Listening to Stakeholders III: Potential Users Evaluate Product Content and Design for Subseasonal Extreme Precipitation Forecasts

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ABSTRACT

Extreme precipitation over a two-week period can cause significant impacts to life and property. Trustworthy and easy-to-understand forecasts of these extreme periods on the subseasonal-to-seasonal timeframe may provide additional time for planning. The Prediction of Rainfall Extremes at Subseasonal to Seasonal Periods (PRES^{2}iP) project team conducted three workshops over six years to engage with stakeholders to learn what is needed for decision-making for subseasonal precipitation. In this study experimental subseasonal to seasonal (S2S) forecast products were designed, using knowledge gained from previous stakeholder workshops, and shown to decision-makers to evaluate the products for two 14-day extreme precipitation period scenarios. Our stakeholders preferred a combination of products that covered the spatial extent, regional daily values, with associated uncertainty, and text narratives with anticipated impacts for planning within the S2S timeframe. When targeting longer extremes, having information regarding timing of expected impacts was seen as crucial for planning. We found that there is increased uncertainty tolerance with stakeholders when using products at longer lead times that typical skill metrics, such as critical success index or anomaly correlation coefficient, do not capture. Therefore, the use of object-oriented verification, that allows for more flexibility in spatial uncertainty, might be beneficial for evaluating S2S forecasts. These results help to create a foundation for design, verification, and implementation of future operational forecast products with longer lead times, while also providing an example for future workshops that engage both researchers and decision-makers.

CAPSULE

A workshop was conducted for stakeholders to evaluate subseasonal to seasonal precipitation products, using knowledge from previous workshops. A combination of products helped participants interpret uncertainty and thus was viewed as more usable.

SIGNIFIGANCE STATEMENT

There has been an increase in demand for forecasts between the 10-14 day weather forecast timeframe and 1-3 month seasonal timeframe with respect to periods of extreme precipitation amongst decision-makers, yet this relies on trustworthy and usable forecasts. In this study experimental forecast products were designed and shown to decision-makers to evaluate the products for two 14-day extreme precipitation period scenarios. Participants preferred a combination of map products, daily regional products and text narratives with

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anticipated impacts when making decisions at long lead times. These results help to create a foundation for design and implementation of future operational forecast products with longer lead times, while also providing an example for future workshops that engage both researchers and decision-makers.

Introduction

Skillful prediction of extreme precipitation periods, defined in Dickinson et al. (2021), is a topic of significance for a variety of sectors, including civil protection (e.g., Curriero et al. 2001), water resource management and optimization (e.g., Feldman et al. 2021), flood disaster prevention (e.g., Wilhelmi and Morss 2013), ecosystem modifications (e.g., Knapp et al. 2008), agricultural production (e.g., Klemm and McPherson 2017), transportation planning (e.g., Liu et al. 2022), and infrastructure security (e.g., McPhillips et al. 2021). In a changing climate, characteristics of trends, seasonality, and variability in extreme precipitation are imperative to explore and better understand resulting impacts. Specifically, a measured increase of atmospheric water vapor concentration in recent decades (Held and Soden 2000; Santer et al. 2007; Schneider et al. 2010; Wang et al. 2023) has been linked to increases in frequency and magnitude of extreme precipitation on various spatiotemporal scales (Donat et al. 2016; Myhre et al. 2019; Zhang and Zhou 2019; Xu et al. 2021).

Long-duration extreme precipitation may cause compounding impacts within a region. Planning for these impacts would ideally begin at the subseasonal to seasonal timeframe (S2S; i.e. 2 weeks to 3 months), ahead of the typical weather timeframe (i.e. 0-10 days ahead). This timeframe is highly important to stakeholders for planning and preparation for extreme weather hazards as regional disaster preparedness actions require time for execution. For example, it can take several weeks to procure disaster-response or mitigation supplies (e.g., first aid kits, cleaning supplies, water-purification tablets, sandbags to reinforce riverbanks; White et al. 2017). Additionally, decision-makers within water management could utilize S2S forecasts of rainfall as input into streamflow modeling. Potentially emphasizing the heightened risk of flooding on the S2S timeframe when streamflow volumes are already high (White et al. 2015). Forecasts targeting the S2S timeframe can extend time to pre-purchase and preposition essential materials in the at-risk region, reducing response time.

An ongoing challenge in the prediction of extreme precipitation on the S2S timeframe is the relatively low skill of forecasts and, subsequently, the ability to convey the associated

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risks and uncertainties to decision-makers. On average, skill of precipitation across the United States within S2S models is low past Week 1. Although, increases in skill are seen when large-scale circulations (e.g., MJO or ENSO) are present at the time of the event within the model (de Andrade et al. 2019, Domeisen et al. 2022). However, recent research has demonstrated an increase in application of S2S forecasts for monsoon onset and flooding events for "horizon scanning", i.e. looking ahead for early signs of an event (White et al. 2022).

Integrating effective S2S forecasts of extreme precipitation into decision-making processes is difficult and complex - rooted in interactions among physical and social systems and collaborations among forecasters, scientists, policymakers, and local decision makers. In fact, weather and climate prediction products are often under-used by decision makers (Rayner et al. 2005; Morss et al. 2008; Weaver et al. 2013), most likely because forecasters and end-users perceive scientific information in different ways (Lemos and Morehouse 2005). For example, information that forecasters deem useful may not be usable by decision makers due to regulatory, political, or resource constraints (Morss et al. 2005; VanBuskirk et al. 2023b). Engaging users of the forecast products throughout the research development process has increased information adoption (Lemos et al. 2012) and resulted in "actionable science," i.e., science that is directly applied by decision makers and, by extension, benefits society (e.g., Vogel et al. 2016; Norström et al. 2020; Nyboer et al. 2021). There are multiple approaches to develop collaborations among researchers and stakeholders (or rightsholders in the case of Tribal nations) that are not extractive (i.e., benefit only the researchers). The chosen approach should align with the project's goals and resources (e.g., time, people, funding), commitment level of all collaborators, and the culture, constraints, and needs of the stakeholders/rightsholders.

To address the gap in S2S extreme precipitation forecasting and encourage knowledge exchange among researchers and decision makers, the Prediction of Rainfall Extremes at Subseasonal to Seasonal Periods (PRES^{2}iP) project, funded by the National Science Foundation (NSF), applied the stakeholder engagement approaches of "participate" and "empower," as defined by Bamzai-Dodson et al. (2021). Specifically, the PRES^{2}iP team collaborated with decision makers who routinely use precipitation forecast products in water management, emergency management, and tribal environmental management across the contiguous United States during three workshops: two in person in Norman, Oklahoma, and one online (during the pandemic). These workshops prioritized collaboration among the

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researchers and workshop participants to steer PRES^{2}iP research questions and co-develop S2S precipitation forecast products.

In this manuscript, we present the evolution of these collaborative activities during the six years of the PRES^{2}iP project, including a brief summary of lessons learned from workshops 1 and 2 (detailed in VanBuskirk et al. (2021) and VanBuskirk et al. (2023a), respectively) and details of the design, implementation, and results from workshop 3 in April 2023. Finally, this manuscript provides guidance on workshop design for gathering stakeholder feedback throughout a project while allowing for student engagement and discusses future avenues for S2S product design and verification.

Background

To support those individuals whose jobs require decision-making regarding flooding events and ultimately enhance societal preparedness and resilience against extreme precipitation impacts, the PRES^{2}iP researchers used best practices for co-development of new science and products (models, tools, graphics, etc.) with practitioners. We hosted workshops and applied proven methods, such as icebreakers, focus groups, testbed, and role-playing activities, to engage participants and produce knowledge with our stakeholders to be incorporated in future research.

Workshop 1, the Research Priorities Workshop, took place in person on 12-13 July 2018 in Norman, Oklahoma, with 21 practitioners participating. The workshop was designed to prioritize the types of S2S extreme precipitation events to study throughout the PRES^{2}iP project. Discussions included: (1) how participants defined “extreme precipitation,” (2) how these events impacted their jurisdiction, (3) how participants accounted for uncertainties within their decision processes, and (4) how they interpreted precipitation forecast products (VanBuskirk et al. 2021). The PRES^{2}iP team learned the importance of place-based experiences of participants regarding extreme precipitation events. For example, the decision-making process and forecast uncertainty tolerance among stakeholders may change for differing regions, with various timelines of actions based on historical local or regional impacts (Schroers and Martin 2022). Further, statistically extreme rainfall that caused little damage, few injuries, and no fatalities was not considered “extreme” by participants. In addition, established relationships with forecasters or scientists, and personal experience or familiarity with S2S forecast products, were identified as the two most important aspects for building their confidence in making decisions on the S2S timeframe.

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Workshop 2, the Product Definition Workshop, occurred virtually from 4-6 October 2021, with 19 participants. The workshop aimed to (1) identify the products participants use at longer lead times, (2) gather feedback on prototype fact sheets designed to communicate the climatology of extreme precipitation periods and regional impacts, and (3) understand how the participants perceived uncertainty at the S2S timeframe (VanBuskirk et al. 2023a). The PRES^{2}iP team heard how participants had limited knowledge of S2S products, regardless of the participant's job and jurisdiction. Participants stated that probabilistic products would be the best fit for those produced for S2S lead times, although the desired probabilities to trigger participant actions tended to be high—above 50% in most cases. Lastly, participants stressed the need for a suite of products that showed location, timing, intensity, and antecedent conditions for S2S extreme precipitation. The results from both workshops informed our research goals and guided our next steps with focus on meeting stakeholders needs.

Approach and Methods

The PRES^{2}iP team hosted our third stakeholder workshop in person on 13-14 April 2023, in Norman, Oklahoma. This workshop built on knowledge gathered during the prior two workshops. Logistical planning for this workshop occurred from November 2022 to April 2023. All 31 participants who attended one or both previous PRES^{2}iP workshops were invited to this workshop; four attended alongside five new participants. Backgrounds of the nine participants were: emergency managers (2), water resource managers (6), and a decision-maker who worked with water utilities (1). Low response rate from our previous participants, due to spring scheduling conflicts and the inability to travel during their storm season, created the need for us to reach out to new participants. In order to increase the sample size of stakeholders, we hosted a three-hour virtual mini-workshop in February 2023 with three participants from prior workshops. These three participants evaluated the planned activity sheet and corresponding product website, providing necessary feedback to ensure our materials were clear. As a result, we added more antecedent conditions to each case study, and replaced titles of "1 in 10" to our 90th percentile products to "Worst-Case" throughout all materials. Although the small sample size of stakeholders available for this workshop may limit the breadth of knowledge we may gain, it will provide a good foundation for future research.

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The full workshop consisted of three sessions. Session 1 introduced the project's goals and results from previous workshops, focusing on how the information learned from participants in prior workshops had been incorporated into the research itself. The participants also networked with fellow participants and PRES^{2}iP team members through an icebreaker activity. Lastly, to inspire thinking on the S2S timeframe, participants were placed in small groups and tasked to rank various meteorological phenomena, (e.g. tornadoes, hurricanes, monsoons) based on their respective time scale, from shortest to longest.

The remaining two sessions examined experimental S2S forecast products designed by the PRES2iP team using two impactful 14-day extreme precipitation case-studies from differing seasons and locations sourced from the PRES2iP 14-day extreme precipitation database (Dickinson et al. 2021). The first scenario (S1) session covered an extreme precipitation period across the Pacific Northwest that occurred from 6-19 December 2015. During this two-week period, Oregon experienced an estimated $21.6 million in property damages due to flooding - both coastal and inland, debris flow, and high winds. Furthermore, an additional $14.9 million in property damages were reported in Washington (NCEI 2023). S1 was characterized by wet antecedent conditions combined with an anomalously wet forecast 7 and 30 days ahead of the event. The second scenario (S2) occurred from 21 April to 4 May 2017, predominantly across Missouri, with heavy rains also affecting parts of surrounding states. Property damages in Missouri alone were estimated to surpass $137 million as extensive destruction was observed in the form of damage to roads, residential homes, businesses, and crop fields across the entire state (NCEI 2023). S2 exhibited relatively normal antecedent conditions with the longer-range forecasts depicting a dry weather forecast.

During the scenario-based sessions, participants were placed in groups of 3-4 people to complete a six-part guided activity packet facilitated by a member of the PRES^{2}iP team (packet found in supplementary material). Another team member took notes of participant statements and reactions. The session packet contained relevant background information on each case study, instructions about how to access the available products, and questions for each activity (described in Table 1). The PRES^{2}iP team developed an accompanying website housing the forecast products, antecedent conditions, and outlooks for both scenarios; all products included were identified as being used by participants in prior workshops. To highlight possible impacts, the following antecedent conditions were provided: soil moisture conditions, the U.S. Drought Monitor (Svoboda et al. 2002), and precipitation totals from the prior month. We also included snowpack information for S1. We provided the following

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commonly used outlooks: seasonal, monthly, day 8-14, and day 6-10 precipitation from the Climate Prediction Center (CPC); CPC hazard outlooks; and the Day 3 and Day 1 excessive rainfall outlooks from the Weather Prediction Center (WPC). The website simulated how participants would gradually access products over time in an operational setting. Although our focus was receiving feedback on our experimental forecast products, our PRES^{2}iP team encouraged participants to use any of the existing operational products provided.

PRES^{2}iP's experimental S2S products were derived from real-time forecasts using the National Center for Environmental Prediction (NCEP; Saha et al. 2014) model from the S2S model database (Vitart et al. 2017). The NCEP model, version 2 of the Climate Forecast System (CFSv2), was initialized daily and had 16 ensemble members. Precipitation anomalies were created using a daily precipitation climatology using a hindcast period of 1991-2010 following the methodology of Pegion et al. (2019). On each case-study website, we linked our experimental forecast products at lead times of 30, 21, 14, 7, and 3 days ahead of the start of the extreme precipitation period, summarized with respect to Scenario 1 in Fig. 1. Table 1 and Figs. 2-5 detail the forecast products in each packet. Participants were not told which model we used until the conclusion of the workshop to prevent any *a priori* biases that could affect their responses.

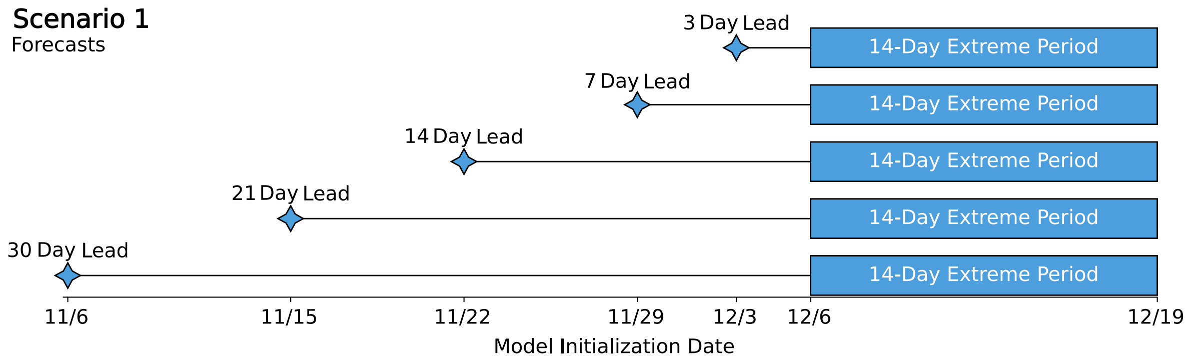

Figure 1. Summary of the five forecasts periods used for the experimental products that were given to the participants. As an example, model initialization dates are included for Scenario 1, that occurred from 6 – 19 December, 2015.

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Activity Name	Activity Goal	Corresponding Experimental Forecast Product or Activity Focus
#1 Action vs. Lead Time	Connect stakeholder actions related to extreme precipitation to forecast lead time using forecasted precipitation.	Ensemble mean 2-week total precipitation and precipitation anomaly maps.
#2 Benefits and Limitations of Text Products	Gather feedback on three different types of text products associated with S2S forecast products.	Descriptions of the 2-week period following various styles.
#3 Precipitation Forecasts by Day	Interpret and discuss pros/cons of forecasted daily precipitation values at a given location for various lead times.	Time series of best case, mean, and worst-case daily precipitation and accumulated precipitation.
#4 Precipitation Forecasts by Amount	Compare and contrast probabilistic precipitation forecasts by amount to ensemble mean forecasts.	Probability precipitation > 5 in,10 in (Scenario 1); 3 in ,5 in (Scenario 2)
#5 Worst-Case Scenario	Examine “Worst-Case Scenario” forecast product at various lead times and compare to ensemble mean forecasts.	90th percentile of 2-week total precipitation
#6.1 Forecast Error - Model Skill	Examine estimated forecast error within an S2S model to discern model uncertainty tolerance.	Table of mock POD and FAR (see Table 2)
#6.2 Forecast Error - Object Oriented	Rank forecast and observation pairs to show spatial uncertainty tolerance on the S2S timeframe.	Fig. 1 from Davis et al. (2006) and self-drawn hypothetical forecast/observation pairs.

Table 1. Goals of each workshop activity and corresponding forecast product provided.

Results

In the following sections, we will discuss the design, implementation, and feedback of the six activities that the groups completed for both scenarios.

Action versus Lead Time Activity

Based on discussions from our previous workshops, we understand that users make decisions at specific lead times ahead of a potential event. Therefore, this activity tasked the participants to match possible actions to specific lead times (see supplementary material). For each lead time, we provided the ensemble-mean total precipitation and anomalies for the 14-

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day period of interest (Fig. 2). We designed this product to emulate the WPC's quantitative precipitation forecast (QPF) to ensure easy interpretation, as QPFs are one of the most used forecast products with regard to precipitation-related decision making (VanBuskirk et al. 2023b).

For each lead time, participants reviewed the list of actions - adding others that were relevant to their work, and analyzed the forecast products to note which of these possible actions they might take. Reported actions were distinctly different between the two scenarios. In S1 (wet antecedent conditions), participants indicated that they would begin actions at lead day 30 through 14, primarily preparing dam-failure emergency action plans, inspecting dams or other flood-mitigation equipment, and engaging in discussions on probability of extreme precipitation with colleagues. On lead days 7 and 3, more actions would be taken, including preparing the region for hazard mitigation, briefing public officials, and increasing the dialogue with colleagues and staff. In S2 (normal antecedent conditions), three of seven participants did not list any actions until lead day 7; the actions listed for the shorter lead times closely resembled those in S1.

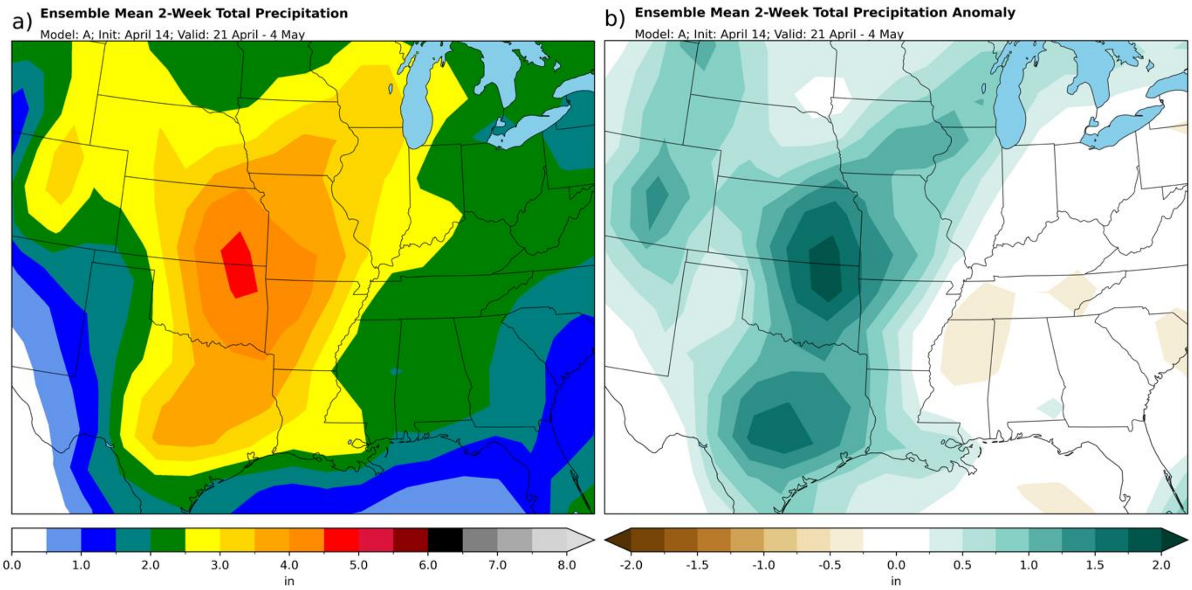

Figure 2. S2S experimental forecast products designed by the PRES^{2}iP research team as a result of participant feedback in workshops 1 and 2. Scenario 2 (21 April to 4 May 2017) is displayed, showing forecasts for Missouri and surrounding states at a lead time of 7 days prior to the start of the extreme precipitation period. (a) Ensemble-mean, 14-day total precipitation and (b) ensemble-mean, 14-day precipitation anomalies are shown. Precipitation values are in inches for workshop participants.

Text Product Activity

In previous workshops, participants emphasized the need for supporting narratives associated with S2S forecast products. Specifically, during the first workshop many participants stated

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that having a narrative would help with interpretation of unfamiliar products (VanBuskirk et al. 2021). Furthermore, participants reaffirmed in workshop 2 that having text-based information regarding possible losses could facilitate proactive planning for an extreme period (VanBuskirk et al. 2023a). Therefore, in this activity, we drafted three different text forecast products for each scenario at a 3-7-day lead time (found in supplementary material). Each text product was designed intentionally to address prior workshop participants' requests in different formats. The first product was modeled after a National Weather Service forecast discussion, encompassing a synopsis and a long-term forecast discussion. The second product was the shortest, had the least jargon, and focused on amounts, timing, and potential impacts of forecasted precipitation. The final and lengthiest product included the content of the second product as well as technical information on the synoptic scale set-up observed in S2S models and existing teleconnection patterns that could support extreme precipitation.

After reading each text product, participants were tasked to detail its advantages and disadvantages. For both scenarios, participants favored the second text product because its information regarding expected impacts and the forecasted range of precipitation at different locations was the most useful. While many participants appreciated the first text product, some felt it was too technical or jargon-heavy, making it challenging to extract useful information. The third text product was considered excessively detailed and lacking in actionable information. Overall, participants found S2S forecast-related text products to be most useful when they included "calls to action" with anticipated impacts, forecasted precipitation ranges over specific dates, and location-specific differences when necessary. This result is consistent with studies on the weather timeframe that show impact-based severe weather warnings increase the public's understanding and intention to take protective action (Ripberger et al. 2015; Casteel 2016; Potter et al. 2018).

Precipitation by Day Activity

An important lesson from workshop 2 was that a suite of forecast products must include both the spatial distribution of precipitation and information on timing and intensity (VanBuskirk et al. 2021). In response, this activity gave participants daily precipitation forecasts for Seattle, WA, in S1 and Springfield, MO, for S2. The PRES^{2}iP team designed a product with four graphs (Fig. 3) that showed precipitation values, accumulated precipitation values, ensemble standard deviation, and precipitation anomalies for each of the 14 days. Daily values were presented for the best case (10th percentile of the ensemble) and the worst-case scenario (90th percentile of the ensemble). We included daily values of the ensemble's

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standard deviation to show model uncertainty, as prior workshop participants indicated that uncertainty information might help to increase trust in the forecast product (VanBuskirk et al. 2023a).

Overall, all participants provided positive feedback on this activity's product, stating that it was useful to have both map and graph products (and not either alone) to increase their confidence in the forecast. Many participants emphasized that the ensemble standard deviation information helped to clarify the forecast, though some preferred the information displayed as whiskers on the daily precipitation product rather than a bar graph. In contrast, the daily anomalies were deemed less useful, as they required additional interpretation; the other three panels were considered sufficient.

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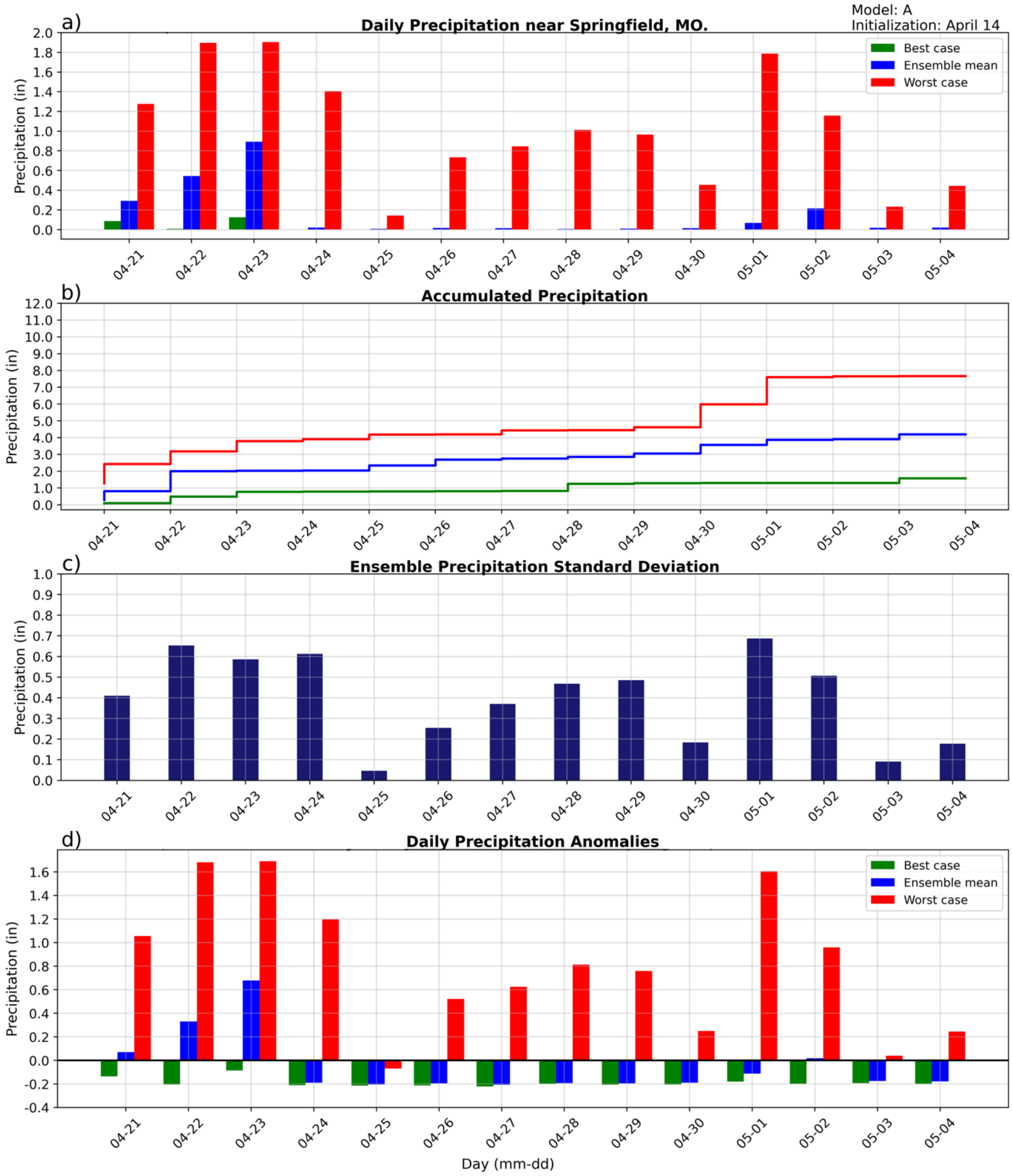

Figure 3. As in Figure 2, but for the time series product that includes (a) daily precipitation, (b) accumulated precipitation, (c) ensemble standard deviation and (d) precipitation anomalies for 21 April to 4 May 2017.

Precipitation by Amount Activity

During workshop 2, all participants preferred probabilistic forecasts over deterministic products because the former conveyed forecast uncertainty (VanBuskirk et al. 2023a). Accordingly, the PRES^{2}iP team created two map products that displayed the probability that 2-week precipitation totals would exceed two different thresholds (e.g. Fig.

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4). Prior workshop participants stated the importance of place-based thresholds tailored to their specific jurisdiction (VanBuskirk et al. 2021); however, limited resources prohibited us from creating a user-selected threshold. Instead, we chose our lower threshold to align with the region's climatology, set at 5 inches for S1 and 3 inches for S2. Higher thresholds of 10 and 5 inches, respectively, represented a more "extreme" value.

The participants were tasked to compare this product to the other available map products and discuss potential applications. Participants thought the products effectively depicted where the highest probability of large precipitation amounts would occur but noted that the location information was not useful without timing information. For example, one participant stated, "That could mean less than 1 inch per day," while another added, "Or it could be 5 inches in one day." All participants agreed that a suite of products that included QPF, text description, and daily time series products would be more useful than this probabilistic product.

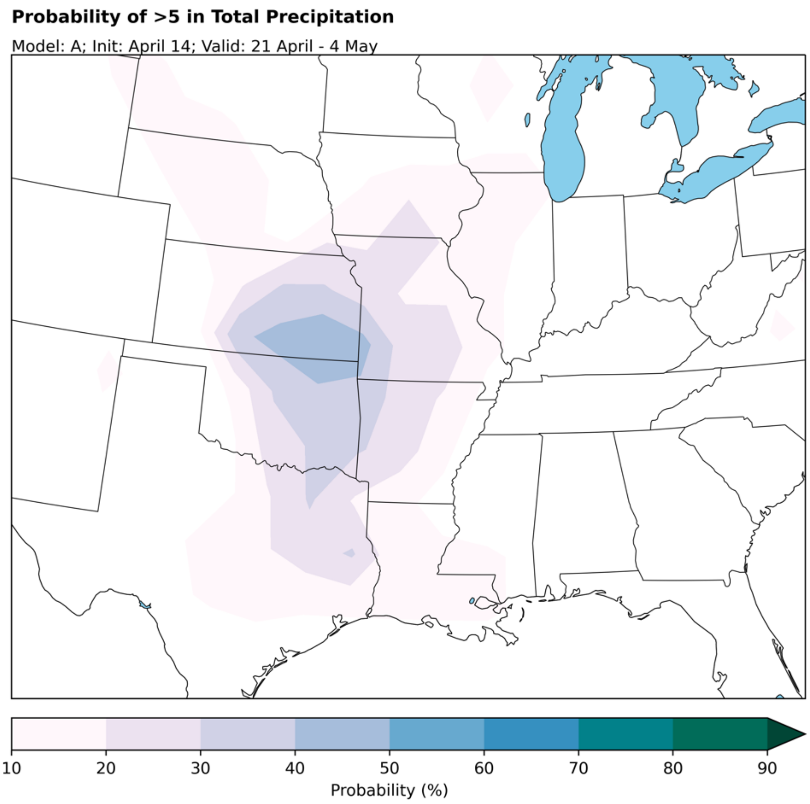

Figure 4. As in Figure 2, but probability of 14-day total precipitation above 5 inches (127mm).

Worst-Case Scenario Activity

During the "Precipitation by Day" activity, we provided daily precipitation values for the worst-case scenario (90th percentile) at a single point, which did not inform participants

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about the spatial distribution of the precipitation. During workshop 1, participants noted that extreme-event planning might involve the use of a worst-case scenario map product (VanBuskirk et al. 2021). Therefore, we asked participants to discuss whether the worst-case map product (Fig. 5) added useful information to the "Precipitation by Day" products. All participants agreed that the worst-case map product was useful at longer lead times to show the possible extent of the extreme period, but the product was not useful alone because it did not highlight *when* the precipitation would fall within the 14-day period. One participant stated, "[The bar chart of daily precipitation] is good in short range, but further in time it is better to have a map. With a point forecast for Seattle 30 days out, you might miss what is happening in the area surrounding unless it's a map." Ahead of day two of the workshop, participants also had discussed changing the language of "Worst-Case Scenario" to "Maximum in Precipitation over 2 weeks" because it would allow decision makers to decide what is the worst-case for their region, given current conditions.

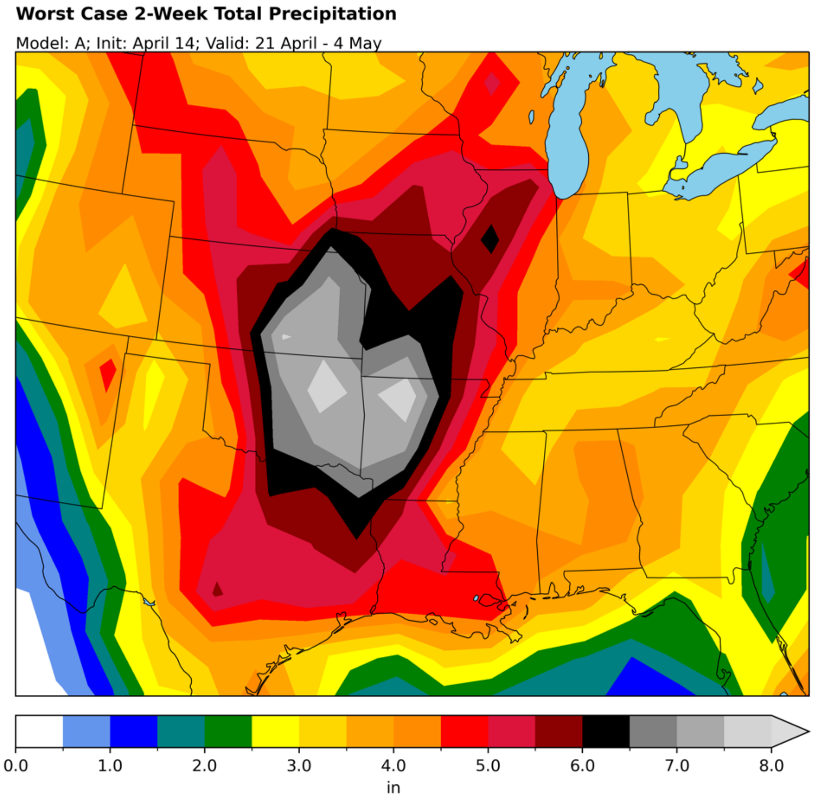

Figure 5. As in Figure 2, but for 90th percentile of 14-day total precipitation, labeled for participants as the Worst-Case.

Forecast Error Activity

Through discussion with stakeholders in workshop 2, we understand that stakeholders may be reluctant to use forecast products if past forecasts were perceived as "poor."

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Conversely, trust can be built over time with models that produce reliable forecast products (VanBuskirk et al. 2023a). During workshop 3, many participants saw S2S model output for the first time, prompting our interest in forecast-error tolerance of stakeholders on the S2S timescale using “traditional” skill metrics. Thus, for all lead times, we provided estimated values of Probability of Detection (POD) and False Alarm Rate (FAR) in a typical S2S model regarding our extreme precipitation periods (Table 2). Participants expressed caution when dealing with forecasts beyond 14 days and did not consider these metrics. They became more interested in lead times of 14 days (and shorter) and PODs of 50% and larger. Intriguingly, participants also preferred FARs of 50% or less, indicating that end-users desired confidence levels and skill metrics to be “more yes than no” before considering products to be actionable. These results coincide with those in workshop 2, where participants wanted probabilities of occurrence above 50% to prompt action (VanBuskirk et al. 2023a).

Participants preferred high PODs rather than low FARs with one participant noting, “Everybody forgets the false alarm you prepared for, everybody remembers the [miss] you didn’t prepare for[…].” Yet, the metrics themselves were seen as not useful to understanding forecast error. Some participants stated that it would be more interesting to have a model-to-model comparison tool.

Lead Time	POD across 2,000 square-mile area	FAR across 2,000 square-mile area
30 days	30%	85%
21 days	40%	80%
14 days	50%	75%
7 days	70%	55%
3 days	80%	30%

Table 2. Estimated Statistics for a dynamical model forecasting large-scale 14-day extreme precipitation periods as a function of lead time.

Object-Oriented Activity

One of the pivotal insights of workshop 2 was that end-users inherently anticipated forecasts changes over time and thus have a certain level of tolerance to spatial displacements in expected impacts (VanBuskirk et al. 2021). This result suggested that an object-oriented verification scheme—one that treats the forecast as a contiguous region instead of a series of grid-boxes—might be more useful in evaluating forecast quality and usability. Therefore, our

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team designed an activity to understand the types and magnitudes of error tolerance in this context.

The activity used theoretical pairs of forecast and observation contiguous regions (Fig. 6), as in Davis et al. (2006). Each participant ranked the perceived forecast quality from best to worst in the context of subseasonal extreme precipitation periods. Three of our seven participants identified panel ‘a’ as the best. However, the remaining four participants ranked panel ‘e’ as the best. Conversely, most participants ranked panels ‘b’ and ‘d’ as the worst.

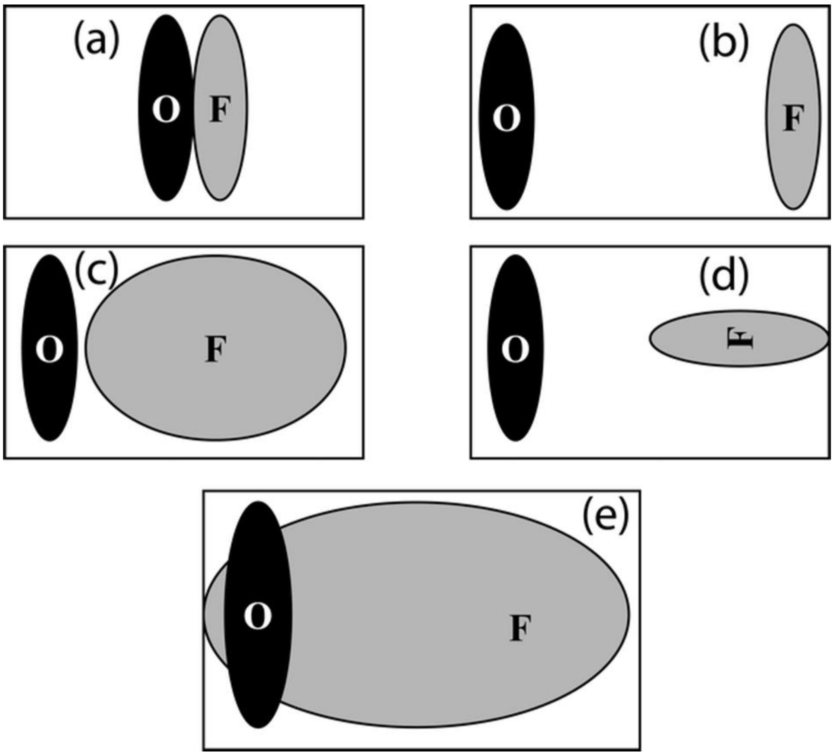

Figure 6. Schematic examples of hypothetical Forecast (F) – Observation (O) combinations, from Davis et al. (2006, Fig. 1)

Participants then were given more realistic forecasts with a lead time of 3 days (Figs. 7-8, black) and a polygon of the actual extreme precipitation region (Figs. 7-8, red), with distances between centroids given to participants in miles (see Dickinson et al. 2021 for details). The forecast objects were adapted from an experimental model from the PRES^{2}iP team. Three maps (Fig. 7) focused on the spatial proximity of forecast-observation pairs and utilized polygons with similar sizes. In Fig. 7a, the polygon centroids were approximately 150 miles apart; all participants agreed the forecast was a “hit.” When polygon centroids were 220 miles apart (Fig. 7b), participants were more hesitant to call the forecast a “hit,” with one participant definitively identifying it as a “miss.” One participant described Fig. 7a,b as “really good” forecasts while others made comments such as “good on a state level” and “the forecast generally covers the same area…it is ok.” The northernmost shift in the forecast

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(Fig. 7c), with centroids about 350 miles apart, prompted unanimous agreement that the forecast was too distant from the observed location. Participants also noted that, under otherwise equal conditions, the *direction* of spatial errors was unimportant; however, changes in antecedent conditions, for example, could affect their tolerance to translations in the forecast.

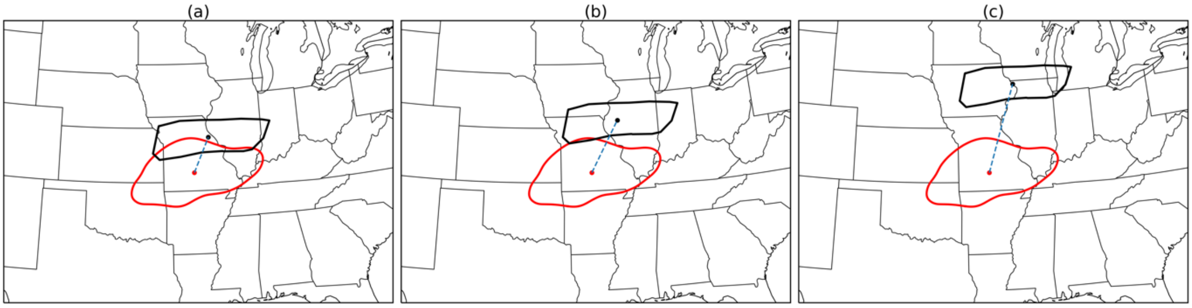

Figure 7. Various pairings of forecasts (black) and truth (red). Colored dots represent the polygon centroid. Distances between centroids are about (a) 150 miles, (b) 220 miles, and (c) 350 miles.

Finally, participants compared the relative sizes of the forecast and observed regions while maintaining a small distance between centroids (~100 mi, Fig. 8). Six of seven participants classified Fig. 8a as a "hit" and generally preferred the larger forecast region. However, one practitioner expressed a preference for forecasts with higher precision (e.g., Fig. 8b) if they were associated with higher likelihood. The consensus was that a forecast akin to Fig. 8a at long lead times would be useful for planning before using a forecast akin to Fig. 8b at shorter lead times.

Traditional metrics, such as critical success index or anomaly correlation coefficient, would yield scores near 0 for a scenario such as Fig. 7b despite nearly every participant considering the forecast to be a "hit." Hence, this activity reaffirmed the utility of object-oriented verification schemes in the context of S2S extremes. However, participants assessed size and proximity in isolation, so future conversations are needed to diagnose how end-users would balance these two factors.

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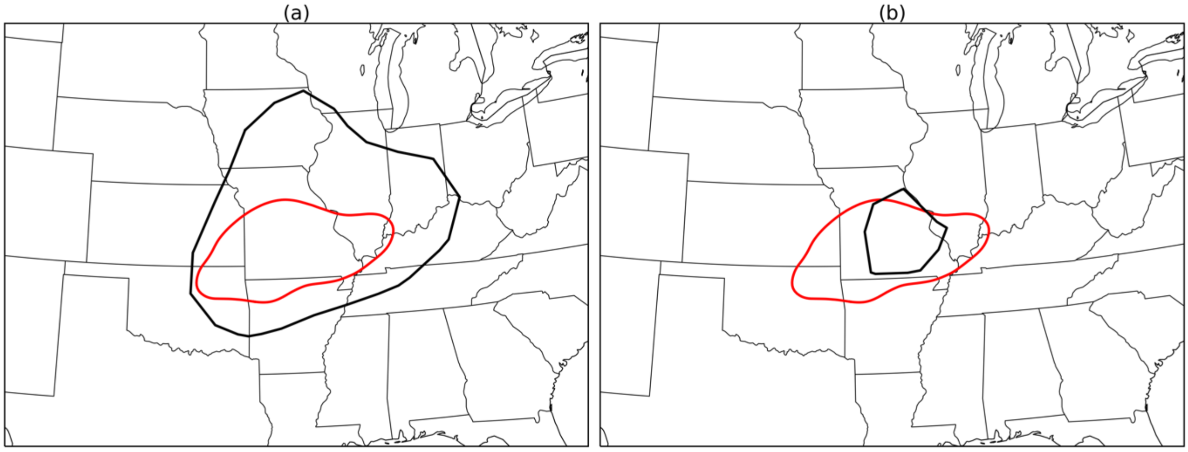

Figure 8. As in Figure 7, but for polygons with similar centers but different spatial scales.

Summary

During this workshop, the PRES^{2}iP team presented a suite of experimental S2S 14-day precipitation forecast products developed using knowledge gained through collaboration with decision makers at two previous workshops. The products covered two different 14-day extreme period scenarios: one in the Pacific Northwest with wet antecedent conditions and an anomalously wet forecast (S1) and another in the eastern Plains with normal antecedent conditions and a drier forecast (S2). Both scenarios resulted in an impactful observed event, although the participant perceptions of the severity of the 14-day period differed between scenarios, owing to the differences in forecasts. All potential decision actions associated with the experimental S2S products focused on planning at lead times of 14 days or longer, with more actions for risk mitigation taken at lead times less than 14 days. The actions listed at S2S lead times for S1 were consistent with previous studies (e.g., White et al. 2017). For S2, participants stated they would take less action, or no action for three participants, until lead day 7. Thus, the inaccurately dry forecast for S2 at S2S lead times, 30, 21 and 14 days ahead of the extreme period, led to less planning occurring. The perceived usability of the products did not change based on the scenario, yet the outcomes changed with differences in forecast skill. This emphasizes the need to engage with decision-makers about product content and design, while also studying the improvement of precipitation skill at S2S lead times.

The extended nature of the 14-day extreme precipitation periods that were targeted during this workshop led to a lot of discussion regarding the importance of timing information. During every activity regarding a product the lack, or the inclusion, of timing information was brought up by participants. This highlights the need for a suite of products that cover the spatial extent, as well as timing information. Thus, the participants valued a combination of ensemble-mean map products (e.g., 14-day QPF), text narrative with “calls to action,” and

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daily time series products. The combination of different forms of products helped to increase their trust in the forecast and, thus, its usability. One participant stated, "All graphs had value for a singular perspective – but confidence is low. Looking at them in combination increased trust and confidence in what was going to happen." Interestingly, these types of products are already heavily used on the weather timeframe, and therefore there is less interpretation needed by the stakeholder that are already comfortable with weather products. On the other hand, all products showing anomalies were perceived as less usable due to the additional interpretation needed to gauge the severity of the anomaly. This result may be due to the stakeholders within the workshop not knowing other regions' precipitation normals, whereas they may be more comfortable working with anomalies within their own region.

Additionally, the PRES^{2}iP team explored participants' tolerance of uncertainties on the S2S timeframe, finding multiple examples that depicted higher tolerance for differences in location and spatial coverage than seen during the weather timeframe. Despite some increased nuance in forecast evaluation, the implementation of object-oriented schemes to verify S2S forecasts presents a clear opportunity for increased education, awareness, and actionability on these timeframes.

Although the PRES^{2}iP forecast products were experimental and not meant to be transitioned into operations, this work provides the foundation for future enhancement and development of products that are useful for and usable by decision makers. Due to low availability of our stakeholders, this workshop was only conducted with nine stakeholders and thus limits the ability to generalize the findings to all stakeholder communities. In the future, similar workshops should be conducted, avoiding peak storm season, with larger sample sizes to further validate our findings. Furthermore, future studies should strive to get input from more perspectives, such as agriculture, to ensure the results shown here are more widely applicable or determine additional needs from other decision maker communities. The PRES^{2}iP team and resulting research have been immeasurably influenced by stakeholder input and engagement through our three workshops. By engaging with stakeholders throughout the entire project, we have conducted more meaningful research. Documentation of our three workshops - their design and implementation, and their results - is intended to encourage a broad range of researchers to engage with decision makers, managers, underserved populations, or any parties deemed appropriate, throughout the entire research and development process. Our activity examples can be modified for similar uses in research projects or serve as examples in classroom coursework to educate the next generation of researchers on how to listen to product users.

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Data Availability Statement.

The NCEP CFSv2 model output, from the S2S project database, are openly available at https://iridl.ldeo.columbia.edu/.

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