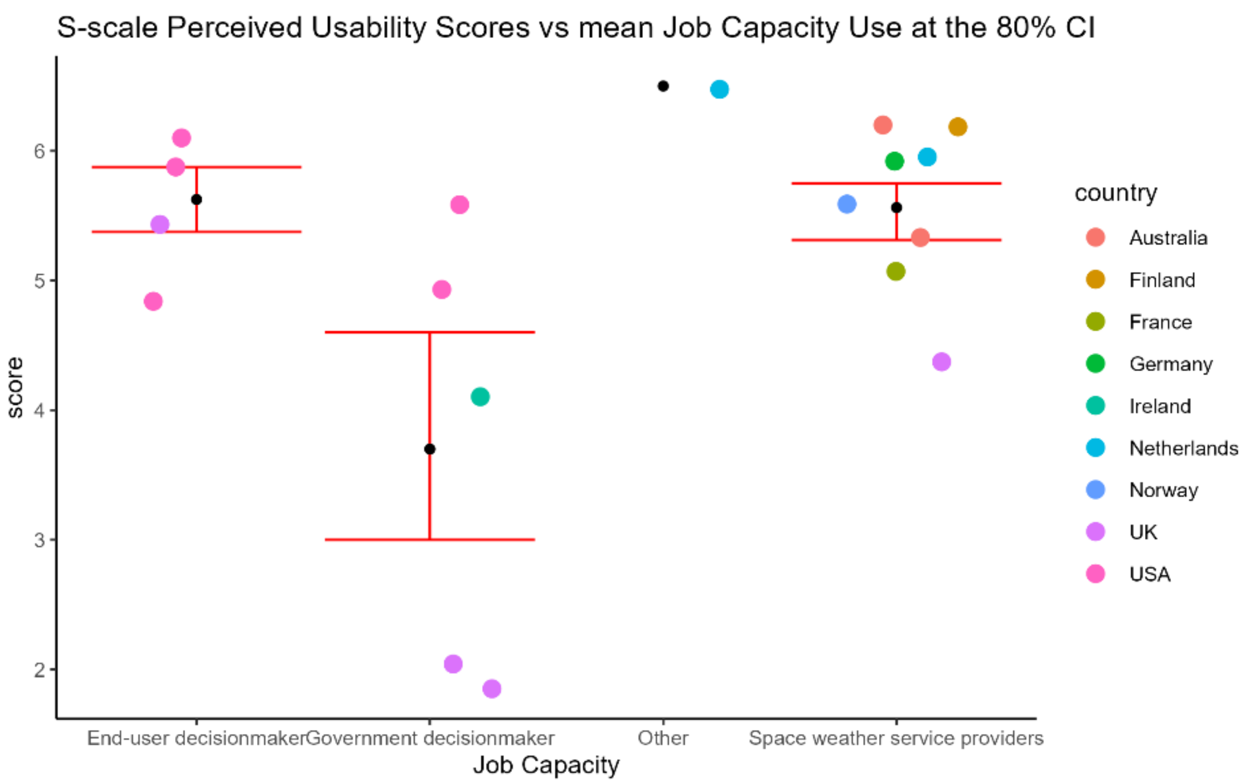

Figure B-6. S-Scale Usability Score Versus Job Capacity

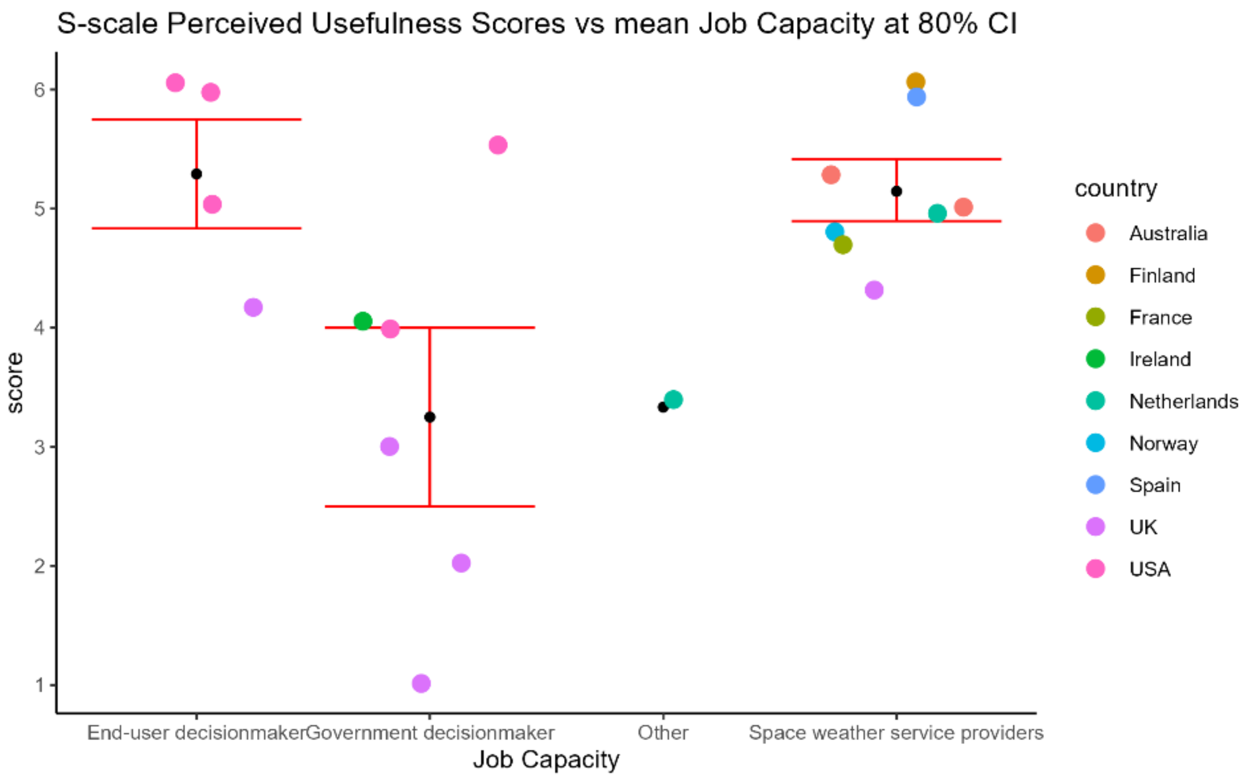

Figure B-7. S-Scale Usefulness Score Versus Job Capacity

None of the other demographic information, including how respondents use the SWS, affects how they perceive the SWS usability and usefulness with statistical significance at the 80 percent confidence level.

Reaction to Proposed Changes to the SWS

We presented survey respondents with potential changes to the SWS (Figures B-8–10), proposed by other SWS users during interviews, group engagements, and international engagements, and asked the respondents to rate the usefulness of the proposed changes. The overwhelming majority of respondents thought the changes presented to them would lead to the scales being more useful, with the exception of simplifying scales into fewer levels. Across scales, the majority of people did not want fewer levels. Generally respondents identified adding information on geographic specificity, uncertainty around estimates, additional information on limitations, and clearer ties to mission effects as useful.

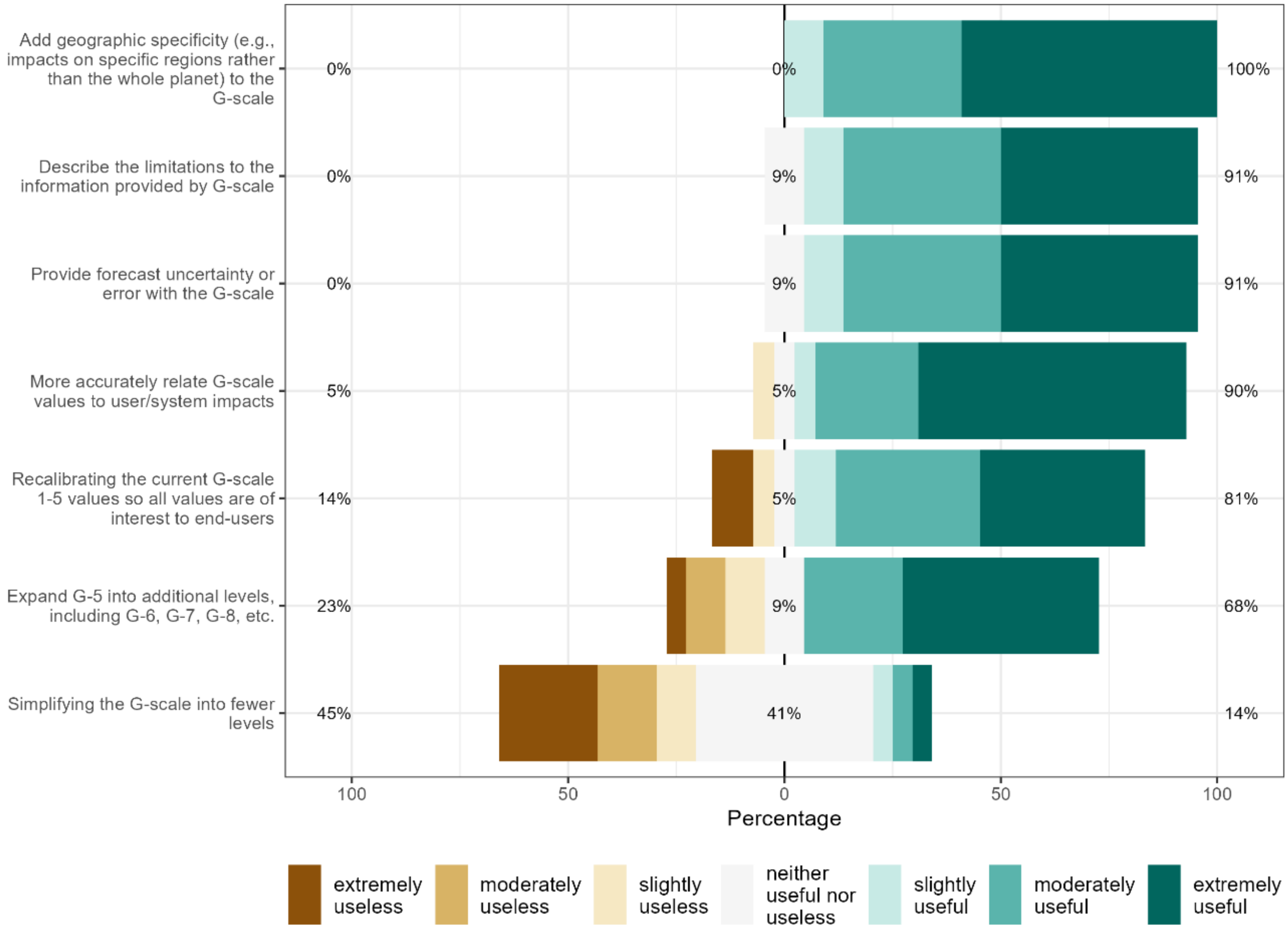

Figure B-8. Responses to Potential Changes to the G-Scale

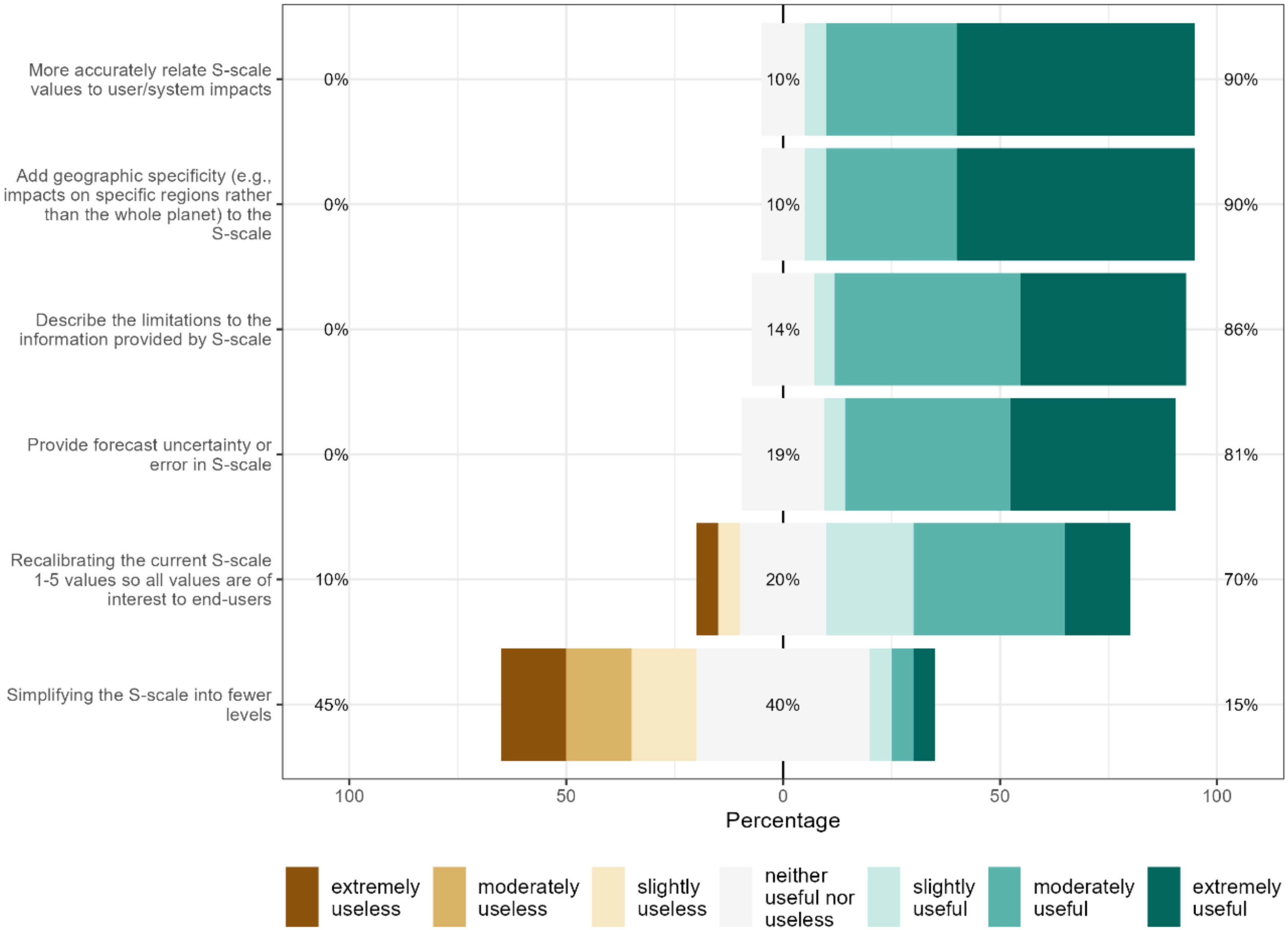

Figure B-9. Responses to Potential Changes to the S-Scale

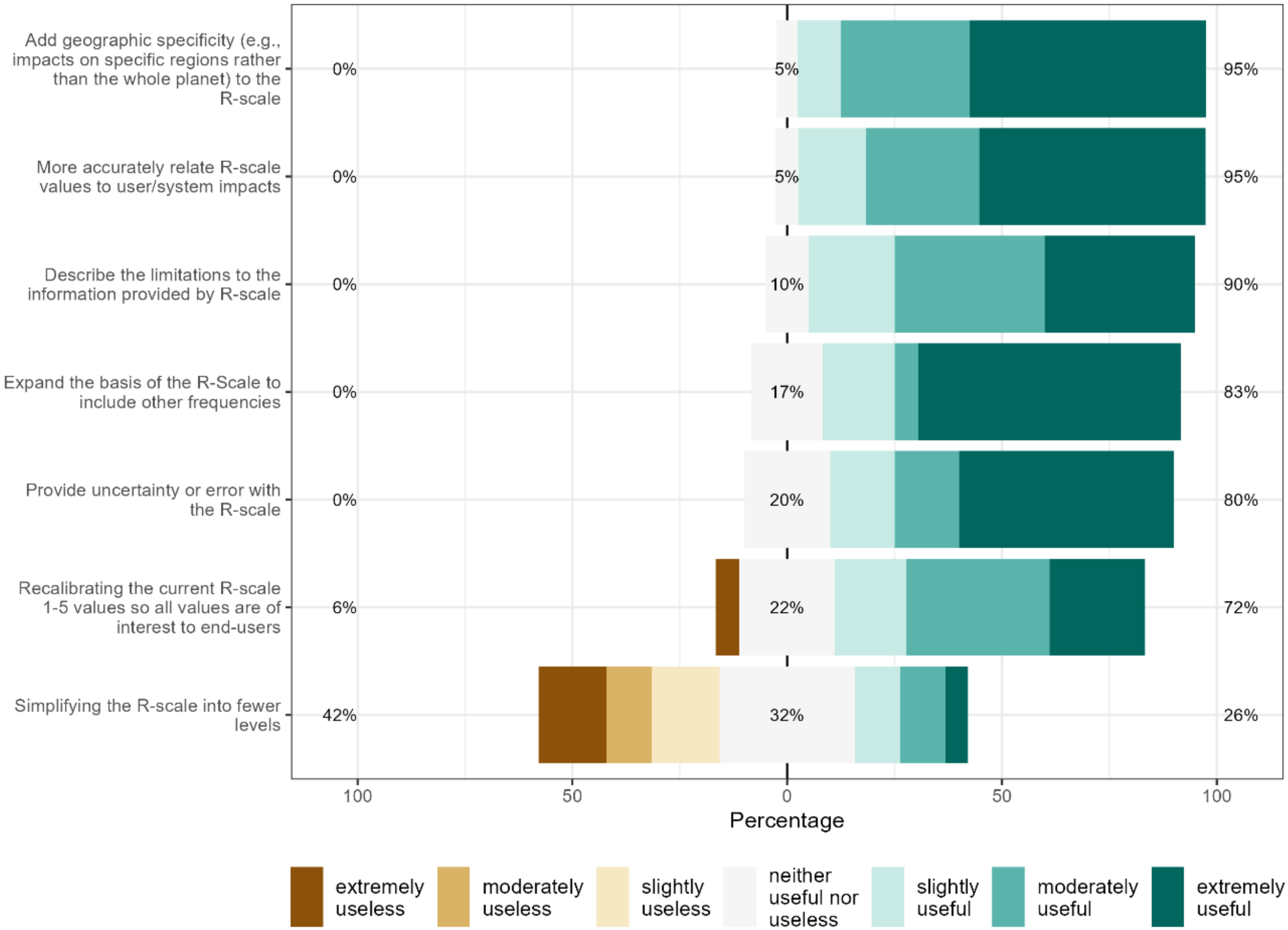

Figure B-10. Responses to Potential Changes to the R-Scale

Usability and Usefulness Survey Questions and Associated Responses

We include the usability and usefulness of survey questions and responses to highlight the raw responses. We could not draw additional conclusions beyond what the composite usability and usefulness score indicated.

However, we noticed one pattern in the usefulness questionnaire (Figures B-14–16), "I find the [X]-scale useful" is always the most endorsed and positive endorsement of each scale, with all the other responses being less positive. This could imply that the SWS are useful to respondents, but not in ways that are linked to the other statements (faster task completion, easier task completion, more effective at tasks, more productive, better at tasks). STPI suggests that future studies investigate if there is something that would make the SWS useful that is not captured by the scales. Studies could also investigate whether respondents like the SWS as a resource despite being unable to point to how they are useful. Additionally, if more data could be collected to support a usefulness versus demographic analyses, we could examine whether job capacity or the other demographics, such as how the scale is used (e.g., do they have a procedure that utilizes the SWS), influence how useful a respondent perceives the SWS to be.

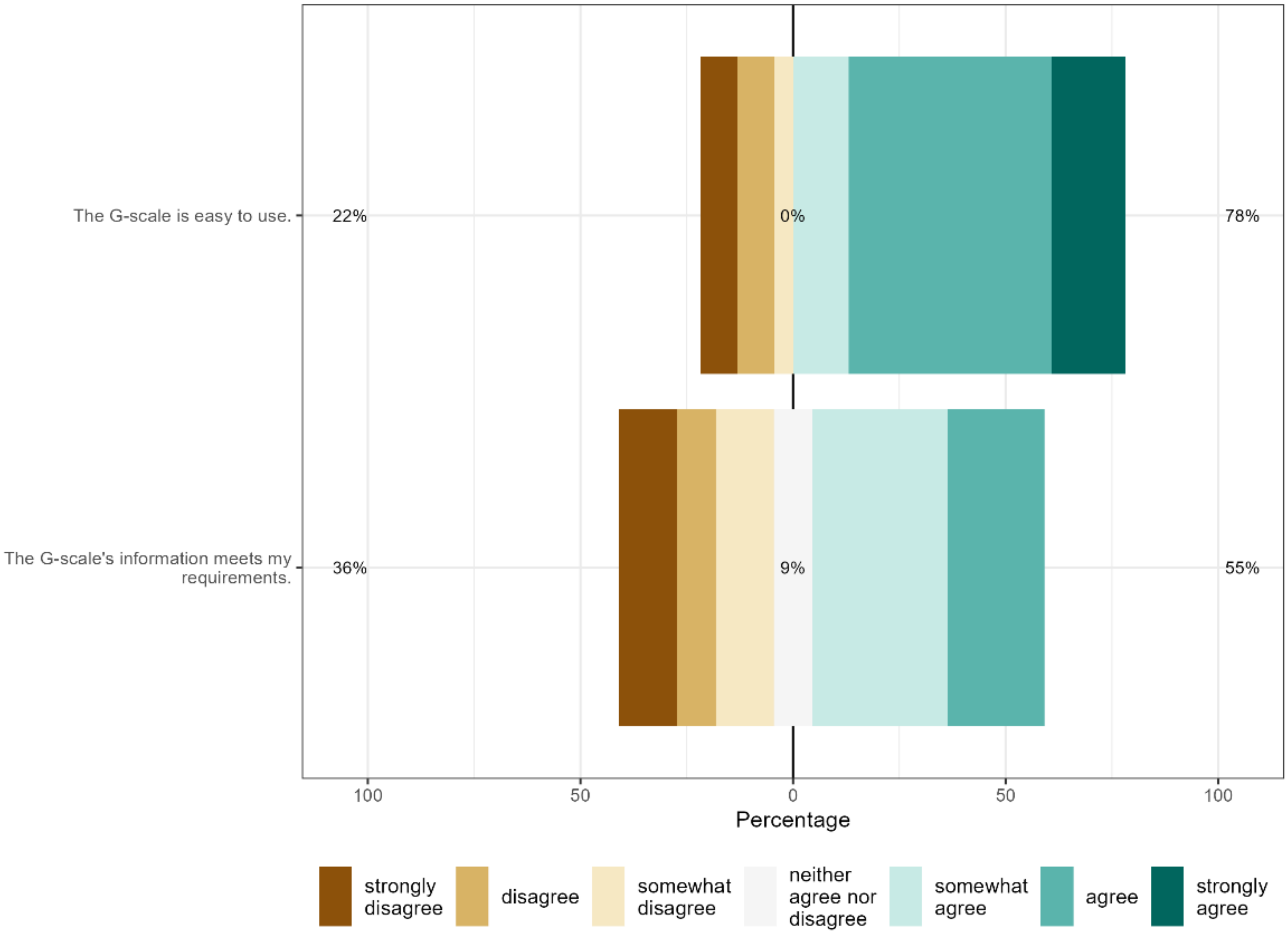

Figure B-11. G-Scale UMUX-Lite Responses

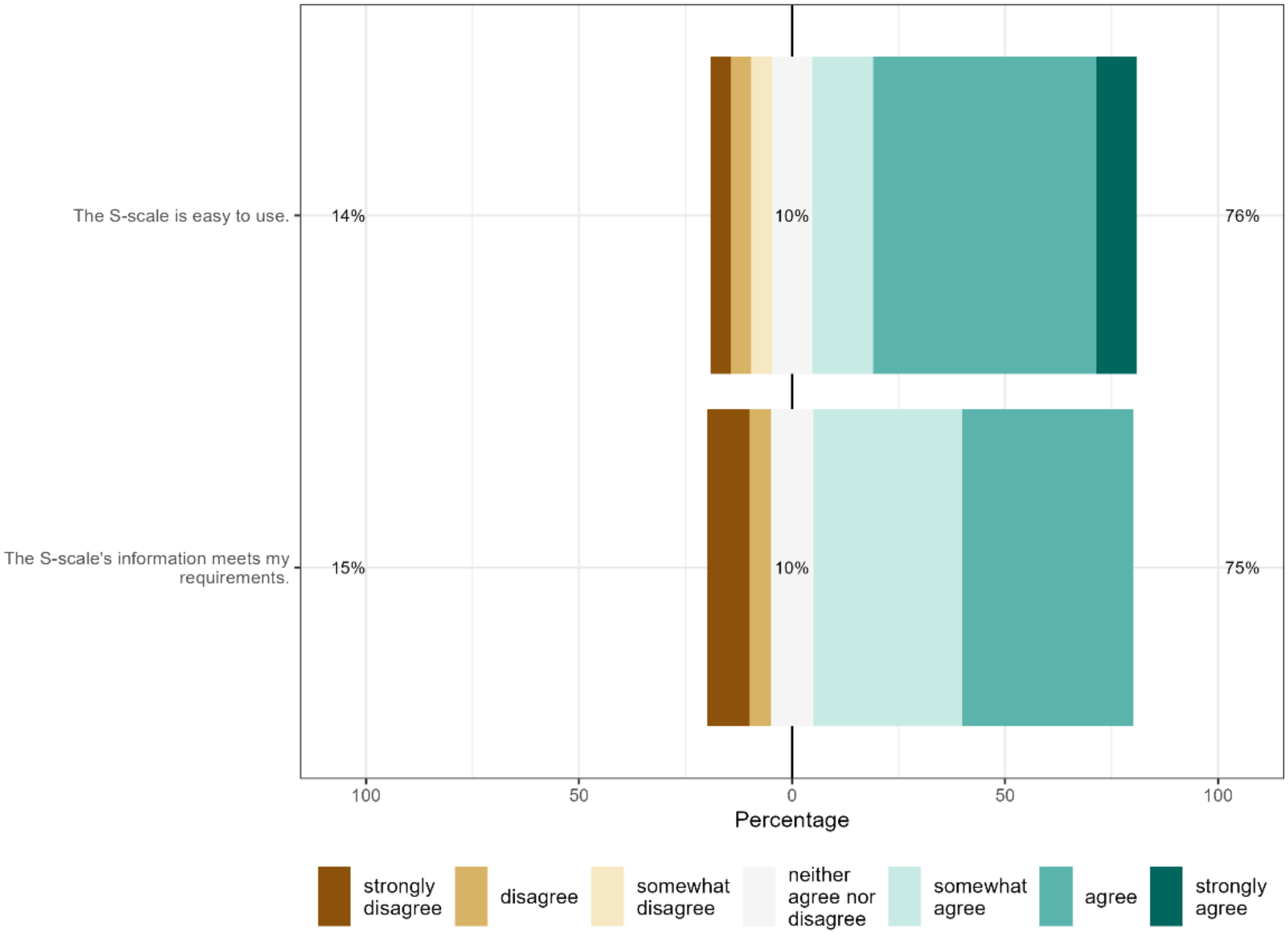

Figure B-12. S-Scale UMUX-Lite Responses

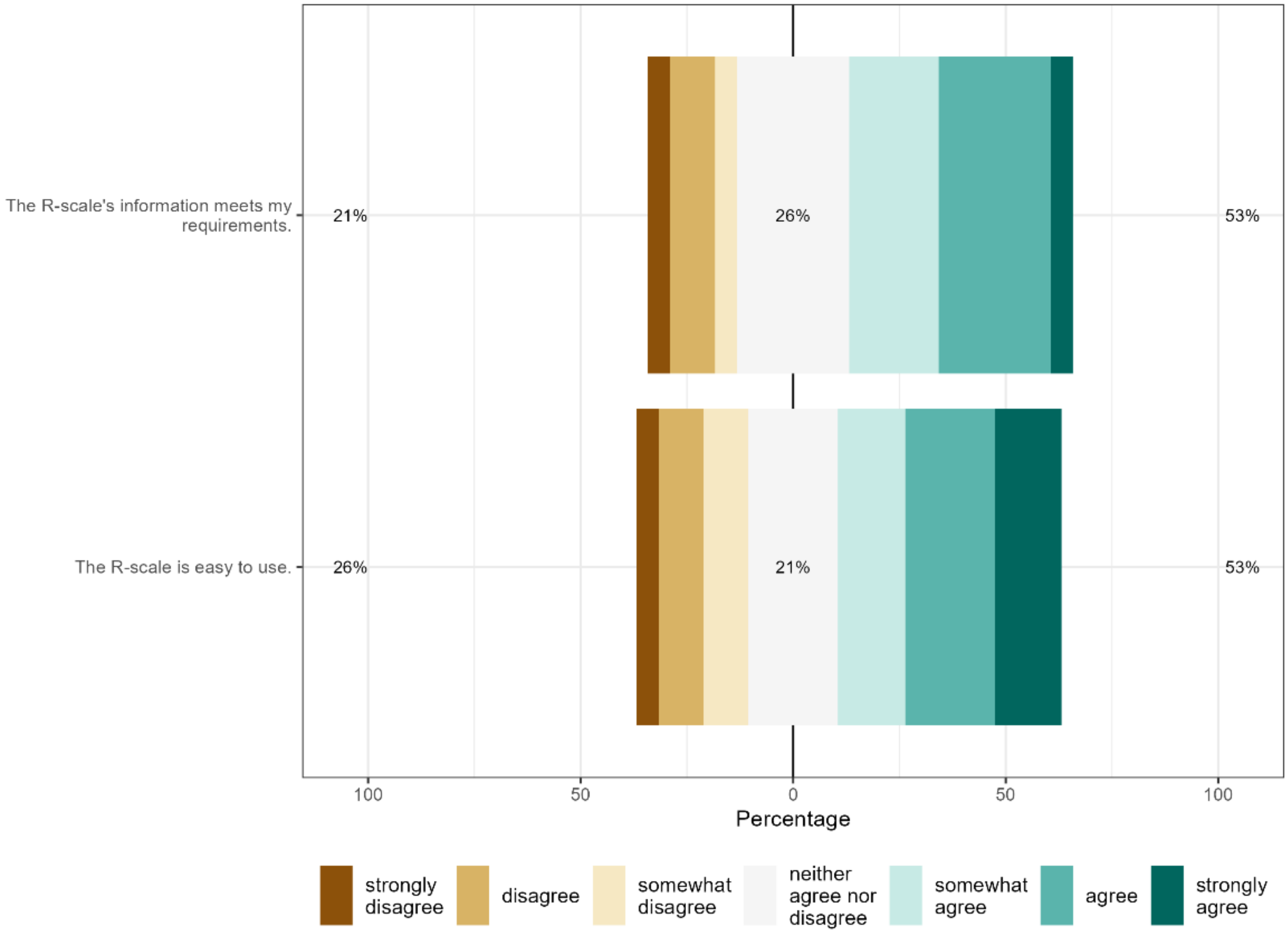

Figure B-13. R-Scale UMUX-Lite Responses

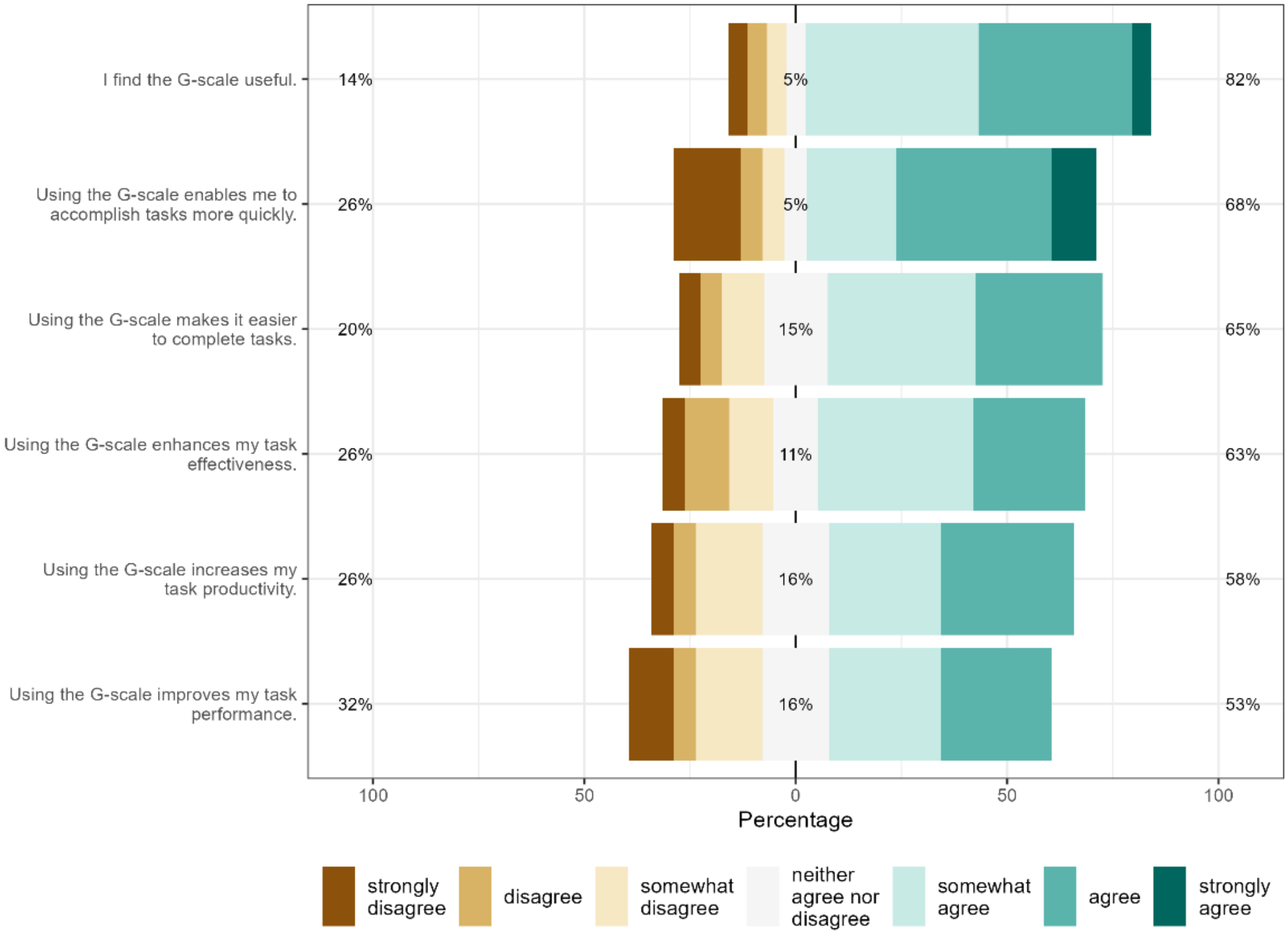

Figure B-14. G-Scale Usefulness Responses

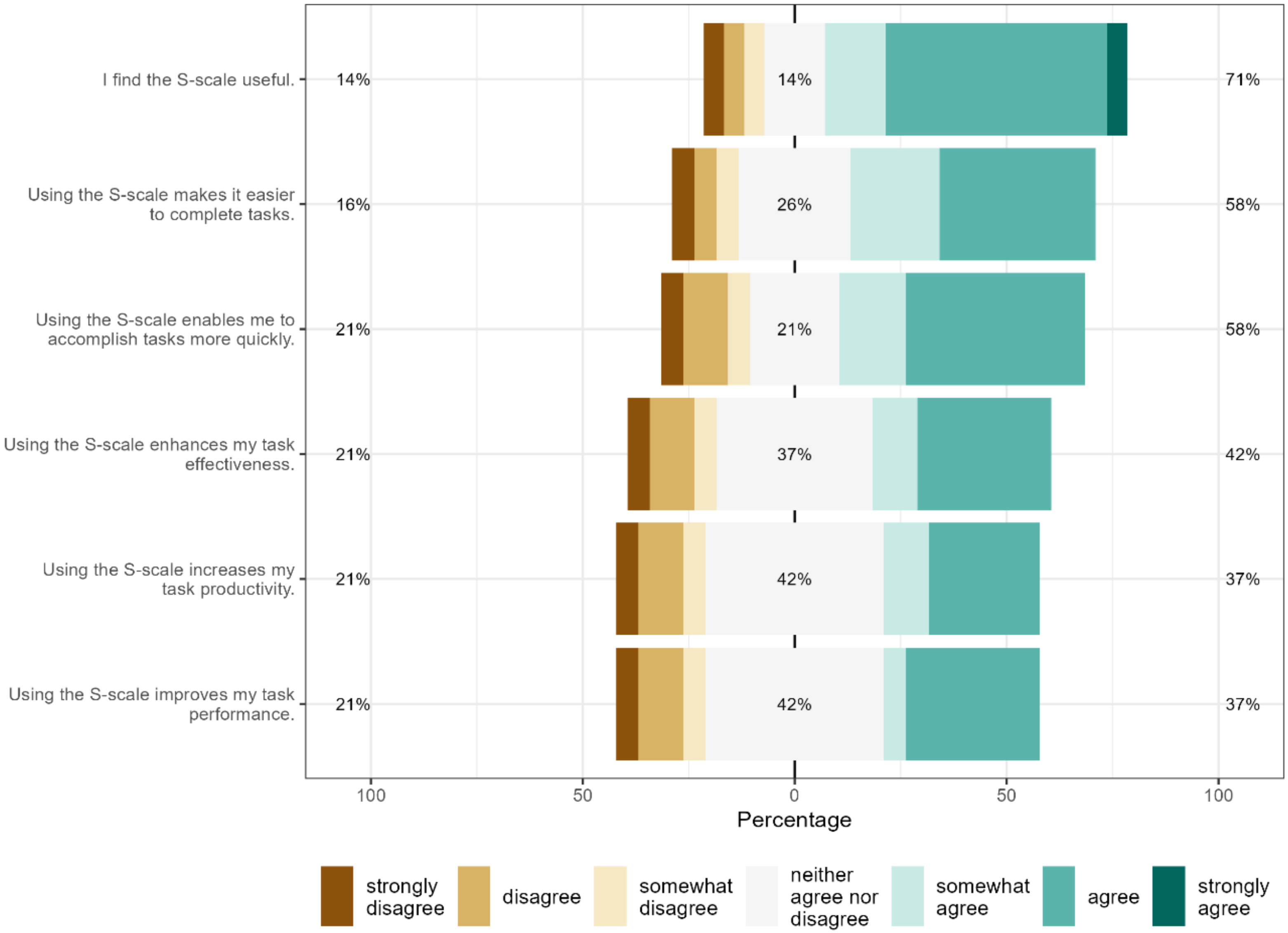

Figure B-15. S-Scale Usefulness Responses

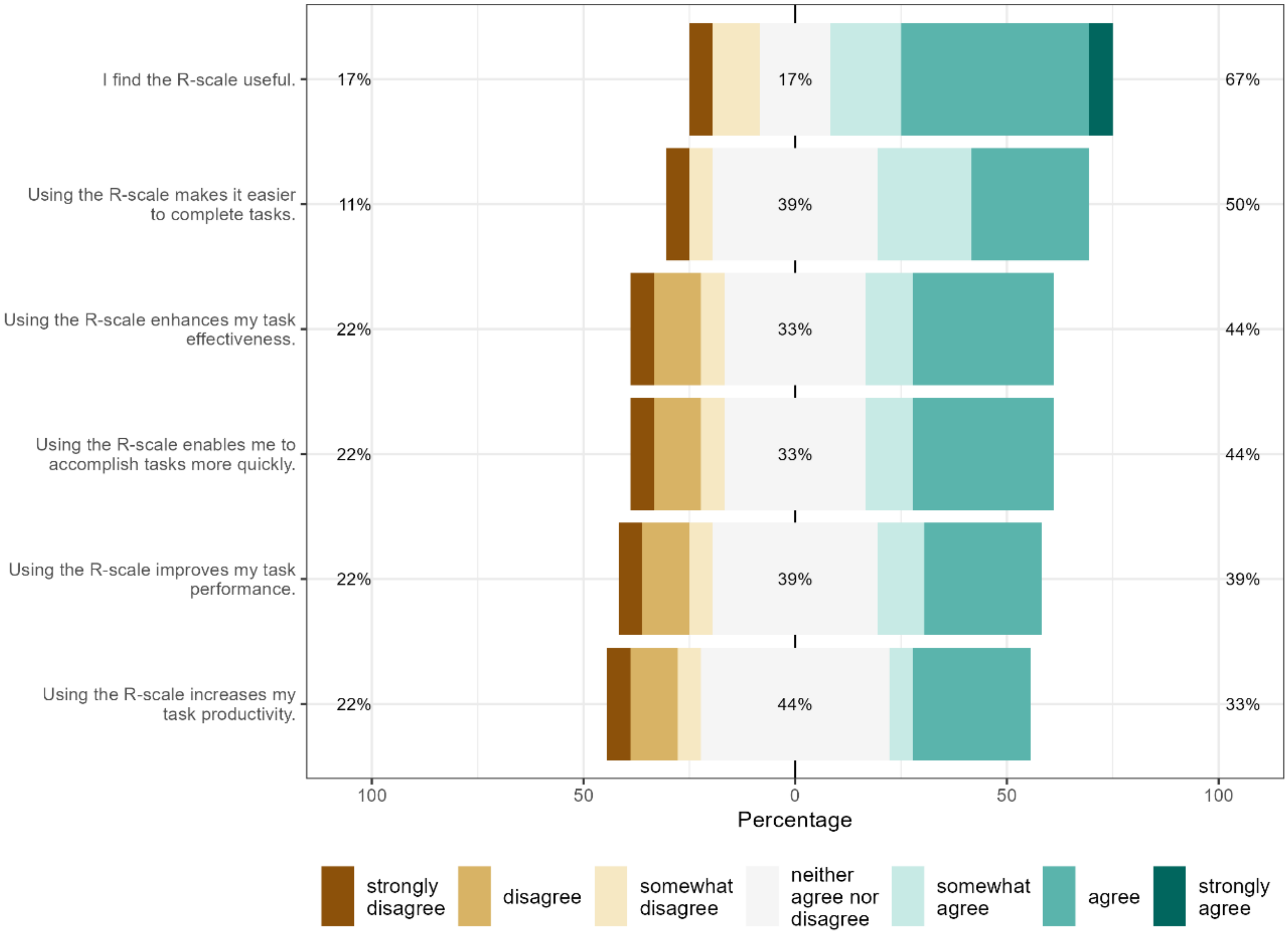

Figure B-16. R-Scale Usefulness Responses

Appendix C.
Space Weather Phenomenology

Space weather refers to the collection of varying environmental conditions caused by the Sun that can affect technologies and human health in space and on Earth. Space weather originates from solar flares, solar radio bursts, solar wind, CMEs, and energetic solar charged particles. These phenomena send electromagnetic waves, charged particles, and clouds of electrically charged and magnetized gas from the Sun to the Earth and its surrounding environment (NOAA 2024f). Solar electromagnetic emissions either ionize the atmosphere or propagate to the Earth's surface, both of which can interfere with communication, radar, or navigation signals. The charged particles can disrupt spacecraft operations, increase astronaut radiation dosage, and ionize particles in the atmosphere. The clouds of electrically charged and magnetized gas—referred to as magnetized plasma—can interact with and change the Earth's magnetic field, enhancing electric fields and currents in the atmosphere and on the ground; increasing the number of ionizing charged particles entering the atmosphere; and changing the density of the upper atmosphere (Australian Government Bureau of Meteorology 2024). These plasma-induced effects in the Earth's environment can lead to disruptions of the power grid and spacecraft operations as well as interfere with communication, radar, or navigation signals.

This appendix describes solar flares, solar radio bursts, solar wind, CMEs and solar charged particles; how they induce effects in the Earth environment; and the impacts those effects have on technology and human health. We limit our discussion to the phenomena and effects that inform the three NOAA SWS and the information the scales communicate.

Solar Flares

Solar Flares are sudden releases of energy stored in sunspot magnetic fields. These magnetic fields build and store energy as they become coiled and twisted while the Sun rotates—with the equator rotating faster than its poles. The stored energy is released when the field lines break and reconfigure, converting the magnetic energy into other forms that typically generate intense x-rays, extreme ultraviolet light, radio emissions, and release energetic particles (predominantly electrons and protons with a small number of ions) into the solar system (Knipp et al. 2016; Odenwald 2024). Some strong flares produce gamma rays and intense white light. The sudden outburst of electromagnetic emissions travel at the speed of light, arriving and affecting the outer atmosphere of the sunlit side of Earth in approximately 8 minutes and can last from seconds to hours (Frissell et al. 2019; Knipp et al. 2016; Baker and Lanzerotti 2016). Because of the travel speed, space weather observers detect the solar flare at the same time the electromagnetic radiation interacts with the Earth, making advance warning difficult. The associated energetic particles can arrive in the space environment surrounding the Earth less than 30 minutes after a flare occurs (NASA 2024h).

The Effects of Solar Flares

Solar x-rays and extreme ultraviolet are constantly colliding and photoelectrically knocking electrons off of atoms and molecules, creating positively charged ions and negatively charged free electrons in the Earth's upper atmosphere. The Earth's upper atmosphere contains layers of ions and free electrons at different altitudes that are collectively known as the ionosphere. In these regions, air pressure is low enough that ions can travel freely for a long time without colliding and recombining into neutral atoms or molecules. The variations in electron density in the two upper ionospheric layers, known as F_1 and F_2, are used to bounce, or refract, HF (3 to 30 MHz) radio signals back to the Earth's surface, enabling a form of over the horizon communication known as skywave propagation. When a strong solar flare occurs, its x-rays ionize the lower, denser, D layer of the ionosphere, increasing its electronic density. An HF radio signal passing through the dense D region collides with a relatively large number of ions causing much of the signal's energy to be transferred to ion motion or atmospheric heating (Lusis 1983; Australian Government Bureau of Meteorology 2016). The energy loss causes the HF radio signals to become degraded or completely fade out on the dayside of the Earth for a period ranging from minutes to hours. These radio fadeouts are also known as HF radio blackouts. HF radio is still used for long-distance communications by aircraft, ships at sea, amateur radio operators, and as a backup for emergency communications during disaster relief (Frissell et al. 2019; NOAA 2024b).

The enhanced D layer ionization also affects low frequency (LF) (30 to 300 kHz) ground-based navigation systems by advancing the arrival of skywave signals compared to reflections off higher regions in the ionosphere when there is no solar activity. LF signals reflect off the ionosphere and then interfere with the LF signals propagating along the Earth's surface. Older LF ground-based systems, such as DECCA, were prone to position errors due to the signal interference. While newer LF systems include integrity checks to warn when location data are not accurate, we could not find a source quantifying the effects of space weather on those systems. Today, most LF navigation systems have been taken out of service in favor of more accurate GNSS (Schrijver et al. 2015; Ishii et al. 2024; United States Coast Guard 1992).

Changes to the ionosphere also affect satellite communications, GNSS, and radar signals, with carrier frequencies in VHF (30 to 300 MHz), UHF (300 MHz to 3 GHz), L-band (1 to 2 GHz band), and S-band (2 to 4 GHz band), passing through the different layers. The irregular electronic density structures within those layers cause random amplitude and phase shifts of radio waves known as scintillation as the radio waves refract, or bend, around the ionospheric structures. Scintillation typically manifests itself as radio noise and can lead to degradation of the signal quality or a loss of satellite communications, GNSS data, or radar signals if the receiver's signal protocol does not mitigate for such degradation (American Meteorological Society Policy Program 2011). Scintillation can lead to large errors in GNSS positional and timing information and radars can experience range and azimuthal errors (Ishii et al. 2024). Scintillation tends to be most severe in the equatorial regions, especially at dusk and dawn, and within the auroral regions. In general, the longer the radio propagation path through the electronic density variations, the greater the effect. For GNSS, this applies to single-, dual- and multi-frequency systems used in numerous applications today as well as to dual- and multi-frequency systems, where scintillations and other turbulent ionospheric effects lead to considerable signal disruption, impairing any advantages associated with the use of multiple frequencies (Ishii et al. 2024; Baker and Lanzerotti 2016). However, ionospheric scintillation has less of an effect on frequencies above 10 GHz, so for satellite communication systems above 10 GHz, scintillation is almost negligible compared to other effects such as rain fall (Flock 1983; Ippolito, Kaul, and Wallace 1983).

Solar Radio Bursts and their Effects

Active regions of the Sun can occasionally produce intense flashes of radio waves called solar radio bursts. Solar radio bursts can emit noise, across a wide range of frequencies, that acts like a "jammer" lowering the single-to-noise ratio of any radio receiver pointed at the Sun. Solar Radio burst can affect systems that receive radio signals, such as GNSS, communications, and radars (Ishii et al. 2024; Knipp et al. 2016; Cerruti et al. 2008; Marqué et al. 2018). Additionally, they can cause dropped cell-phone calls near sunrise and sunset when base station antennas are facing in the direction of the Sun during a solar radio burst (Gary, Lanzerotti, Nita et al. 2004).

Solar Wind and Coronal Mass Ejections

The Sun has two primary mechanisms that transmit magnetized plasma to the Earth: solar wind and CMEs. The solar wind is a continuous flow of protons, electrons, and some ions, contained within an electrically neutral plasma state that carries a magnetic field. It is highly variable, with different regions on the Sun's corona producing solar wind at different velocities, densities, and magnetic field directions. Solar wind is observed in two primary states, "slow" (200–500 km/s) and "fast" (> 500 km/s). The "slow" solar wind is persistent, but varies in velocity, changing with the state of the corona. "Fast" solar wind comes from coronal holes, which occur where the magnetic field lines of the corona open out into the solar system and act like pipes through which hot high-density coronal plasma can flow quickly outward. “Fast” solar wind events last hours to days (McIntosh 2019; Odenwald 2024; Baker and Lanzerotti 2016).

The ever-present “slow” solar wind streams outward from the Sun into the solar system and is constantly interacting with and fluctuating the Earth’s magnetic field. The level of fluctuation depends on solar activity and the alignment of the plasma’s magnetic field with respect to the Earth’s magnetic field. If the two magnetic fields have opposite orientation, there will be an efficient transfer of energy from the solar wind to the space environment surrounding the Earth, changing the Earth’s magnetic field, enhancing the electric fields and currents within the upper atmosphere, and increasing the energetic particle participation into the upper atmosphere, all leading to changes in the electron density and structure within the ionosphere. Disturbances in the Earth’s magnetic field are called geomagnetic storms (McIntosh 2019; NOAA 2024e; NOAA 2024).

Large geomagnetic storms arise from the Earth’s magnetic field interacting with dense or fast-moving solar winds or CMEs. CMEs contain 1 to 10 billons of tons of solar plasma, with an embedded magnetic field, that erupt from the Sun’s outer atmosphere, the Corona, and move outward into space at more than 3,000 km/s (Baker and Lanzerotti 2016; Rajput et al. 2021). Like solar flares, CMEs are associated with releases of magnetic energy close to sunspots. The magnetic field lines twist and bend until the lines rupture and realign, producing the eruption. Typically, they rise out of or near solar flare sites, but they can develop independently of each other. It takes Earth-directed CMEs between 15 hours to 4 days to arrive at the Earth (Knipp et al. 2016; Dahl and Steenburgh 2023). Their effects last hours to days. The longer a significant geomagnetic storm lasts the stronger its effects will be.

The Earth’s magnetic field shields the planet from most of charge particles by deflecting them around the Earth, but some charged particles get trapped within Earth’s magnetic field. Perturbations in the Earth’s magnet field cause its magnetic field lines to couple together, break and reconnect. During the reconnection process, electrons trapped in the Earth’s magnetic field are accelerated along the Earth’s magnetic field toward the Earth’s polar regions. These electrons strike neutral atoms in the atmosphere, exciting their valence electrons to higher energy states before returning to their initial lower energy state. Photons, making up the visible light of the auroras, are released when the electrons return to their initial state. The particles streaming down the magnetic field of the Earth reach the neutral atmosphere in a rough circle called the auroral oval. This pseudo-circle is centered over the magnetic poles and is approximately 3,000 km in diameter during quiet times. The aurora circles grow larger when there are larger fluctuations of the Earth’s magnetic field created by fast-moving solar winds or CMEs (Combs and Viereck 1996).

Effects of Solar Wind, CMEs and Geomagnetic Storms

Geomagnetic storms, especially ones from CMEs, can severely disturb the Earth's magnetic field and ionosphere, causing sudden changes in aurora zone (often referred to as sub-storms; Combs and Viereck 1996). The large disruption moves the auroras in the direction of the equator and induces intense currents in the Earth's magnetic field, including ring currents around the Earth and currents flowing within the auroral ionosphere. All these currents fluctuate the Earth's magnetic field that induce changing electric fields, both of which can be observed on the ground. The resulting electric field drives potentially harmful GICs in grounded long-distance electric power lines and pipelines, potentially heating transformers to the point of interfering with power system operation and causing corrosion in the pipelines (Boteler 2001; Marshall et al. 2012; NOAA 2024; Rajput et al. 2021).

Like solar flare x-rays, geomagnetic storm-induced changes in the ionosphere's electronic density and structure can disrupt HF communications, satellite communications, GNSS, and radar systems through radio frequency absorption, refraction, and scintillation. The causes and their effects are discussed in detail in the "Effects of Solar Flares" section.

Induced atmospheric currents and precipitating particles from geomagnetic storms heat the atmosphere, causing it to expand radially outward from the Earth. Low density layers of air low in Earth orbit altitudes rise and are replaced by higher density layers that were previously at lower altitudes. This change in atmospheric density increases the drag force on satellites orbiting below 700 km. It is unclear how much the atmospheric density changes over time, resulting in large uncertainties in satellite orbital predictions and in turn, large errors in probability of collision estimates (Bussy-Virat et al. 2018). Additionally, when the Sun is less active, low Earth satellites may boost their orbits about four times per year to make up for atmospheric drag. During solar maximum, when the Sun's solar activity is at its greatest over the 11-year solar cycle, satellites may have to be maneuvered every 2–3 weeks to maintain their orbit (NOAA 2024c). The associated drag forces can change as satellites orbit, making orbital prediction challenging, and even cause some satellites to prematurely reenter the atmosphere (Berger et al. 2023).

Magnetic surveys are used to determine locations where changes in the Earth's magnetic field might indicate location of a valuable resource. Changes in the geomagnetic field can survey magnetic field measurements inaccurate, causing surveys to be postponed for days when geomagnetic storms are predicted or are occurring (Baker and Lanzerotti 2016).

Solar Charge Particles

Solar flares and the leading edge of CMEs can generate and propel energetic electrons, protons, and some ions towards the Earth. These events are referred to as either solar radiation storms or solar proton events. Protons are often referred to because they are the primary momentum carrier associated with the disturbance (Knipp et al. 2016). The energetic particles can reach Earth anywhere from 20 minutes to many hours following the initiating solar event and typically last from several hours to 2 days. The polar regions are most affected by energetic particles because the magnetic field lines at the poles extend vertically downwards, allowing the particles to spiral down the field lines and penetrate into the atmosphere. The penetrating particles, in particular protons, collide with atmospheric particles, ionizing them and increasing the irregular ionospheric D region electronic density (NOAA 2024a).

The Effects of Solar Charged Particles

Like solar flare x-rays, solar radiation storms induce changes in the ionosphere's electronic density and structure that can disrupt skywave communication, satellite communication, GNSS, and radar systems through radio frequency absorption, refraction, and scintillation. But instead of affecting the sunlit side of Earth, the proton-induced ionization is contained to the Earth's polar regions where effects occur day and night (stronger on the dayside compared to the nightside) and equatorward down to approximately 60–65 deg geomagnetic latitude. These proton-induced effects are a concern to aircraft flying polar routes (above 80 degrees latitude) that rely on HF skywave radio communications when geosynchronous communication satellites cannot be seen from the polar region (Ishii et al. 2024; Baker and Lanzerotti 2016).

Aircraft crews flying at typical aviation cruising altitudes and astronauts can both receive increased hazardous radiation doses during solar proton events. Aircraft crews are at risk if the proton energies are greater than or equal to 500 MeV (Meier and Matthiä 2014; Bain et al. 2023); protons with lower-energy cannot typically penetrate the upper atmosphere (Meier and Matthiä 2014; Meier et al. 2020). Astronauts can receive increased radiation doses if the proton energy is in the 30 to 50 MeV range; at this energy level, protons can penetrate spacesuits and thinly shielded spacecraft or habitats (Chancellor et al. 2014; Reames 2021). Thicker shielding, around 7.5 cm of aluminum, can withstand solar protons energies up to about 150 MeV (Reames 2021).

Satellites in geosynchronous and low-Earth orbits are also susceptible to energetic protons originating from solar flares and CMEs. These particles can cause spacecraft charging and single event upsets, which occur when an energetic proton produces a change in memory state in the system's digital electronics. A single event upset can cause damage to or loss of stored data, damage to software programs, onboard processor stops, hardware failures (including solar panels), or even various unplanned events including loss of mission. Energetic protons can cause physical damage, such as the damage of dielectric materials and solid-state devices. They can also cause a false sensor reading, particularly with star sensors that are used by the satellites for attitude control. A proton impact event on the star sensor can give a false star detection, and the detected star pattern will no longer match its internal star map, possibly causing the satellite to spin and reorient itself in an effort to regain its orientation. This can cause intermittent loss of communications with a satellite, loss of satellite power, and, in extreme cases, loss of the satellite (NOAA 2024a; Knipp et al. 2018).

Appendix D.
Qualitative Codebook

STPI developed a codebook to qualitatively code each comment or piece of information participants shared that was relevant to the main study questions. Each comment was coded with the following information:

- Scale: STPI researchers analyzed which scale the comment was referring to.
- Question: STPI researchers indicated which aspect of the study question the comment addressed:
    1. Do you use the NOAA scales?
    2. How did you use the scales?
    3. How, if at all, where the scales useful?
    4. How could the scales be improved?
    5. If there were no scales, what would the impact be?
    6. What are your suggestions for new scales?
- Themes: STPI researchers identified common themes across comments within the same study question and identified the theme as a "Theme" code.
- Sub-Theme: For certain comments, STPI further described the comment with a sub-theme to capture the information more precisely. This was mainly used for comments assigned under the question "How could current scales improve?" with the "Communication" theme.
- Interviewee: STPI researchers recorded which comment was provided by which participant.
- Sector: STPI researchers identified the sector of the participant.
- Type of Engagement: STPI identified the type of engagement (i.e., interview, panel, RFI).

Tables D-1 through Table D-7 contain the codebook developed by STPI, which contains common themes and sub-themes that were assigned to each comment collected through the RFI, interviews, and group engagements. Figures D-1 through D-7 visualize the themes with the greatest number of coded responses.[19] Figure D-5 is a visualization of the sub-themes coded under the Communication theme for question 4. How could the scales be improved?

Table D-1. Qualitative Codebook for Question 1

Question	Theme	Description
1. Do you use the NOAA scales?	*Yes*	Yes, the participant used the scales.
	No	No, the participant did not use the scales.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned are reported in the table and figure.

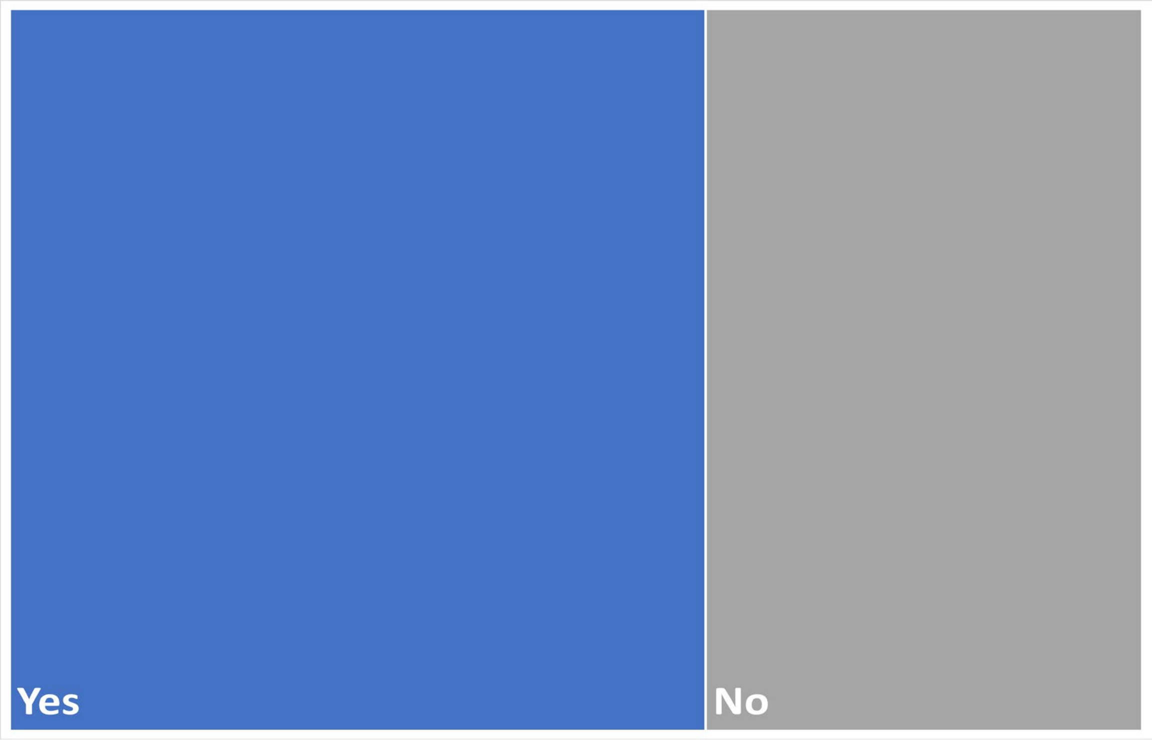

Figure D-1. Treemap of Coded Responses to Question 1: Did you use the NOAA scales?

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[19] Only themes/sub-themes that had five or more comments assigned to them are reported in the tables and figures.

Table D-2. Qualitative Codebook for Question 2

Question	Theme	Description
2. How did you use the scales?	*Taking action*	Participant watched the scale levels to inform a decision and/or action such as posturing systems, employing mitigations, or delaying activities. This theme includes any action that is not communication or seeking additional information.
	Monitoring	Participant paid attention to whether the scales changed levels but did not take action. In some cases, this theme could include being aware of the space weather situation, and in other cases it may be simply categorizing current SWx conditions. Monitoring includes planning for action based on possible SWx changes.
	Sharing information	Participant communicated the change in scale level as part of their alert or communication to others. This theme also includes actions that relate to education on or about the scales.
	Briefing leadership or other stakeholders	Participant requested SWPC provide information about uncertainty, probability, and confidence, as well as improve the accuracy of forecasts.
	Seeking additional information	Participant watched the scales and whether they changed; they sought additional information or data related to space weather.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned to them are reported in the table and figure.

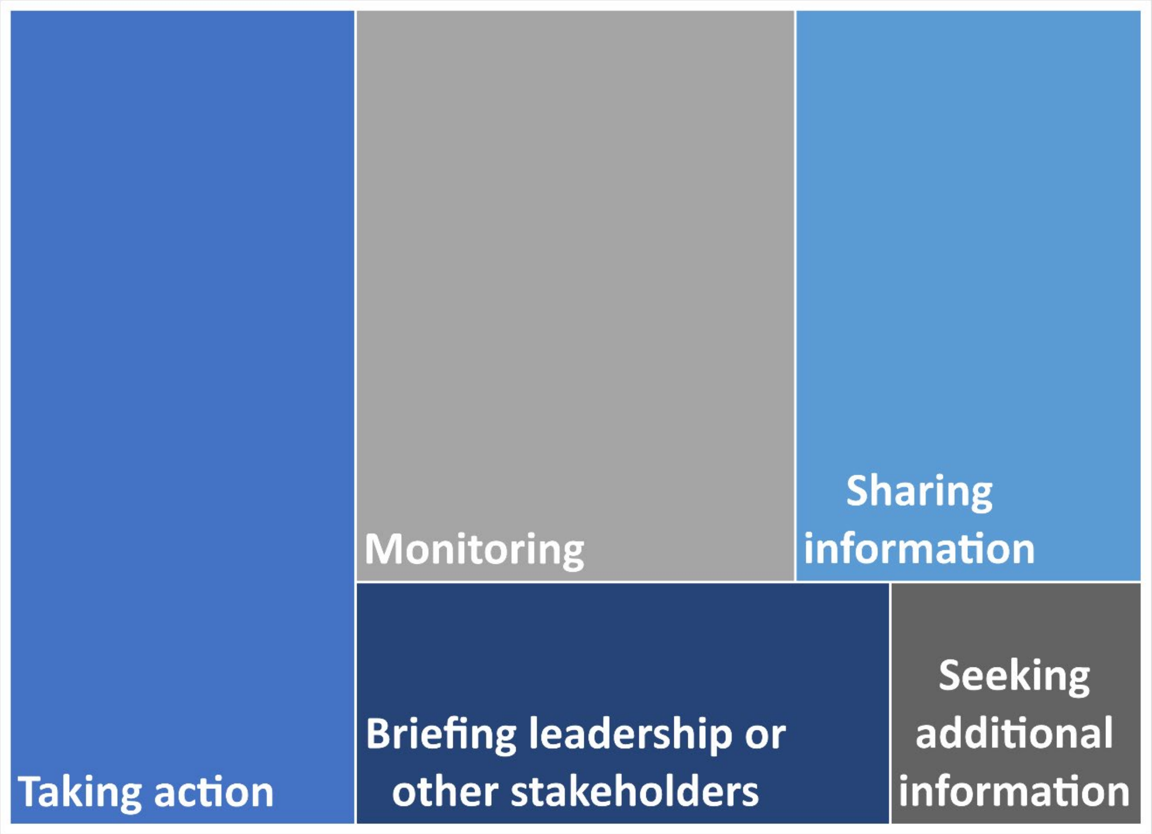

Figure D-2. Treemap of Coded Responses to Question 2: How did you use the scales?

Table D-3. Qualitative Codebook for Question 3

Question	Theme	Description
3. How, if at all, are the scales useful?	*Simplicity*	Participant described the scales as simple or easy to follow, and their simplicity makes them easy to understand.
	User familiarity	Participant described users' familiarity with the scales and suggested this made them easy to use.
	Forecasting	Participant described that the forecasts, provided by virtue of the scales, have useful information for the stakeholder.
	Not useful	Participant indicated that the scales are not helpful or useful.
	SWx general knowledge	Participant described that the scales provide useful general information about space weather and current space weather conditions.
	Standardization	Participant described that the scales provide standardization across data and/or stakeholders that allows for collaboration and eases communication.

Question	Theme	Description
	Historical information	Participant described that some element of historical context or comparison, provided by the scales, is useful.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned to them are reported in the table and figure.

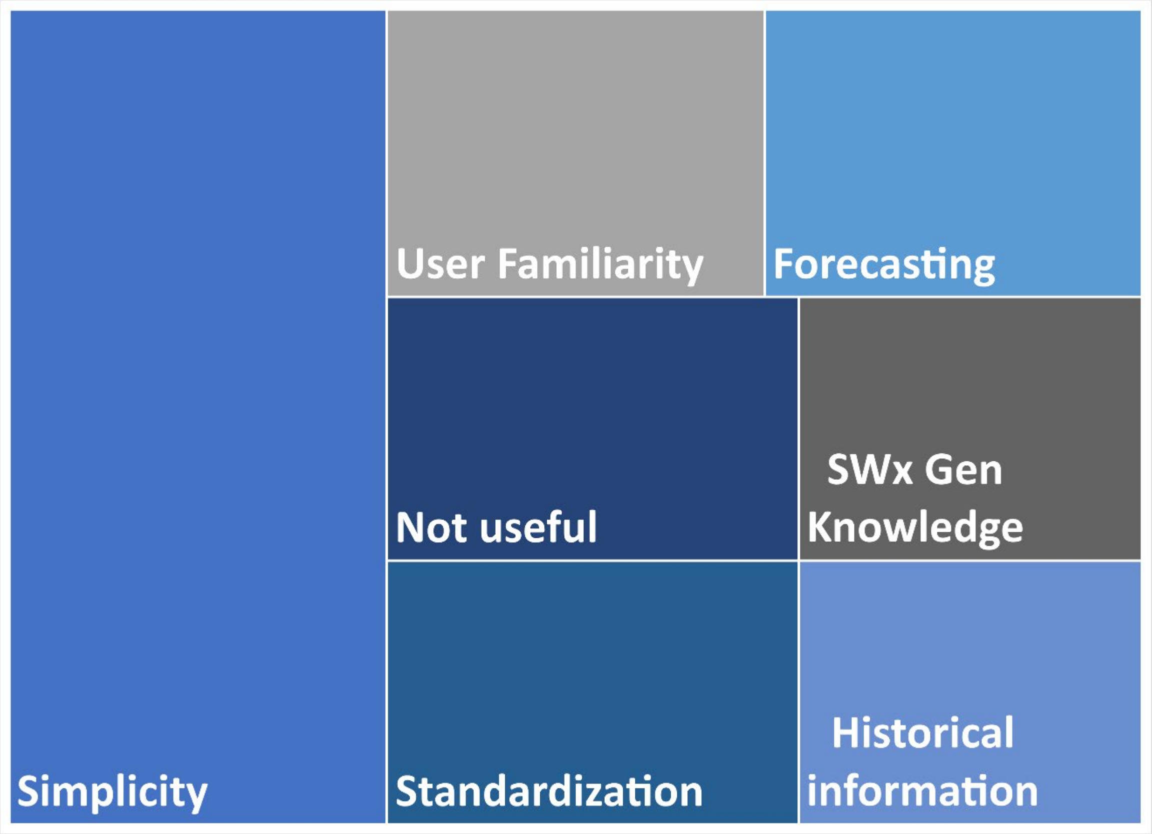

Figure D-3. Treemap of Coded Responses to Question 3: How, if at all, are the scales useful?

Table D-4. Qualitative Codebook for Question 4

Question	Theme	Description
4. How could the current scales improve?	*Communication*	Participant described some aspect of the communication of the scales could improve; see sub-themes.
	Expansion of levels	Participant said there should be an increase in the number of levels within the scales. *(Opposite of "Reduce scale levels" theme)*

Question	Theme	Description
	Geographic specificity	Participant described desiring geographic specificity information to be provided along with the scales.
	Impacts	Participant would like to see the scales based on effects to users rather than solar phenomenon or environmental disturbances.
	Other	Assorted comments that did not fit within STPI-identified themes.
	Change underlying data	Participant wanted underlying data of the scales changed.
	Include uncertainty information	Participant requested SWPC provide information about uncertainty, probability, and confidence, as well as improve the accuracy of forecasts.
	Additional data	Participant wanted to add additional data to the scales.
	Reduce scale levels	Participant wanted to decrease the number of levels within the scales. *(Opposite of "Expansion of levels" theme)*
	Get rid of scales	Participant wanted to eliminate the scales.
	S-scale energy threshold	Participant requested information about higher energy protons (e.g., 50 MeV, 100 MeV, 500 MeV) be added to the S-Scale.
	Alignment with other measures	Participant would like the scales to align with other types of measurements.
	More lead-time	Participant would like greater advance notice of space weather events.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned to them are reported in the table and figure.

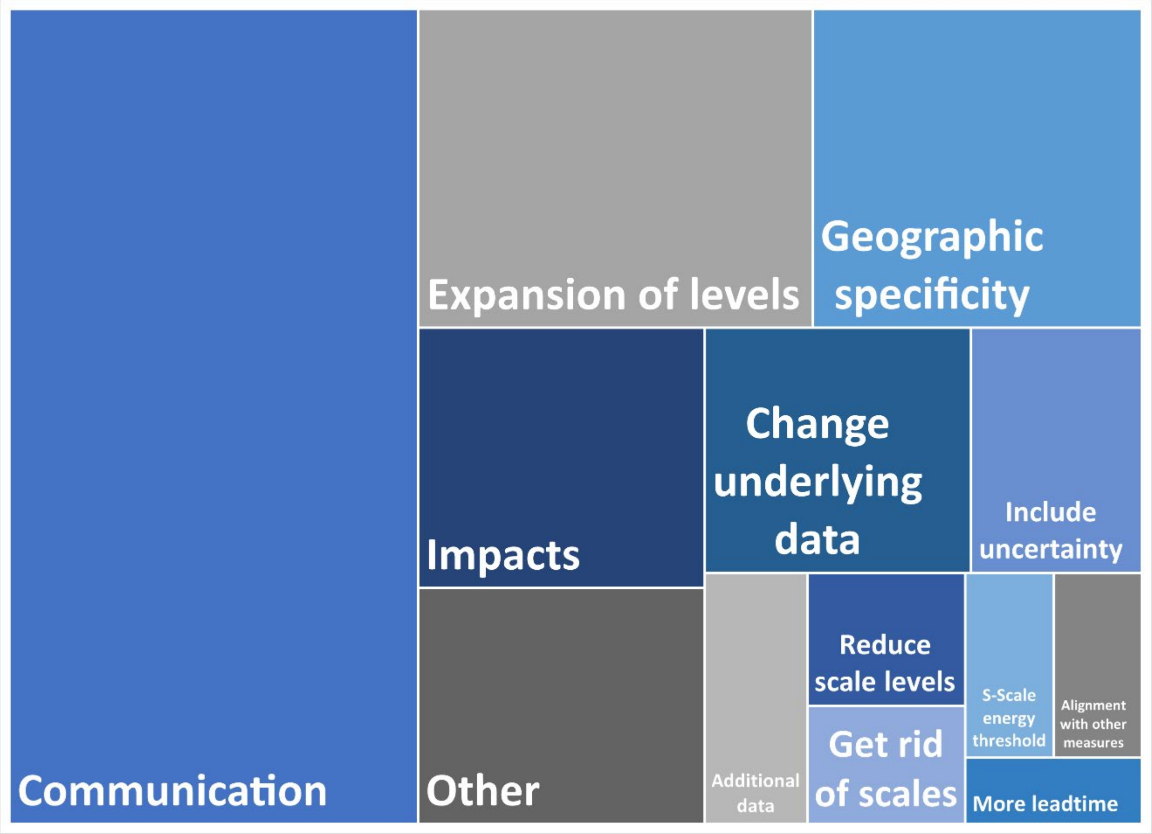

Figure D-4. Treemap of Coded Responses to Question 4: How could current scales improve?

Table D-5. Qualitative Coding of Communication Theme within Question 4: How Could Current Scales Improve?

Question	Theme	Sub-Theme	Description
4. How could the current scales improve?	*Communication*	*Communicate impacts*	Participant would like more communication on the effects of space weather to users.
	Communication	*Simplify*	Participant requested the scale language be less complex.
	Communication	*Education*	Participant discussed how more education on space weather is needed for some groups.
	Communication	*Update description*	Participant described that the descriptions of the scales are inaccurate and need to be updated to include more recent information (e.g., accounting for changes in technology).
	Communication	*Color scale*	Participant requested that the scales use color coding (e.g., red, yellow, green) to convey space weather information.
	Communication	*Audience-specific*	Participant suggested the scales be audience-specific.
	Communication	*Clarify location*	Participant requested the scales specify the applicable locations for described effects (i.e., altitude, LEO, MEO, GEO).
	Communication	*Improve information accessibility*	Participant highlighted the need to improve accessibility of the information related to the scales (e.g., website).
	Communication	*Change scale name*	Participant suggested renaming the scales to better represent the underlying space weather phenomenology.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only sub-themes that had five or more comments assigned to them are reported in the table and figure.

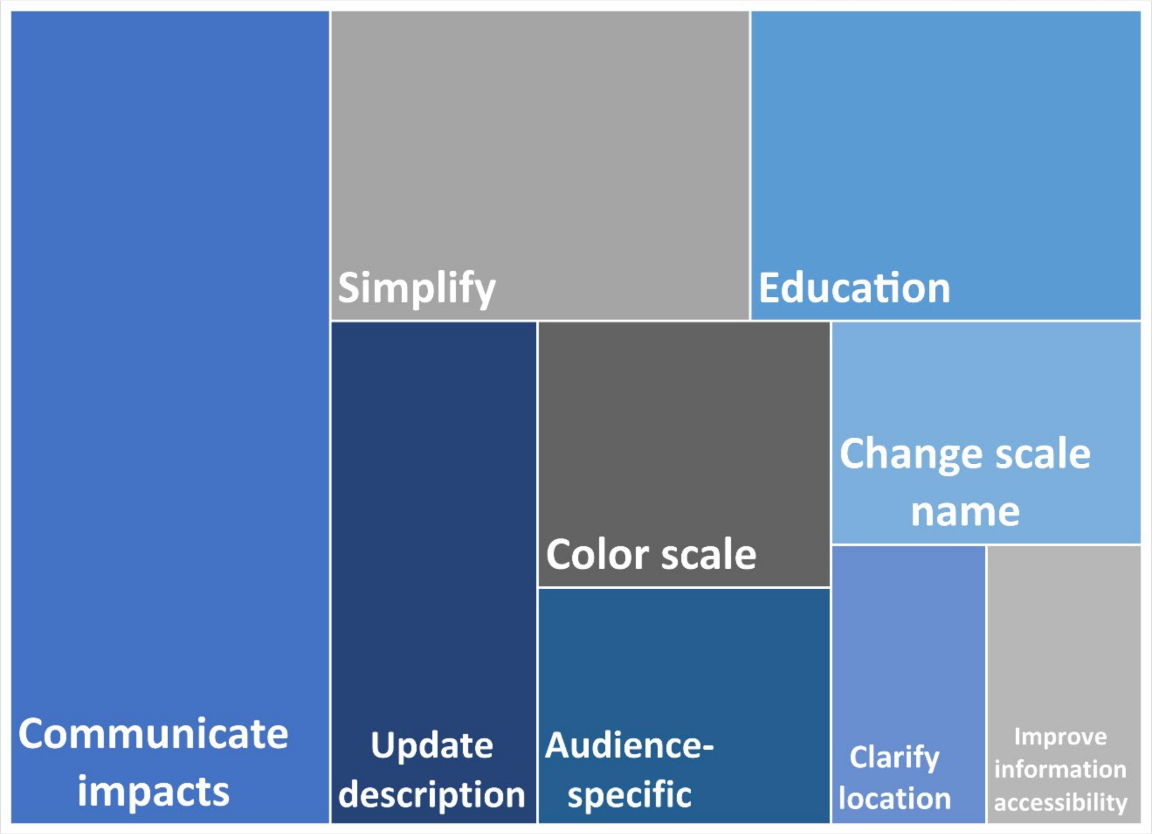

Figure D-5. Treemap of Sub-themes Coded within Communication Theme of "How could current scales improve?"

Table D-6. Qualitative Coding for Question 5

Question	Theme	Description
5. If no scale, what would the impact be?	*No impact*	Participant described that there would be no impact to them.
	Confusion among stakeholders	Participant described that there would be confusion among stakeholders.
	Mitigatable Impact	Participant discussed that any impacts of having no scales would be mitigatable.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned to them are reported in the table and figure.

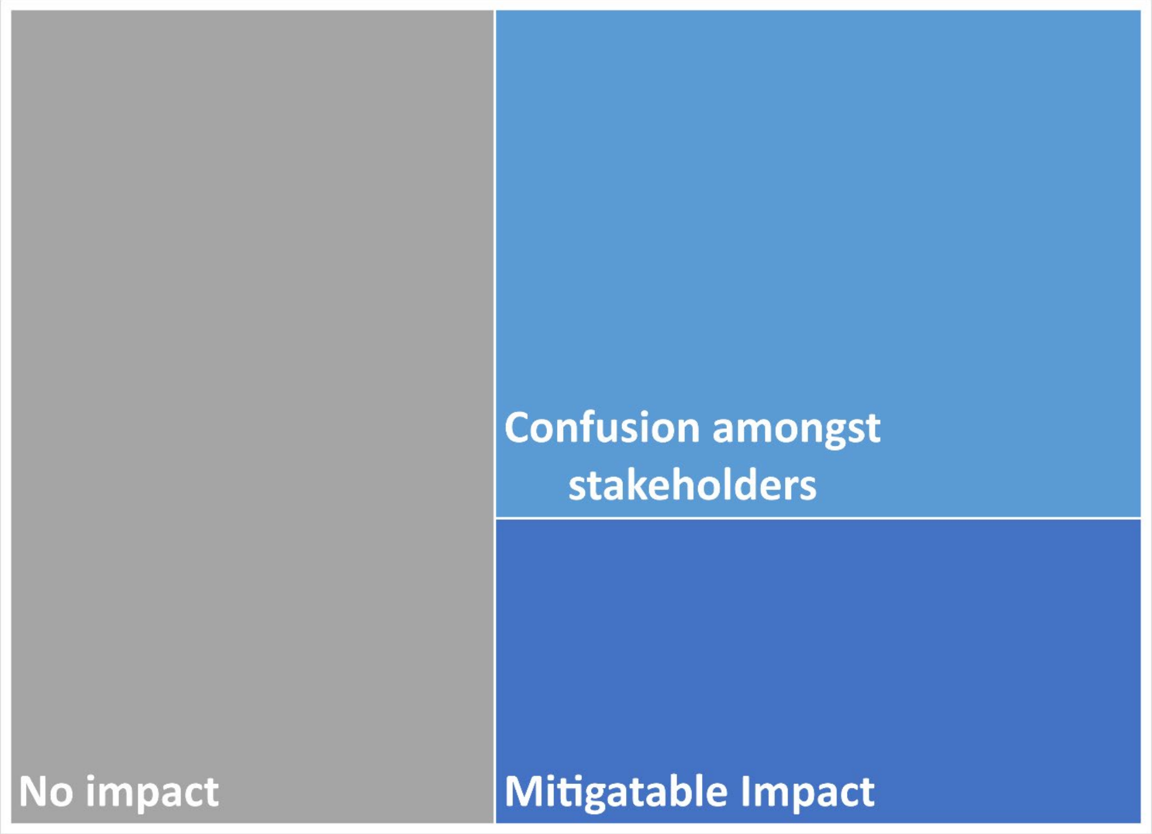

Figure D-6. Treemap of Coded Responses to Question 5: If no scale, what would the impact be?

Table D-7. Qualitative Coding for Question 6

Question	Theme	Description
6. What are your suggestions for new scales?	*Ionospheric Scintillation Scale*	Participant discussed the need for a trans-ionospheric scale, or T-scale, that captures the magnitude of scintillation.
	Product	Participant requested additional space weather information that they suggested SWPC should offer in a product (in addition to the scales).
	D-scale	Participant discussed adapting the D-Index (Meier and Matthiä 2014) as a new scale to characterize the radiation dose rate for humans in aviation.
	Neutral density	Participant discussed the need for a neutral density scale to describe atmospheric expansion and drag.
	Geoelectric field	Participant discussed the need for a Geoelectric Field Scale or E-scale.

Question	Theme	Description
	Single scale	Participant discussed combining all scales (i.e., G, R, and S) into one scale that can be customized.
	Aviation scale	Participant discussed the need for an aviation-specific scale, such as the need for ground-based neuron monitors or other aviation products.
	Ionospheric Scintillation Scale	Participant discussed the need for a trans-ionospheric scale, or T-scale, that captures the magnitude of scintillation.

Note: Table is organized by greatest number of codes assigned to a theme/sub-theme to least number of codes assigned to a theme/sub-theme. Only themes that had five or more comments assigned to them are reported in the table and figure.

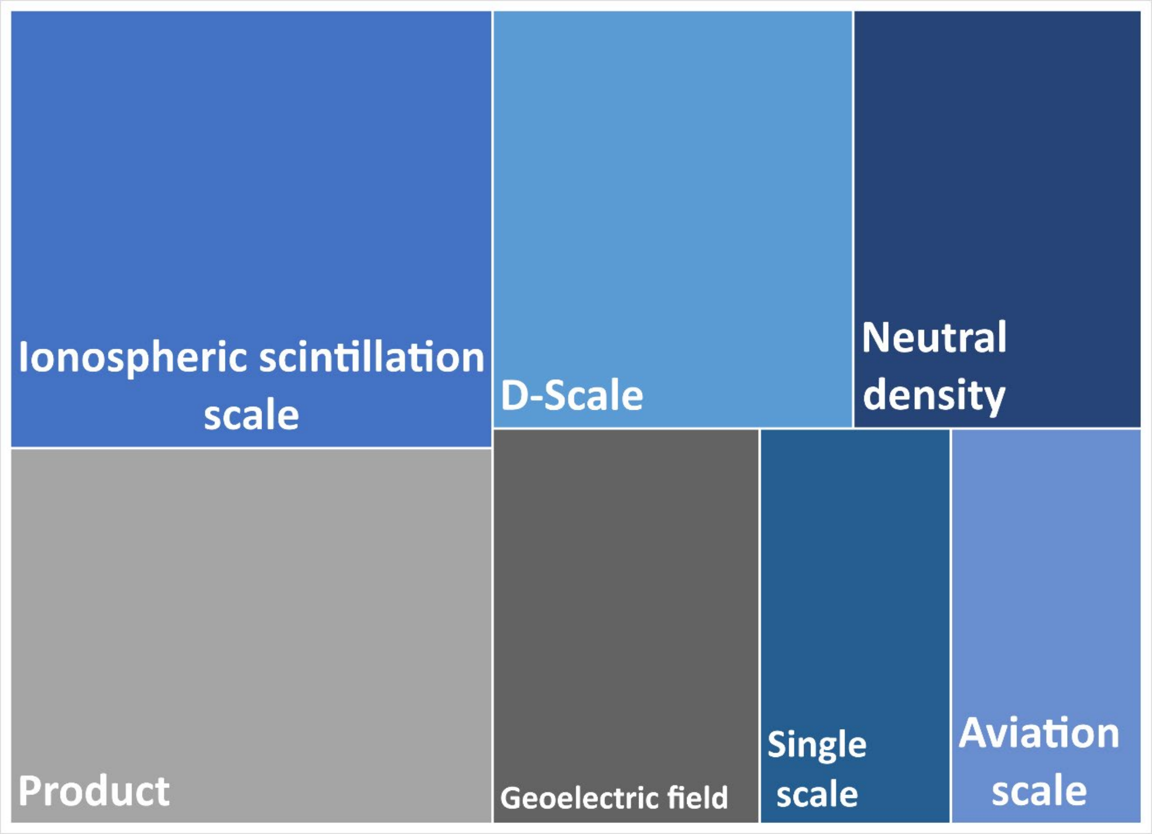

Figure D-7. Treemap of Coded Responses to Question 6: What are your suggestions for new scales?

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Abbreviations

ACE	Advanced Composition Explorer
CCOR 1	Compact Coronagraph
CMEs	coronal mass ejections
COSPAR	Committee on Space Research
DHS	Department of Homeland Security
FTAC	Fast-Track Action Committee
GEO	geosynchronous orbit
GICs	geomagnetically induced currents
GMD	geomagnetic disturbance
GNSS	Global Navigation Satellite Systems
GOES-18	Geostationary Operational Environmental Satellites 18
G-scale	Geomagnetic Storm Scale
HF	high frequency
Hpo	half-hourly or hourly, planetary, and open-ended
ICAO	International Civil Aviation Organization
LEO	Low-Earth Orbit
LF	low frequency
MeV	million electron volts
nT/min	nanoteslas per minute
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
pfu	particle flux units
RFI	Request for Information
R-scale	Radio Blackouts Scale
SATCOM	satellite communications
S-scale	Solar Radiation Storm Scale
STPI	Science and Technology Policy Institute
SUVI	Solar Ultraviolet Imager
SWAG	Space Weather Advisory Group
SWFO-L1	Space Weather Follow-On Lagrange 1
SWORM	Space Weather Operations, Research, and Mitigation
SWPC	Space Weather Prediction Center
SWPT	Space Weather Prediction Testbed
SWS	Space Weather Scales
TEC	Total Electron Content
UMUX-LITE	Usability Metric for User Experience LITE
V/km	Volts/kilometer

VHF	very high frequency
WMO	World Meteorological Organization

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The National Oceanic and Atmospheric Administration (NOAA) introduced three Space Weather Scales (SWS) in 1999 as a way to communicate current and future space weather conditions, and their possible effects on people and systems, to the public. The NOAA Space Weather Prediction Center (SWPC) tasked the Science and Technology Policy Institute (STPI) to assist in the revision and eventual deployment of the revised SWS. The three scales under consideration for revision are the Geomagnetic Storm Scale (G-scale), the Solar Radiation Storm Scale (S-scale), and the Radio Blackouts Scale (R-scale). The G-scale is a measure of global geomagnetic activity due to solar wind activity and coronal mass ejections. The S-scale is a measure of energetic proton flux associated with the immensity of a solar radiation storm. The R-scale is a measure of x-ray flux from solar flares that corresponds to the strength of radio interference on the sunlit side of the Earth. The SWS are used worldwide to initiate hazard preparedness and mitigation operations, as well as to inform anomaly attribution and research activities. STPI engaged multiple stakeholders to identify user needs and interests, and to ensure that their views are incorporated into any revision of the SWS

15. SUBJECT TERMS
National Oceanic and Atmospheric Administration (NOAA); Space Weather Scales (SWS); Space Weather Prediction Center (SWPC); Geomagnetic Storm Scale (G-scale); Solar Radiation Storm Scale (S-scale); Radio Blackouts Scale (R-scale)

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