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Fire Weather Testbed Evaluation #001: The Warn-on-Forecast System for Smoke

August 2024

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Global Systems Laboratory
Boulder, Colorado
August 2024

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Gina Raimondo
Secretary

NATIONAL OCEANIC AND
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Assistant Administrator

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Executive Summary

The Warn-on-Forecast System for Smoke (WoFS-Smoke) was developed by the National Severe Storms Laboratory as a tool to support convection-allowing (3 km), rapid-refresh (15 minute data assimilation, 30 minute update cycle, 5 minute forecast output), ensemble-based (36 member analysis, 18 member forecast) information for high impact weather events over a 900 x 900 km domain in the Conterminous United States. The addition of a smoke transport module to the Warn-on-Forecast System and outputs relevant to wildland fire applications extends the model's capability to support fire and emergency management in pre-fire, active fire, and postfire situations. In short, WoFS-Smoke assesses how rapid (i.e., sub-hourly) changes in weather can impact the fire environment, smoke transport, and postfire hazards.

On 30 November 2023, the NOAA Global System Laboratory's Fire Weather Testbed facilitated a one-day virtual training and evaluation of WoFS-Smoke. The primary goal was to "Determine how useful WoFS-Smoke products are to both pre- and active fire decision making processes, and use that information to motivate future WoFS-Smoke development." The evaluation included seven National Weather Service (NWS) participants–four of whom are active Incident Meteorologists–representing the Eastern, Central, Western, Southern, and Alaska Regions. The evaluation began with a short training, followed by three scenarios highlighting key capabilities of WoFS-Smoke: (i) a probability of smoke situation based on a prescribed fire, (ii) a Red Flag Threat Index scenario, and (iii) a rapidly changing fire environment scenario. The evaluation concluded with a focus group discussion that included an additional scenario applying WoFS-Smoke to a short-duration, high-intensity postfire rainfall event.

Based on feedback received during the one-day virtual evaluation, participants support the inclusion of the WoFS-Smoke system into NWS fire weather operations. The WoFS-Smoke system can help at both the office and incident levels by providing impact-based decision support (IDSS) to fire management as well as to other partners (e.g., air quality managers) by quantifying and effectively communicating uncertainty at high temporal and spatial resolution. Areas of technical improvement include the need for: 1) sufficient computational resources to enable consistent runs of multiple WoFS-Smoke domains for ongoing high-impact events or as events develop, 2) higher resolution (~1 km) simulations for small fires, 3) an extension of WoFS-Smoke domains to Hawaii and Alaska, and 4) an extension of the forecast time out to 12 hours. By quantifying the uncertainty of actionable outputs, the WoFS-Smoke system will advance NWS' capability to support wildland fire management.

Key Evaluation Findings

1. WoFS-Smoke provides actionable probabilistic information to support a range of fire-related management aspects in rapidly changing environments during the main phases of

wildland fire including the pre-fire phase (e.g., onset and cessation time, magnitude, and spatial extent of extreme fire weather conditions), the during-fire phase (e.g., alerting fire suppression personnel to wind shifts and providing timing of smoke plume arrival and departure to partners), and the post-fire phase (e.g., guidance regarding short-duration high-intensity precipitation capable of initiating post-fire flooding and debris flows).

2. WoFS-Smoke complements existing operational products (e.g., the NOAA High-Resolution Rapid Refresh Smoke and the National Blend of Models) by providing rapidly-refreshing, high resolution probabilistic guidance.
3. WoFS-Smoke requires additional computational resources and a well-defined prioritization system in order to achieve reliability for operational use and further improving horizontal resolution for applications in complex terrain.
4. Participants noted the importance for the information to be displayed on a visualization platform that allows more interactivity of the user, such as gaining the ability to zoom in to the forecast region(s) of concern, inclusion of additional map variables such as topography and critical assets, and the ability to display particulate matter concentrations using air quality index or visibility values.

1. Introduction

The Warn-on-Forecast System (WoFS) project began in 2009 at the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory (NSSL) by merging advances in both the capabilities of convection-allowing numerical weather models and ensemble-based data assimilation (Stensrud et al., 2009; Heinselman et al., 2024). The goal of WoFS is to revolutionize the predictive tools available to warning operations to bring about increased lead time for high impact weather warnings. Rather than producing warning products based solely on observations, WoFS leverages model ensembles to support warnings and decision support for severe weather hazards based on near-term (<6 hour lead time) forecasts through providing ensembles that help quantify uncertainty.

A transition to probabilistic hazard information communication represents a key goal of both the National Weather Service (NWS) and World Meteorological Organization, as probabilistic information maximizes the ability of weather information purveyors to provide decision support in uncertain, rapidly changing conditions and helps improve trust, confidence, and understanding of forecast information (Demuth et al., 2022; Heggli et al., 2023). While probabilistic information provided within WoFS aligns with these recommendations, there are many strategies for presenting and communicating probabilistic information. This evaluation intends to address gaps within the WoFS-Smoke system in order to focus on end-user (i.e., NWS forecasters) preferences to drive improvements facilitating the application and communication of probabilistic forecasts in an operational environment to decision makers and core partners.

1.1 Background on the Warn-on-Forecast Systems

Both WoFS and WoFS-Smoke produce probabilistic predictions of individual storm hazards at a rapid-update pace (15 minute data assimilation, 30 minute forecast update cycle, 5 minute forecast output) focusing on the 0-6 hour forecast period. The 2023 version of the model uses a 900 km x 900 km domain located over the conterminous United States, 3 km horizontal resolution, and 51 vertical levels. The systems use the High Resolution Rapid Refresh model (HRRR) Data Assimilation System (HRRRDAS; Dowell et al., 2022) as initial conditions, while boundary conditions are provided by the deterministic HRRR with added variance from the 36-member Global Ensemble Forecast System (GEFS). Observations are assimilated every 15 minutes and include radar reflectivity and velocity from the Multi-Radar Multi-Sensor System (MRMS; Smith et al., 2016), satellite-derived water vapor and cloud properties (from the Geostationary Operational Environmental Satellite (GOES) missions 16, 17, and 18), as well as fire radiative power (Jones et al., 2024). When available, more conventional observations such as radiosondes or surface stations are assimilated.

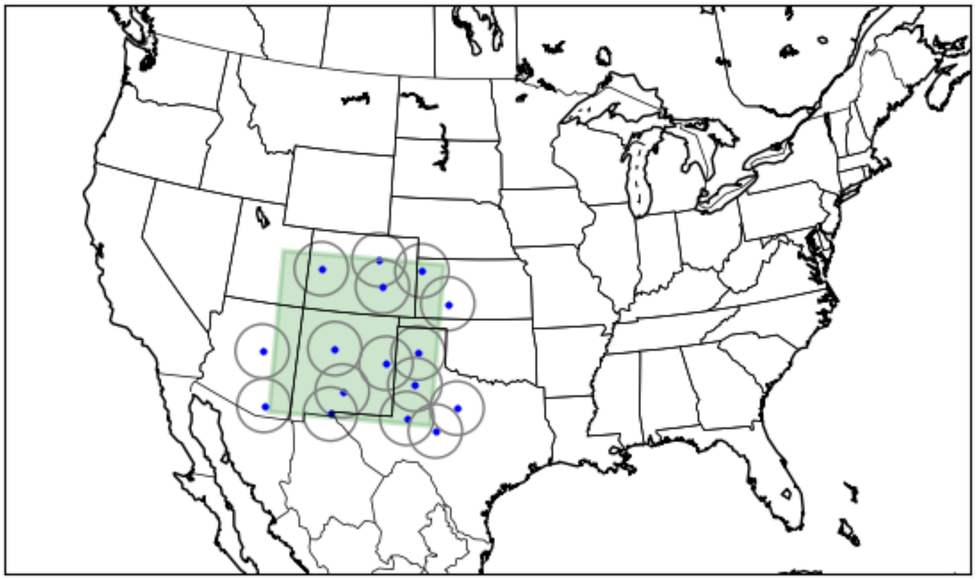

Figure 1: Warn-on-Forecast Smoke (WoFS) system 3 km domain (filled green box) centered over the New Mexico/Southern Colorado region nested within the High Resolution Rapid Refresh Ensemble domain (black box). Radar locations are shown as blue dots with 150 km range rings (gray circles).

For a single domain (Figure 1), the WoFS and WoFS-Smoke 3 km 6-hour forecast runs require approximately 4000 cores (40 nodes) on current hardware. Current cost per case is currently estimated to be $1000-$2000 depending on the specific system configuration. Additional realtime domains would increase cost ~50% for each domain. As evaluated, WoFS-Smoke is run in a cloud-based instance that is configurable on the day of an event. Cloud-based instances provide benefits of adaptivity and scalability as the NWS can respond to new or rapidly changing weather threats and the system can run multiple domains for multiple threats. Cloud-based computing sidesteps reliability challenges with fixed computational resources as there is no need to reserve high-performance computing resources (which may also go down due to scheduled or unscheduled maintenance) and computational resources can be readily added or reduced as demands dictate.

By integrating the smoke plume injection algorithm of HRRR-Smoke (Jones et al. 2022), WoFS-Smoke enhances existing WoFS forecasting abilities to predict the effects of fire and smoke on life, property, and emergency management. WoFS-Smoke provides outputs to assess how changes in weather can impact the fire environment, smoke transport, and post-fire hazards. WoFS-Smoke produces an 18-member ensemble smoke transport forecast using satellite-derived fire radiative power, providing outputs that support probabilistic guidance of downstream smoke impacts. In addition, it supports the issuance of fire weather-related warning products, including Red Flag Warnings and the Red Flag Threat Index (RFTI; Murdoch et al., 2019). Notably, WoFS-Smoke does not include a chemistry module nor are all fire effects (e.g., smoke influences on microphysics or model dynamics) resolved by the model. However, the feedback between smoke and solar radiation is enabled, allowing for surface cooling to occur under heavy smoke-induced increases in aerosol optical depth. The rapid (15-minute) assimilation of radar and satellite data combined with the high temporal resolution output (5-minute timesteps) allows WoFS-Smoke users to promptly deliver decision support information to their partners as the fire environment changes. Under such a changing environment, compared to providing deterministic model output, continuous provision of probabilistic information to partners builds trust (Heggli et al., 2023; Burgeno and Jocelyn, 2023).

Initial testing of WoFS began in 2016. The extension of the WoFS system to include fire weather-related capabilities began in 2018. While the WoFS system has been implemented in operational environments to assess the pre-fire environment, the active (during) fire phase is the next step. Lindley et al. (2023) emphasized the advantages of using convection-allowing models for operational forecasting before and during fires, highlighting the benefits of using an ensemble-based approach. As of this writing, two specific applications are in development for WoFS-Smoke: (i) the ability to generate parameters related to the likelihood of wildland fire ignition and spread based on forecast atmospheric conditions, and (ii) the inclusion of a smoke aerosol assimilation and forecasting capability into WoFS. These applications forecast downstream air quality and environmental impacts, guiding air quality managers and public health partners in the issuance of public messaging and the activation of early warning systems, as occurred in the Pacific Northwest in September 2020 (Hatchett et al., 2021). At present, the focus is on high temporal frequency and the creation of probabilistic air quality products to complement and gap-fill needs left by existing deterministic products.

Longer-term scientific goals of WoFS-Smoke include coupling fire properties with fuels and fire emission characteristics to produce more comprehensive smoke outputs (i.e., emissions and impacts on visibility) and inform fire spread modeling. From an operational perspective, the WoFS-Smoke system aims to be robustly and flexibly accessible when and where conditions dictate. Examples of such conditions include the “areas of most concern” identified by the Storm Prediction Center and National Weather Service Forecast Offices, in areas where Predictive Services has identified large fires having the highest probability of occurrence, or in regions adjacent to critical assets (i.e., wildland-urban interfaces, critical infrastructure, or valued ecosystems).

1.2 Evaluation in the NOAA GSL Fire Weather Testbed

The newly-created NOAA Fire Weather Testbed (FWT), housed at the Global Systems Laboratory (GSL), led a virtual evaluation of WoFS-Smoke on 30 November 2023. The goal of this evaluation was to “Determine how useful WoFS-Smoke products are to both pre- and active fire decision making processes, and use that information to motivate future WoFS-Smoke development.” The evaluation included seven National Weather Service Meteorologists (hereafter "participants") from throughout the United States (including the Alaska, Central, Eastern, Southern, and Western Regions). All participants were subject matter experts, and four of the participants were active Incident Meteorologists (IMETs). This evaluation was the first instance of formal testing of the WoFS-Smoke system by operational meteorologists. This report begins with overviews of the training modules and scenarios and followed by a synthesis of the feedback received from participants of the training and presentation of scenarios, respectively. Key themes and notable feedback from the focus group discussion are discussed and a reflection on the initial evaluation from the FWT perspective is provided. The report concludes with a summary of the evaluation, a suite of specific recommendations, and next steps.

2. Training Overview

The training for the evaluation consisted of a presentation that introduced the WoFS-Smoke system through a brief explanation of convection-allowing models and an overview of the WoFS system. The key differences between WoFS-Smoke and other models, such as the HRRR, were discussed, followed by a detailed explanation of the model configuration, including the model domains, data assimilation process, and computing requirements. The uniqueness of the WoFS guidance was highlighted, specifically the value of accurate initial conditions for individual 'objects' (e.g., thunderstorms in WoFS or smoke plumes in WoFS-Smoke) and how these initial conditions are produced through rapid cycling of data assimilation of remotely sensed observations. Various limitations of WoFS were also discussed, including data assimilation, resolution, spurious convection, spatial errors, and data availability.

After providing the background information, the training shifted to techniques for interpreting the WoFS-Smoke output. To facilitate rapid communication to end-users and address challenges associated with the appearance of mesoscale weather features in ensemble visualizations, WoFS output has been designed to preserve information on the timing, motion, likelihood, and severity of discrete objects such as smoke plumes (Jones et al., 2022; 2024; Heinselman et al., 2024; Skinner et al., 2023). To that end, the training included the use and interpretation of probabilities, specifically noting the benefits of using paintball plots or individual member plots to tell a more complete story than ensemble mean fields of discrete fields, as well as the tandem use of probability of exceedance and percentile products (Figure 2). Because the precision of probabilistic products decreases with increasing neighborhood area, emphasizing the use of smaller neighborhoods was recommended.

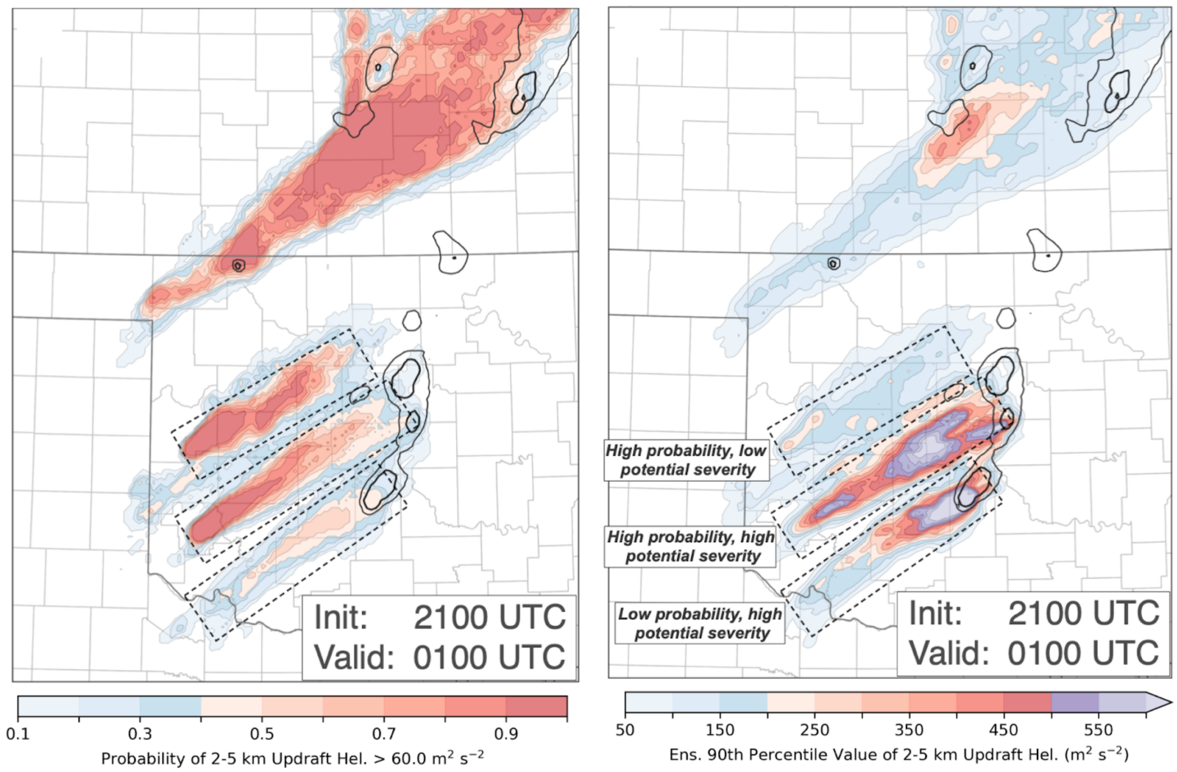

Figure 2: Example joint interpretation of WoFS-Smoke probability of exceedance and percentile products for a severe weather forecast in southwestern Oklahoma.

With the background and key interpretation points outlined, a chance to ask questions about the baseline system was provided before training moved to the new and unique capability of smoke aerosol forecasts (i.e., WoFS-Smoke versus the original WoFS). The motivation for extending WoFS to fire weather applications was introduced, and the key differences from the basic WoFS system were explained to participants. For completeness, features of the fire environment not yet resolved by WoFS-Smoke were addressed, including the relationship between wildfire thermodynamics, cloud microphysics, and smoke aerosol concentrations. The use of fire radiative power, defined as the amount of thermal energy being released by the fire and detected by satellite via the 3.9 µm shortwave infrared channel, to develop smoke aerosol concentrations through a 1-d plume height model was explained.

The next training section included examples of WoFS-Smoke products during various phases of fires: the pre-fire phase, active-fire phase, and post-fire phase. Pre-fire products focused on the fire environment in order to address the question, “Are conditions favorable for wildfire ignition and spread?” Examples of outputs provided included ensemble mean relative humidity and the Red Flag Threat Index (Figure 3; Murdoch et al., 2019).

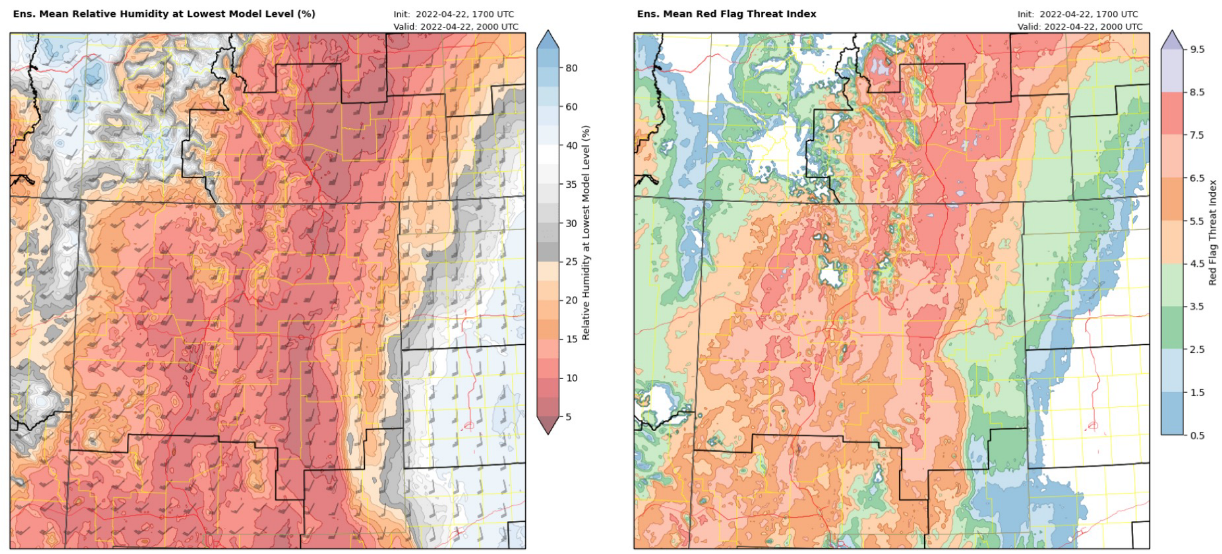

Figure 3: Examples of pre-fire products produced by WoFS-Smoke for a case in New Mexico valid at 2200 UTC 22 April 2022. (Left) Ensemble mean relative humidity at the lowest model level. (Right) Ensemble mean Red Flag Threat Index (Murdoch et al., 2019).

During the active phase of wildland fire, WoFS-Smoke produces a range of products to inform fire management and public safety (Figure 4). These include total column-integrated particulate matter less than 2.5 µm in diameter ($PM_{2.5}$; defined as 'smoke') as well as for various critical levels, including the near-surface (0-200 m above ground level (AGL)), mid-levels (2 km AGL), and upper-levels (6 km AGL). The probability of smoke exceeding certain thresholds is provided as instantaneous probabilities (i.e., not time-integrated). In addition, severe weather products, including the potential for convectively driven gusty winds and dry lightning, are available.

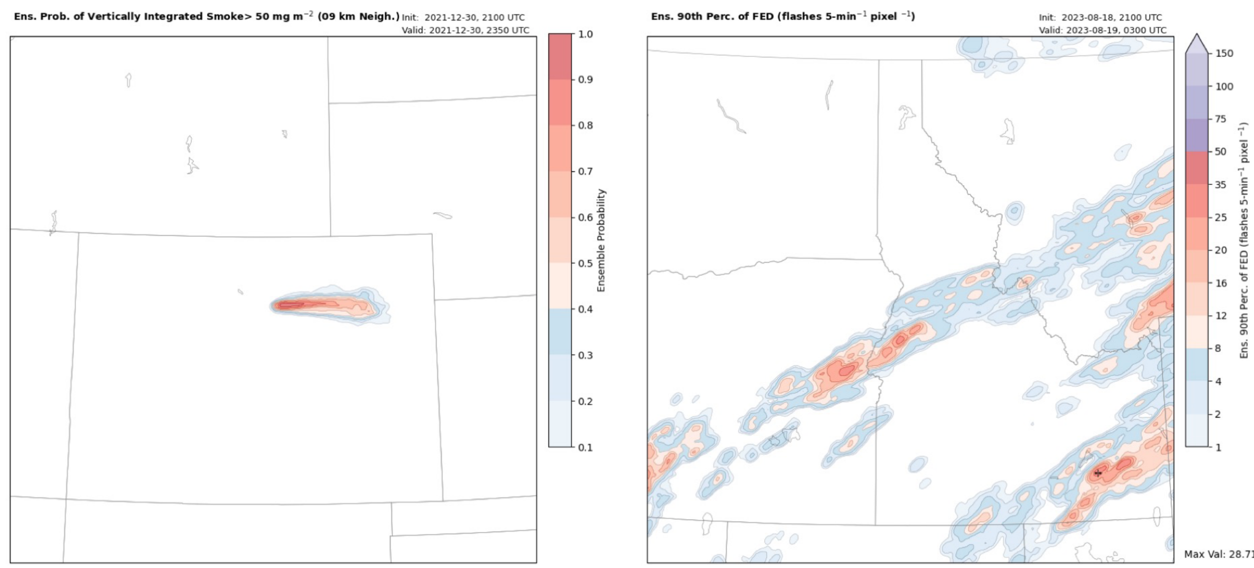

Figure 4: Examples of active (during) fire products for two cases. (Left) Ensemble probabilities of vertically integrated smoke exceeding 50 mg m^{-2} during the 2021 Marshall Fire in Colorado. (Right) Ensemble 90th percentile of five-minute cloud-to-ground lightning flashes during multiple Idaho Fires in 2023.

The WoFS-Smoke system also produces products relevant to post-fire hazards. While not a focus of this training or evaluation, ensemble precipitation products capable of resolving high-intensity, short-duration precipitation at 1-3 km resolution (Figure 5) provide decision support to the National Weather Service and emergency managers regarding postfire hazards such as debris flows and flash flooding (Oakley et al., 2023). The training concluded with a section on the operational use of WoFS-Smoke and a tutorial on using the website, including an overview of display products and keyboard shortcuts.

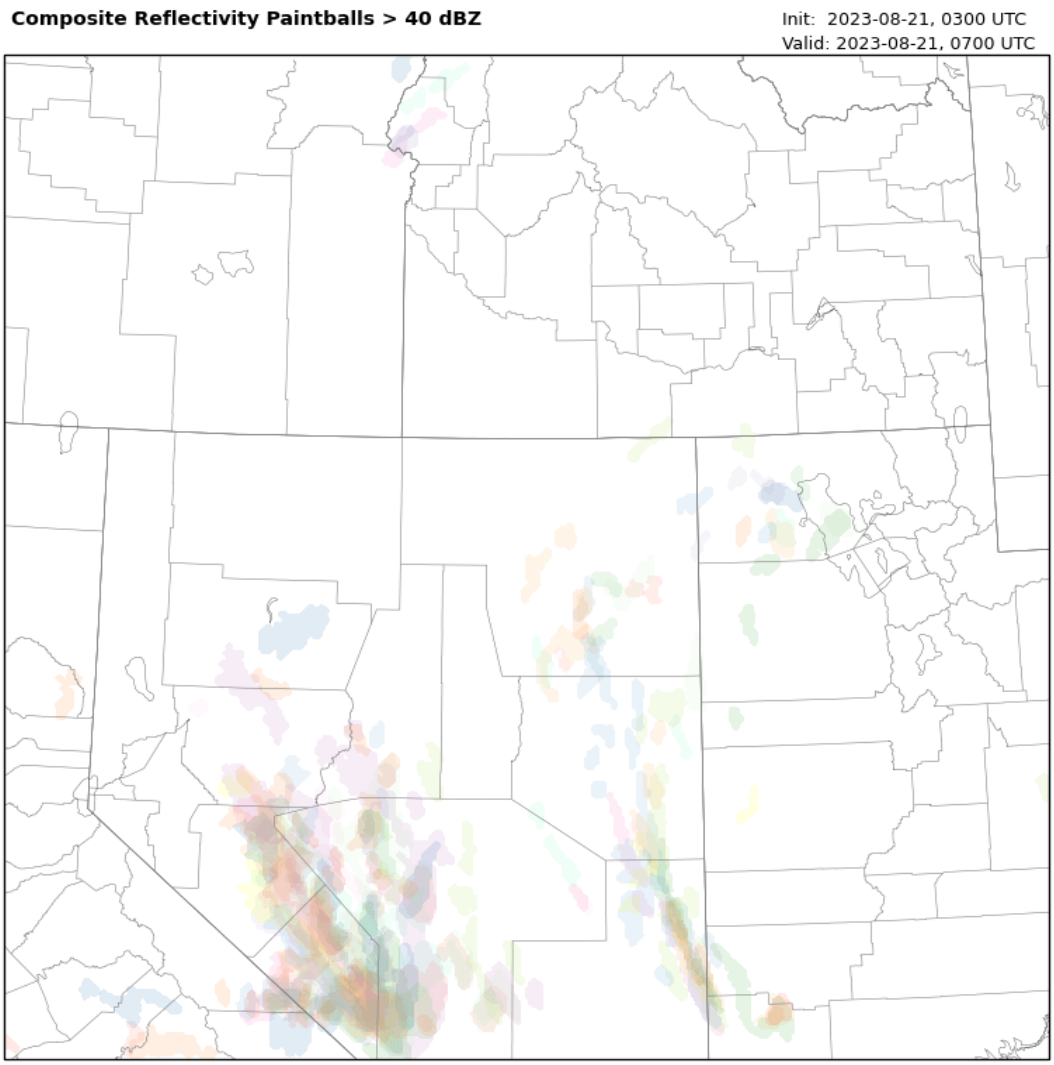

Figure 5: Composite paintball plot of reflectivity exceeding 40 dBZ valid 0200 UTC 21 August 2023 showing potential areas of high intensity precipitation in central Nevada and western Utah. Burned areas are shown as black outlines (thin gray outlines indicate counties).

3. Evaluation Scenarios

Following the training, evaluation participants engaged in four scenarios, such that each of the temporal fire cycle phases (before, during, and after fire) were addressed in at least one scenario. Participants were not provided with details about each scenario ahead of time beyond the basic concepts to be evaluated (see Appendix A for the Agenda provided). The scenarios included:

- Scenario 1: Probability of Smoke for Fire and Smoke Model Evaluation Experiment (FASMEE) Prescribed Burn in Central Utah (9-10 October 2023)
- Scenario 2: Red Flag Threat Index in Northern New Mexico (22 April 2022)

- Scenario 3: Rapidly Changing Environment in Texas/Oklahoma (17 March 2022)
- Scenario 4: Convective Precipitation Event in New Mexico (24 March 2022)

To begin, the WoFS-Smoke team provided a background of each scenario and briefly walked through the WoFS-Smoke products to be evaluated. Participants were reminded of the intent of the evaluation and how the scenarios would be used to gather participant feedback on some of the products they were introduced to during the training component. The first three scenarios lasted 45 minutes. Participants were given 20 minutes to work through each scenario, which concluded with the FWT team asking participants a set of product-specific questions designed to understand their decision support timelines, familiarity with each product, and whether and how each product would aid them in their decision support roles. The facilitation guide and list of focus group questions is provided in Appendices C-D, respectively.

Participation in Scenario 4 was less formal than Scenarios 1-3 and lasted approximately 20 minutes. Scenario 4, which focused on post-fire flood and debris flow risk, involved a more exploratory discussion-based evaluation, during which the WoFS-Smoke team did not provide a formal background and product evaluation questionnaire. Rather, the discussion focused on how WoFS-Smoke products could provide decision support for post-fire flood and debris flow events such as that presented in Scenario 4.

3.1 Scenario 1: Probability of Smoke: FASMEE Prescribed Burn in Central Utah (9-10 October 2023)

The U.S. Forest Service, in partnership with other government agencies and research institutes, conducts a series of landscape-scale (>1000 ac) prescribed burns with the intention of collecting comprehensive data including fuels, fire behavior, fire energy, meteorology, smoke, and fire effects to drive improvements in operational fire and smoke modeling systems. These burns, which also support resource management objectives, are collectively called the Fire and Smoke Modeling Evaluation Experiment (FASMEE).

In 2023, the FASMEE burn was implemented in the Fishlake National Forest of central Utah. This ~1000 ac burn unit, called Monroe South, is composed of mixed fuels including aspen stands, timber, and shrubs spanning elevations from 7,000 ft to 9,000 ft. The objective for the FASMEE burn was to achieve a stand-replacing (high intensity) fire to encourage aspen regeneration as part of the Fishlake National Forest's Management Plan (the Monroe Mountain Aspen Ecosystems Restoration Project) to reintroduce disturbance to the Forest. The 2023 FASMEE Monroe South burn fits the characteristics of either a relatively large prescribed fire or a relatively small wildfire–demonstrating moderate to high intensity fire in both cases–making the FASMEE burn an ideal "simulation of opportunity" for the WoFS-Smoke System.

A moderately amplified ridge of high pressure aloft and no major surface pressure gradients brought quiescent regional weather (Figure 6, left) within prescription (slightly warmer than average temperatures with relative humidities in the 20-30% range; Figure 6, right). Ignitions for a test burn commenced mid-morning on 9 October 2023 with full ignitions occurring on mid-morning 10 October 2023. All ignitions were performed via helicopter.

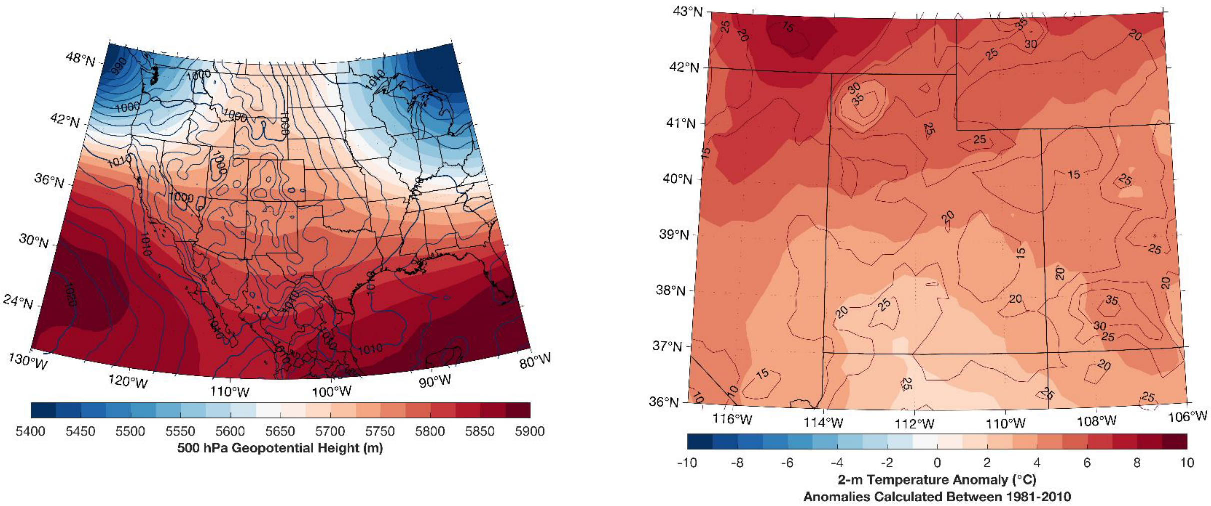

Figure 6: (Left) 500 hPa geopotential heights (m; filled contours) and sea level pressure (hPa; black contours) from the North American Regional Reanalysis for 2100 UTC 10 October 2023. (Right) 2 m temperature anomalies (filled contours) for 2100 UTC 10 October 2023 calculated as differences from the 2100 UTC 10 October 1981-2010 mean. 2 m relative humidity values are shown as black contours.

The model outputs intended to be examined in the FASMEE burn scenario focused on the probabilistic smoke products. These products highlighted how the rapid update cycle allows for ‘on-demand’ provision of decision support for potential smoke impacts to an important roadway (probability of smoke exceeding a threshold; Figure 7). Here, the example highlights how a dramatic decline in ensemble mean vertically integrated smoke occurs in model runs initialized one hour apart (Figure 7 left and right).

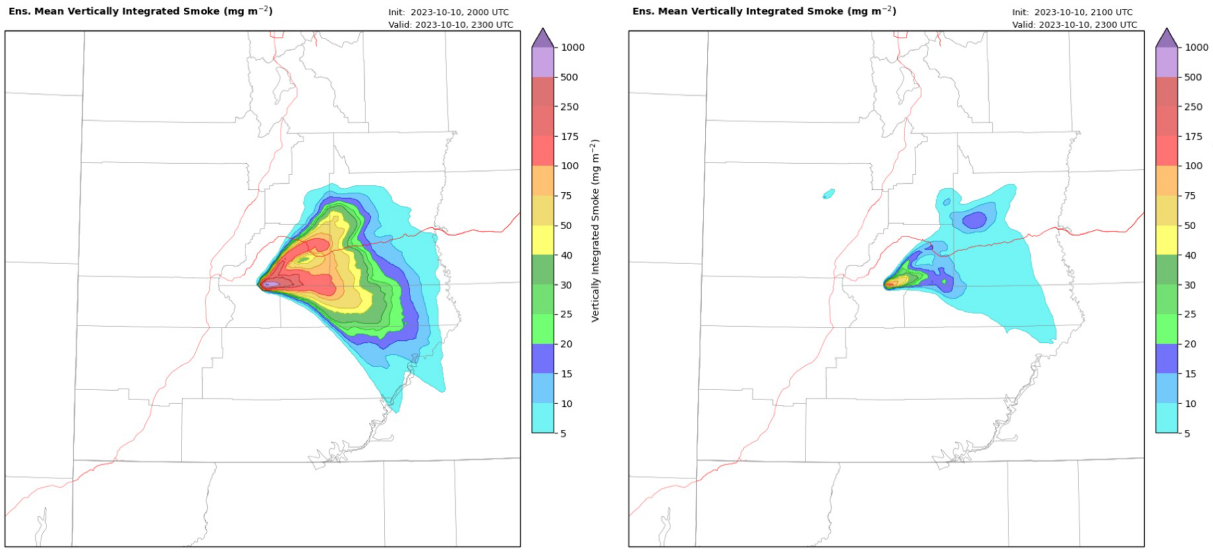

Figure 7: Examples of probabilistic smoke output from Scenario 1. (Left) Ensemble mean vertically integrated smoke (mg m^{-2}) initialized at 2000 UTC 10 October 2023 and valid at 2300 UTC 10 October 2023. (Right) As shown on left and valid for the same time but for the model run initialized at 2100 UTC 10 October 2023. A small wildland fire is burning to the northeast of the Monroe South unit. Major roads are shown as red lines and counties as gray lines.

3.2 Scenario 2: Red Flag Threat Index in Northern New Mexico (22 April 2022)

Following a warm and dry winter and spring characterized by low-to-no snow conditions, multiple high-impact wildfires ignited during April 2022 in New Mexico. Several of these were escaped prescribed burns that were converted to wildfires (e.g., the Cerro Pelado Fire was a pile burn and the Calf Canyon/Hermit's Peak Fire were broadcast burn and pile burns, respectively). On 22 April 2022, an approaching trough behind a surface low pressure centered over northern Texas (Figure 8 left) brought warm, dry, and windy conditions to northern New Mexico (Figure 8 right). These conditions lead to the issuance of a Red Flag Warning by NWS Albuquerque. The southwesterly to westerly winds aloft were oriented favorably with terrain to produce downslope windstorms. The forecast warned of strong and damaging winds reaching 80 mph (69 knots) and coinciding with single-digit relative humidities resulting from adiabatic downslope warming and advection of dry air into the region. With extremely dry fuels across size classes in complex mountainous terrain, this represents an unfavorable scenario from a wildland fire management perspective as fires can easily ignite and rapidly grow.

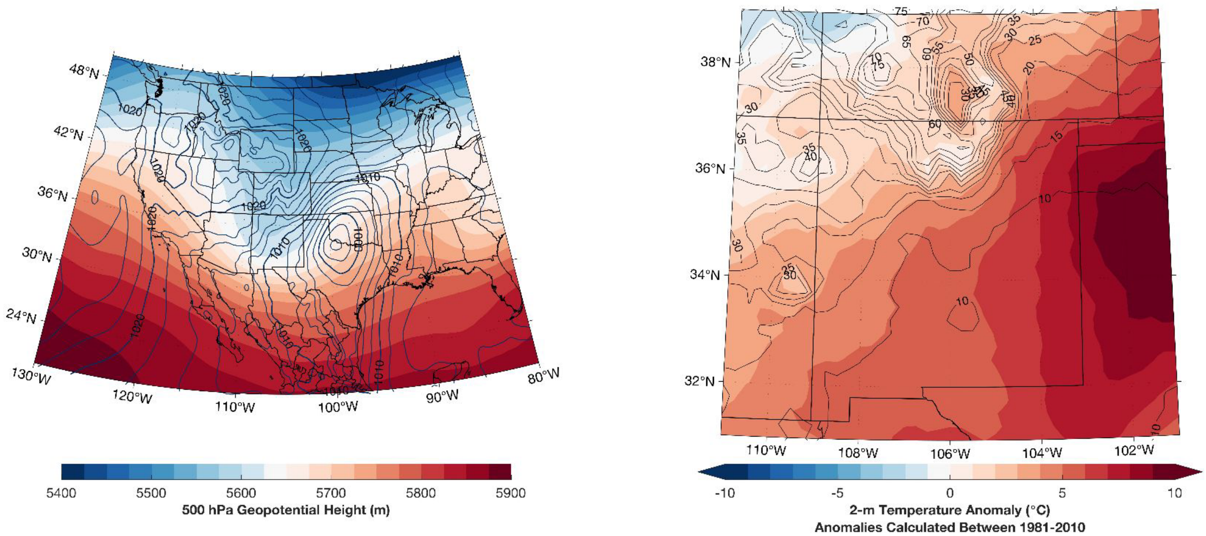

Figure 8: (Left) 500 hPa geopotential heights (m; filled contours) and sea level pressure (hPa; black contours) from the North American Regional Reanalysis for 2100 UTC 22 April 2022. (Right) 2-m temperature anomalies (filled contours) for 2100 UTC 22 April 2022 calculated as differences from the 1981-2010 mean at 2100 UTC 22 April 2022 with 2 m relative humidity values shown as black contours.

The Red Flag Threat Index (RFTI; Murdoch et al., 2019) is a nomogram-based approach to aid NWS offices in communicating to key partners the potential for extreme fire weather conducive to the ignition and spread of wildland fire, as well as the potential for extreme fire behavior. The RFTI, which is a decision support tool and not a direct predictor of fire starts and/or growth, incorporates forecast and/or observed 2 m relative humidity and 6 m wind speed–both commonly used variables in fire weather prediction–as inputs. These inputs are converted to quartile rankings using local and regional fire weather observations when each parameter meets or exceeds the local red flag warning conditions. The ranked quartile values are then summed to produce RFTI values spanning 0 (“Non-Critical”; no input meets or exceeds red flag warning criteria) to 10 (“Historically Critical”; both inputs are in the top quartiles).

Favorable fire weather conditions (warm, dry, and windy) combined with multiple ongoing fires in New Mexico during late April yielded an ideal scenario to apply the WoFS-Smoke system. This scenario allowed the system to provide probabilistic guidance with respect to (i) potential new ignitions, (ii) the spread of new ignitions, and (iii) smoke transport and fire growth potential from ongoing fires. The primary model products examined in this scenario included the RFTI generated from WoFS and probabilistic smoke products (Figure 9) as well as near-surface relative humidity (not shown) once the ‘peak fire weather’ period has been approached at a model initialization time representing potential deployment of suppression resources. The right panel of Figure 9 indicates the time step when potentially impactful smoke reaching a major road occurs with the highest probability.

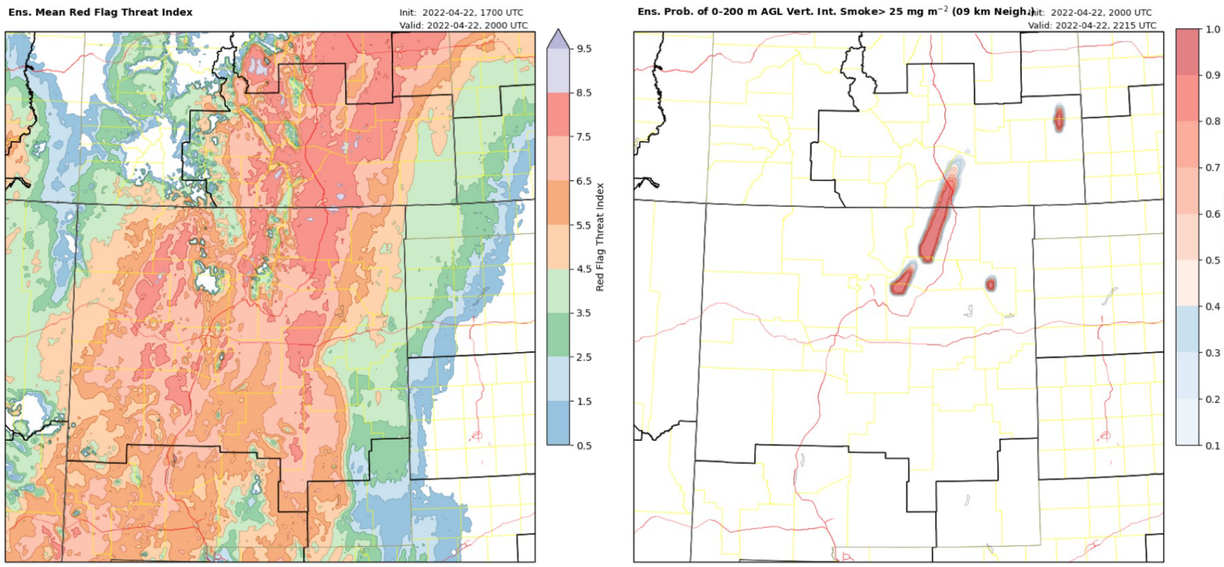

Figure 9: Examples of ensemble mean and probabilistic output from Scenario 2. (Left) Red Flag Threat Index values valid for the same model initialization and forecast time. (Right) Ensemble probabilities of ground level (0–200 m AGL) vertically integrated smoke initialized at 2000 UTC 22 April 2023 and valid at 2215 UTC 22 April 2022. Major roads are shown as red lines and NWS county warning areas are shown as thick black lines in all figures.

3.3 Scenario 3: Rapidly Changing Environment in Texas/Oklahoma (17 March 2022)

The spring of 2022 brought numerous high impact fires to the southern Plains, ultimately becoming one of the most notable wildfire seasons in Texas and Oklahoma. Of the many fires during this period, one of the most impactful was the Eastland Complex of central Texas. Between 17–22 March, 54,000 acres were burned by seven fires (collectively managed as the Eastland Complex). Scenario 3 examined the preceding weather conditions leading up to the rapid formation of the favorable environment for high probabilities of ignition and extreme fire behavior and spread on 17 March 2022.

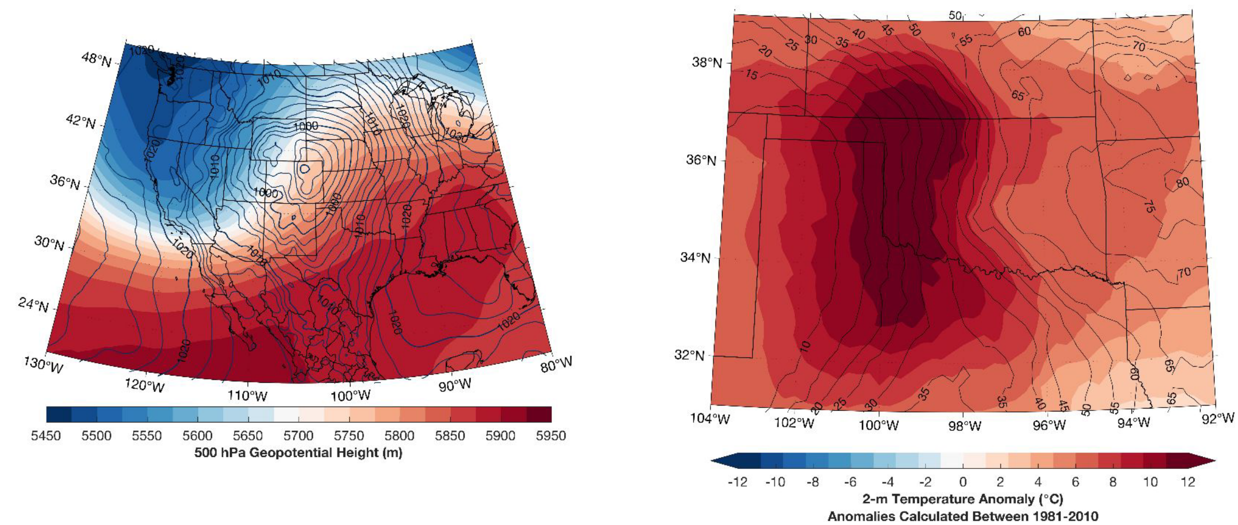

Figure 10: (Left) 500 hPa geopotential heights (m; filled contours) and sea level pressure (hPa; black contours) from the North American Regional Reanalysis for 2100 UTC 17 May 2022. (Right) 2 m temperature anomalies (filled contours) for 2100 UTC 17 May 2022 calculated as differences from the 1981-2010 mean at 2100 UTC 17 May with 2 m relative humidity values shown as black contours.

Weather and climate conditions preceding the Eastland Complex were similar to those in Scenario 3, with critically dry fuels (dominantly grass fuel types) and an approaching deep neutrally tilted trough bringing strong dry and warm southerly flow to the region (Figure 10 left). In this region of warm air advection (the warm sector of the approaching mid-latitude cyclone; Figure 10 left), a classic downstream low level thermal ridge over central Texas formed, which is a known fire-favoring synoptic to meso-alpha pattern in the Southern Plains as it favors dry fuels and downward mixing of higher momentum air leading to strong winds at the surface (Lindley et al., 2017). Southerly winds at 925 hPa approached 20 ms^{-1} (38.8 knots) at 1200 UTC 17 March 2022 over the region (not shown, identified using the North American Regional Reanalysis). Strong (20-30 knots) westerly to southerly 850 hPa winds and temperatures exceeding 20 °C (68 °F; Figure 11 upper left panel). Conditions near the surface included 10 m winds exceeding 20 knots and 2 m temperatures exceeding 85 °F (29.4 °C; Figure 11 upper right). Temperature anomalies at 2 m (calculated between 1981-2010) exceeded 10°C (18 °F) and relative humidities were approaching single digits even in the NARR analysis, though humidities were in the 10-30% range coincident with the largest positive 2 m temperature anomalies (Figure 10 right). Convection parameters were mentioned (convection is often triggered along a dryline) and explored by participants, but the primary focus was on the near-surface fire environment.

Widespread single-digit relative humidities (Figure 11 lower left panels) coincided with winds and warm low level temperatures, indicating the fire-favoring environment. For context, a temperature of 85 °F (29.4 °C) and a relative humidity between 5-9% results in a reference (uncorrected) fuel moisture of 1%; with corrections applied, this value ranged from 2-5%

implying that in flat, unshaded (i.e., grass) fuels, probabilities of ignition ranged from 70-100%. Consistent with this first-order estimate of high likelihood of ignition and spread, forecast relative humidity and wind combination yielded RFTI values in excess of seven (well into critical or higher conditions) oriented north-south with a strong zonal gradient (Figure 11 lower right panel). The eastward progression of the upstream low pressure trough and downstream low level thermal ridge and associated transition to hot, dry, and windy conditions over several hours highlights the rapidly changing environment where fine and dead fuels quickly become receptive to fire. Finally, in further association with eastward progression of the trough, a consistent signal of a southerly to westerly and northwesterly change in near-surface (10 m) winds (referred to as a "wind shift") was also observed in the five-minute output model forecast progression (not shown).

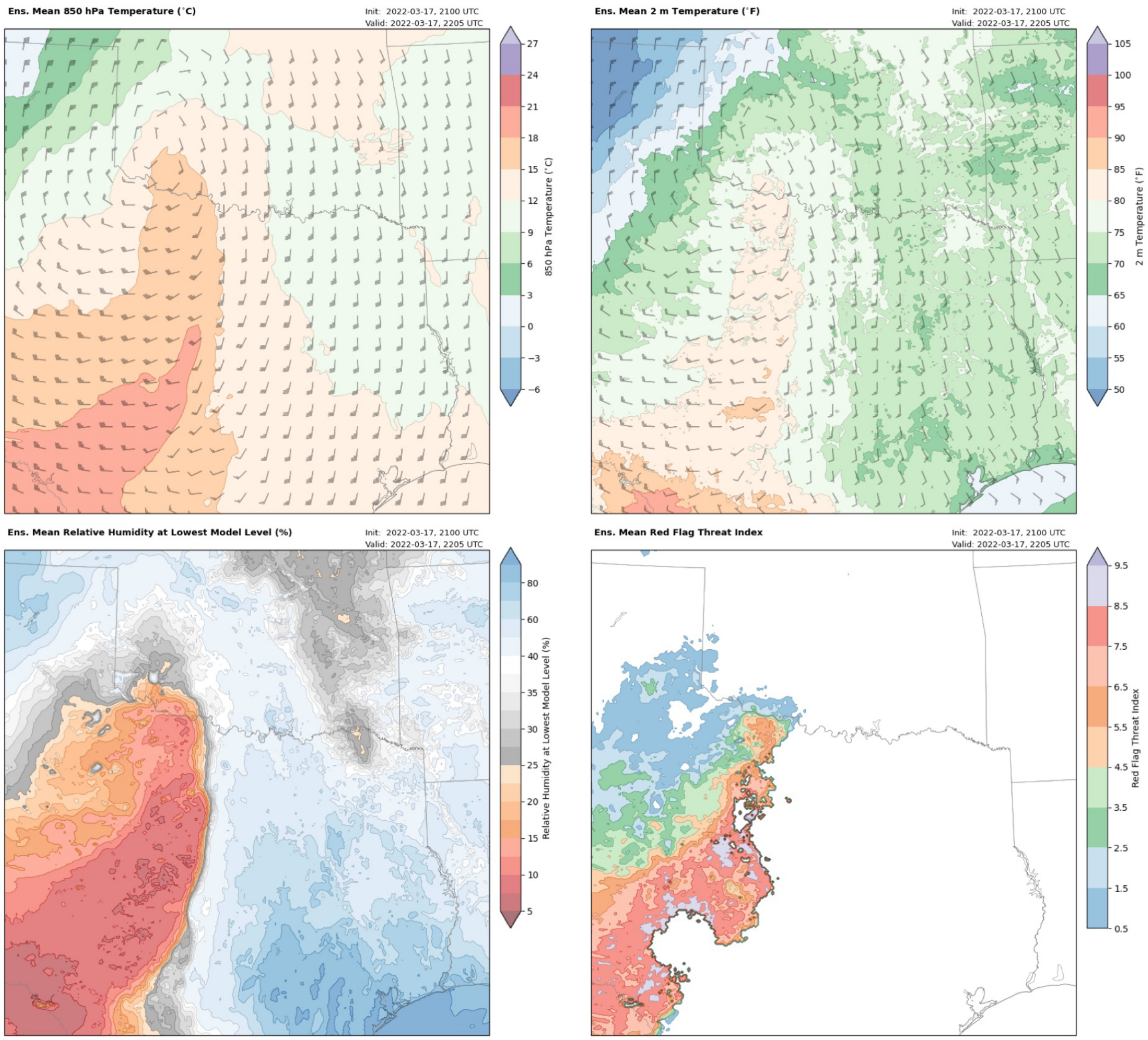

Figure 11: Examples of probabilistic output from Scenario 3. (Upper Left) Ensemble mean 850 hPa winds and temperatures initialized at 2100 UTC 17 March 2022 and valid at 2205 UTC 17 March 2022. (Upper Right) As shown on upper left and valid for the same initialization and forecast time but showing 6 m winds and 2 m temperatures. (Lower Left) As shown on upper left and valid for the same initialization and forecast time but showing ensemble mean relative humidity at the lowest model level. (Lower Right) As shown on upper left and valid for the same initialization and forecast time but showing the ensemble mean Red Flag Threat Index (RFTI; Murdoch et al., 2019); recall RFTI values above five are in the critical range.

3.4 Scenario 4: Convective Precipitation Event in New Mexico (24 March 2022)

The final scenario, which highlighted the application of the WoFS-Smoke system for postfire hazards including flash flooding and post-fire debris flows, was evaluated in a more informal setting during the focus group discussion time. While it followed a similar approach to Scenarios

1-3, Scenario 4's evaluation time was truncated by approximately half (~20 minutes) compared to other scenarios. Scenario 4 focused on a late-spring (24 May 2022) convective precipitation event in eastern New Mexico that occurred while large fires (e.g., Calf Canyon/Hermit's Peak; see Scenario 1) were being actively managed with numerous fire management resources including personnel and infrastructure exposed to potential hazards of postfire flash flooding and debris flows.

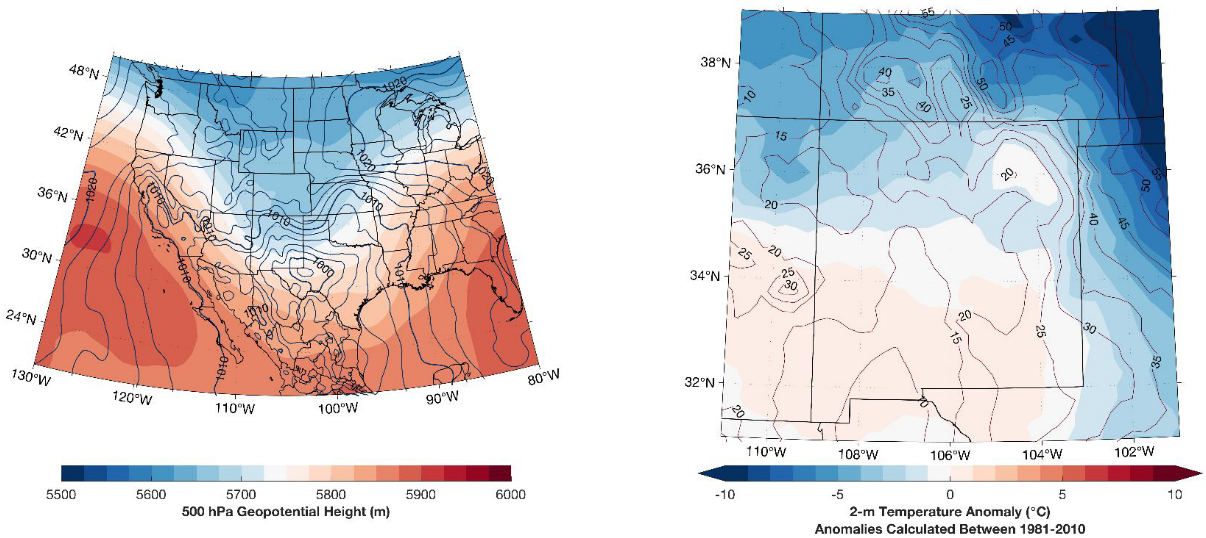

Figure 12: (Left) 500 hPa geopotential heights (m; filled contours) and sea level pressure (hPa; black contours) from the North American Regional Reanalysis for 2100 UTC 24 May 2022. (Right) 2 m temperature anomalies (filled contours) for 2100 UTC 24 May 2022 calculated as differences from the 1981-2010 mean at 2100 UTC 24 May with 2 m relative humidity values shown as black contours.

On 24 May, a broad upper level high pressure ridge with its axis centered just offshore of North America was present to the west of New Mexico while a weak but broad low pressure trough was digging equatorward and eastward into the Southern Plains and amplifying due to lee cyclogenesis (Figure 12 left). This brought a dry cold front into the region with colder temperature anomalies to the north and east and helped to establish a zonal moisture gradient or dryline (Figure 12 right) also evident in precipitable water fields; not shown) with drier air (<10 mm integrated water vapor (IWV)) in western New Mexico increasing to upwards of 20 mm IWV in eastern central New Mexico. Combined with late spring solar radiation inducing topographic heating, upper level divergence and frontogenetical lift, as well as available–though anemic–moisture, this scenario is ideal for convective thunderstorm initiation especially in the vicinity of topography.

In Scenario 4, several WoFS-Smoke parameters were examined to highlight potential for flash flooding or post-fire debris flows. While flash floods can be initiated with even 5-10 minutes of high intensity precipitation, to trigger post-fire debris flows, rates exceeding 25 mm per hour for

15 minutes are typically required, however these rates are dependent on various factors including post-fire soil physical properties, lithology, sediment availability, basin morphology, and post-fire recovery rates. Output parameters included paintball plots of composite reflectivity exceeding 40 dBZ (Figure 13 upper left) and ensemble probabilities of exceeding 0.5 in (12.7 mm) hourly rainfall (Figure 13 upper right). Convective thunderstorms also pose hazards to fire management resources due to the potential for strong, gusty, and variable direction outflow winds as well as lightning. Outputs from WoFS-Smoke pertinent to these weather factors that influence both fire behavior and resource safety include ensemble 90th percentile (or mean; not shown) 10 m wind gust speed (Figure 13 lower left) and 90th percentile cloud-to-ground lightning flashes (Figure 13 lower right).

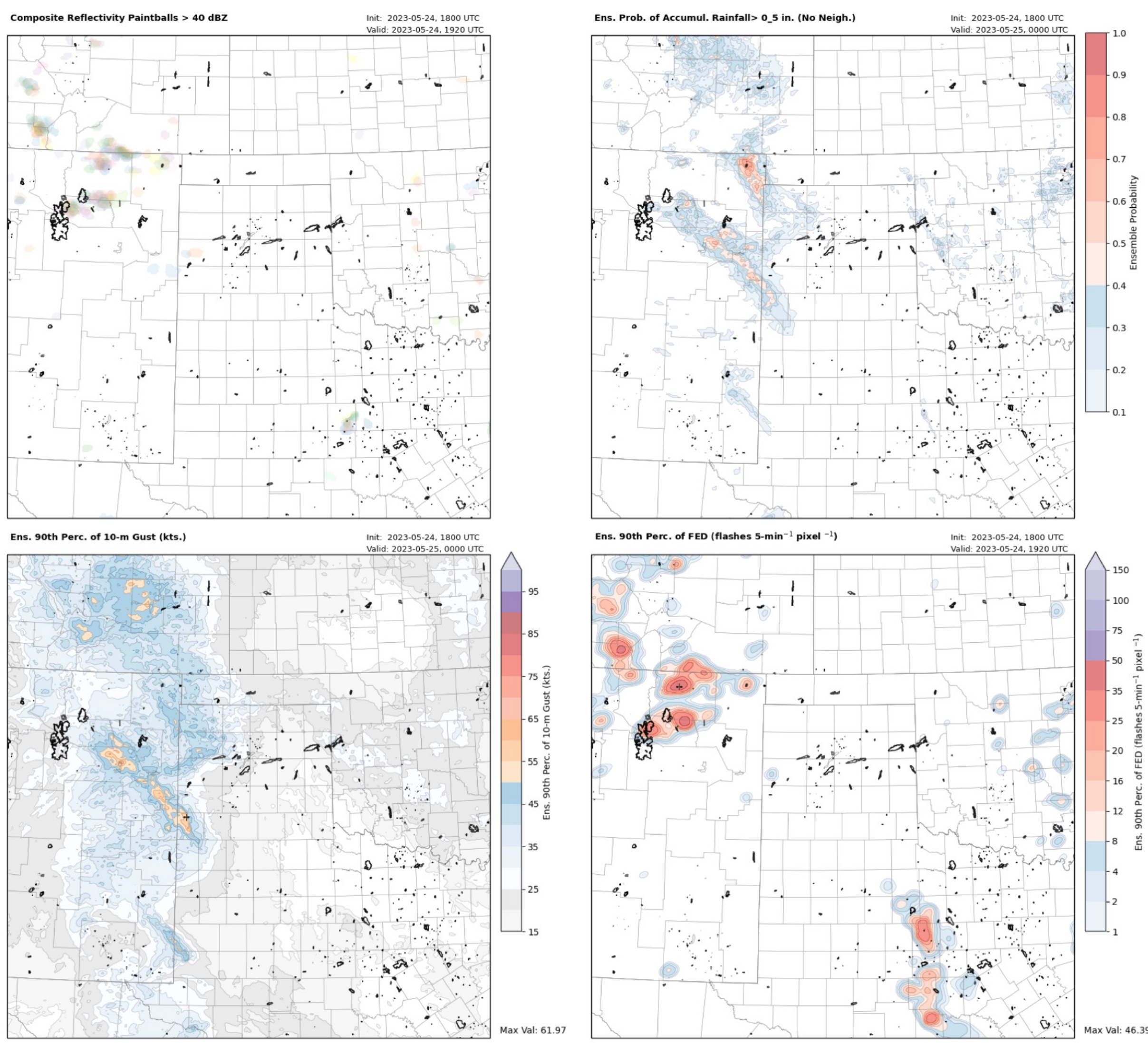

Figure 13: Examples of probabilistic precipitation output from Scenario 4. (Upper Left) Composite reflectivity paintball plots initialized at 1800 UTC 24 May 2023 and valid at 1920

UTC 24 May 2023. (Upper Right) Ensemble probabilities of accumulated hourly rainfall exceeding 0.5 in (12.7 mm) for the run initialized at 2230 UTC 24 May 2023 and valid at 2300 UTC 24 May 2023. (Lower Left) Ensemble 90th percentile of 10 m wind gust initialized at 1800 UTC 24 May 2023 and valid at 0000 UTC 25 May 2023. (Lower Right) Ensemble 90th percentile cloud-to-ground lightning flashes initialized at 1800 UTC 24 May 2023 and valid 1920 UTC 24 May 2023.

4. Fire Weather Testbed Evaluation of Training and Scenarios

The following subsections include specific results and insights from the Fire Weather Testbed evaluation team for the training component and the four scenarios. After each scenario exercise, the FWT collected qualitative data from participants related to their familiarity with the products, the critical decision points or time frames relevant to each scenario, and relevant decision and information needs and gaps (Appendix B) through 10 to 20 minute focus group discussions. Oral and written (in chat) responses were recorded. Participant feedback topics from the shorter discussions following the training and scenarios are also incorporated into the broader results and interpretations from the afternoon focus group discussion (Section 5). Qualitative data from the focus group discussions inform evaluation findings; descriptive numerical results (e.g., "four of six participants said '*X*'") are provided to summarize participant responses and guidance. For the training component and four scenarios, participant feedback is summarized and is then followed by one or more FWT recommendations based upon a synthesis of participant feedback and expert insight from FWT staff.

4.1 Evaluation of WoFS-Smoke Training

Several questions (listed in the Facilitation Guide; Appendix B) were asked during the training component to gauge the participant's familiarity with the WoFS-Smoke product as well as gather information on the relevance and usability of existing outputs and ideas for additional development. Five of the six participants were unfamiliar with the WoFS-Smoke system and had not previously used it. One participant had strong familiarity with WoFS-Smoke and the WoFS modeling framework; this participant provided additional pertinent information to the background training and answered questions from other participants. The level of detail and materials provided in the two-hour introductory training appeared sufficient to give participants a baseline level of familiarity from which to proceed with specific case studies. This information could be broken down into smaller components and provided on a WoFS-Smoke page for users to watch at their leisure.

FWT Recommendation: Record and provide training videos and materials to accompany WoFS-Smoke. A Frequently Asked Questions page would also be highly beneficial to provide more detailed information about model set up (e.g., parameterizations, assumptions), appropriate use cases, and limitations.

4.2 Evaluation of Scenario 1: FASMEE

Participants noted that the probability of smoke scenario (FASMEE) did not include a dispersive plume of smoke; the plume was symmetrical and did not include substantial variability in horizontal dispersion. Participants referred to the plume as “almost binary”. Participants requested more examples spanning a range of plume dispersion behaviors for subsequent training scenarios. Participants discussed the need for probabilistic smoke outputs, which are currently given in units of micrograms per cubic meter (a standard output in atmospheric chemistry), to be converted and provided in terms of Air Quality Index (AQI) and/or visibility. The complexities and values were explained by one participant: “*AQI/health gets into tricky situations with other agencies, but this is [a] great direction*”. This change would facilitate provision of actionable information to decision makers at partner agencies of the NWS by using units they are familiar with and have developed actionable thresholds upon. As an example, participants discussed that transportation partners could be contacted to update their road signs if visibility-impairing levels of smoke were forecast with high certainty. The September 2024 Louisiana superfog incident, which resulted in multiple accidents, traffic delays, eight fatalities, and at least 63 injuries (Oladipo, 2023), was discussed as a highlight use case for this product.

FWT Recommendation: Bearing in mind the challenges with conversion of mass per unit volume estimates of $PM_{2.5}$ to an AQI or visibility value due to required physical and chemical assumptions, we recommend exploring the inclusion of this conversion as it indicates substantial potential benefit for the usefulness of WoFS-Smoke. First-order conversions could utilize those employed by Purple Air sensors and be improved with subsequent inclusion of and/or coupling to more sophisticated atmospheric chemistry models. This could also serve as a verification activity.

Participants discussed the need for specific social media graphics intended to highlight the probability of smoke products. Visual communication of probabilistic information is a rapidly growing field within weather communications (e.g., Heggli et al., 2023) especially as this information is increasingly desired and used (Ripberger et al., 2022). This suggests high potential return on investment for further development of communication tools to explain and visualize WoFS-Smoke outputs to broader audiences. Participants considered the forecast horizon (0–6 hours) and temporal output (15 minute) of WoFS-Smoke to be generally sufficient to provide this type of information. One participant noted that longer forecast horizons are desired for wildfire management applications (18-24 hours, or encompassing one or two operational shifts) where either an NWS office or an IMET provides weather-related decision support information. Last, it was noted that “*[the] HRRR gives one view, but this [WoFS-Smoke] provides a lot of additional information for new forecasts*”. This implies that WoFS-Smoke and the HRRR are complementary products. Although the two models share many similarities, they complement one another given that one provides probabilistic forecasts (WoFS-Smoke) and the other

(HRRR) provides deterministic forecasts; each type of forecast has benefits and limitations depending on the context of the situation and the partners involved.

FWT Recommendation: The WoFS-Smoke team is currently exploring and developing probabilistic visualizations, and we strongly encourage continued investment in this endeavor, especially as an actionable product (e.g., probabilistic visibility forecasts) are developed that can be used by broad audiences.

4.3 Evaluation of Scenario 2: RFTI

All participants were familiar with RFTI at some level though only one had used it previously. While it was mentioned that the forecast horizon of WoFS-Smoke could provide usable information during rapidly evolving events, the forecast horizons needed for Red Flag Warnings and Fire Weather Watches (one to three days) were a limitation. However, the WoFS-Smoke timescales were noted to be valuable for helping forecast when adverse conditions (e.g., winds) would stop, facilitating the cancellation of warnings. For instance, the frequent briefings to emergency managers during the rapidly evolving 2021 Marshall Fire in Boulder County, Colorado was given as an example use-case. Short-turnaround information or rapid updates to forecasts–both strengths of the WoFS-Smoke system's capabilities–were also noted by multiple participants to support Spot Weather Forecasts, with prescribed burns highlighted as a use case. However, go/no-go prescribed burn decisions are often made the evening prior, so the prescribed burn information would be most valuable if this decision were being near the time of proposed ignition or to convey temporally evolving fire weather conditions (e.g., expected timing of a wind shift or exceeding the prescription in terms of temperature or relative humidity), which may require a tactical shift and/or holding of ignitions.

Participants agreed that one-hour RFTI information would help support direct (rather than headline) decisions pertaining to tactical fire management actions both when deployed as an IMET or when providing Spot Weather Forecasts. The RFTI, or other indicators that include a climatological component (to represent an anomaly), was noted as adding important and concise detail that filled information gaps, especially critical during particularly dangerous scenarios. Last, one participant encouraged everyone to:

> "*...think outside the box about legacy products, [and] trends we can observe through mesoanalysis/other tools for identifying fire favorable conditions, wind shifts, cessation of critical conditions. Not traditionally messaged, but capabilities emerging.*"

This final point highlights the full value of these types of products may not yet be realized.

FWT Recommendation: Continue developing archived use cases for products supporting rapid environmental changes, such as the onset or cessation of critical fire weather patterns, changes to the fire environment that alter strategic and tactical decision making, and/or cases that require frequent update briefings to emergency managers. Similar concepts apply to impactful air quality events or even potentially energy demand during extreme heat events. These cases can support table top exercises, additional verification studies, and provide examples of the benefits provided by WoFS-Smoke capabilities.

4.4 Evaluation of Scenario 3: Convection

Participants were more familiar with the convective forecast elements, likely due to the longer availability of original WoFS products. They agreed these outputs met existing needs, and that five minute output was beneficial especially in the case of rapidly changing weather, especially wind shifts, that quickly influence fire behavior (spread and intensity) and thus the safety of fire personnel and critical assets. Such rapid changes impact tactical decisions rather than headline (strategic) decisions. Discussion about the physical environment during Scenario 3 focused on these types of environmental changes, with participants highlighting the ability of WoFS-Smoke to capture a strong wind shift associated with frontal passage–a key critical fire weather pattern. Participants were asked how this information would support their activities from an IMET's perspective. Responses indicated this information would be communicated broadly for situational awareness, and the value of the five-minute output was expressed:

> "*Working in a 100,000 acre complex and give visual play by play, would do radio update for everybody. If accurate, this is very helpful information.*"

It could be used also to encourage (or to require) protective actions to be taken by fireline personnel:

> "*I look at it as this is enough lead time to pull firefighters off the line, but from aviation perspective, 5-10 minutes can be make or break between dump [fire retardant], search and rescue.*"

The need to be able to zoom in on the domain (the 900 km x 900 km area simulated by WoFS-Smoke) was requested. In regions of complex topography, the configuration of terrain greatly influences smoke transport and accumulation (i.e., smoke pooling in valleys overnight), and participants agreed that including terrain and the ability to zoom in would facilitate understanding smoke behavior and potential impacts on critical assets like small communities, airports, and roads. Similarly, during times of rapid environmental changes, like the onset of a shift in wind speed and direction during frontal passage or development of thunderstorms, the capability to assess these changes near critical assets or near the active fire line would provide forecasters with usable information.

FWT Recommendation: Improvements to the viewer interface to provide the capability to zoom, as well as the inclusion of reasonably high resolution topography (e.g., contours developed using a 30 m digital elevation model) and critical assets would elevate the capabilities of WoFS-Smoke to provide critical information in support of tactical decision making in rapidly evolving fire environments by leveraging its high resolution output.

4.5 Evaluation of Scenario 4: Short-duration High-intensity Precipitation

Participants generally found WoFS-Smoke guidance beneficial to forecast short-duration, high-intensity precipitation, especially from an IMET's perspective when convection develops on an active fire. In these situations, with personnel in drainages or using infrastructure susceptible to flooding (e.g., using dirt roads with culverts and small bridges for access), the rapid update cycle is valuable. Participants noted the need for rain rates to be reported using decision-relevant timescales (i.e., rainfall depth per 15 minute or 30 minute duration):

> "*Current products tend to be at too long of a time frame (i.e., 1 hr, 6 hrs) where our rain rates are critical in the 15-30 min time frame.*"

Dry lightning was noted by at least two participants as an additional value-add of WoFS-Smoke, with paintball plots of lightning suggested by three participants.

FWT Recommendation: Calculate and include rain rates at 15-30 minute intervals. Additionally, WoFS-Smoke output could provide rain rates in the units used by the U.S. Geological Survey (rainfall depth per hour sustained for 15 minutes; i.e., "24 mm/hr for 15 minutes"). This could employ a paintball-style plot if the minimum rate for debris flow initiation was satisfied. Last, we recommend developers explore the potential inclusion of parameters to produce a dry lightning forecast.

5. Focus Group Discussion

The WoFS-Smoke training and evaluation concluded with a focus group discussion guided by five overarching questions pertaining to the WoFS-Smoke system. The following paragraphs highlight key themes from the discussion, organized by question. All seven participants engaged in the end-of-day focus group. Zach Tolby, Manager and Lead Scientist for the FWT, led the focus group facilitation. Ben Hatchett and Jamie Vickery took detailed notes and repeated the questions asked by the facilitator within the Google Meet chat.

To begin the discussion, the facilitator asked participants,

> "**What is the WoFS system not currently capable of resolving or predicting as it relates to smoke forecasting? What capabilities could be added that would be helpful [to you all in your decision support roles]?**"

To further prompt discussion, he asked, "**Are there other values at risk that you would like to see displayed on a map that would be helpful?**" to which participants responded: topography, major airports, such as terminal air forecast (TAF) sites, infrared (IR) flights and IR hot spots (areas of anomalous heat), and overlay of current fire perimeters. A discussion followed about smoke being trapped in valleys as the boundary layer stabilizes overnight. Suggested examples included northwestern California fires including the Smith River Complex (2023) and fires in the Happy Camp region. During wildfire incidents, this smoke can impact air operations by keeping aircraft grounding due to limited visibility despite clear skies aloft and in the proximity of the fire itself. Discussion continued with other potential applications including to commercial air operations as well as during conditions of deep smoke injection into the atmosphere (pyrocumulonimbus) and/or long-range transport. Under these conditions, this may influence slant-wise visibility on approach such as when there are fires upwind of major airports: "*We have those issues at [REDACTED] with [fires] to our west.*" Regarding the application of current fire perimeters, a member of the WoFS-Smoke team explained that this is largely "*out of their hands*" because a third-party entity creates shapefiles for them to download each morning to show fire perimeter information. When available, these products would provide important information pertaining to situational awareness as well as strategic and tactical decision making.

Next, we asked participants to provide feedback on the thresholds for and variables included within each of the three products presented, including whether the thresholds and/or variables are actionable in terms of providing decision support to key partners. For the Probability of Smoke Exceedance product, we asked, "**Are the thresholds for smoke actionable (>25μg/m^2, μg/m^2)?**" to which three participants shared that the meaning behind the thresholds were unclear to them and that actionable smoke thresholds may not be especially useful for this particular group. Two participants followed-up to explain that visibility thresholds would be much more useful/actionable than smoke thresholds, further emphasizing discussion during Scenario 1. For the RFTI (Scenario 2), we asked, "**Does the index make sense? And can it be useful in IDSS/conveying information to your key partners?**" One participant shared that the RFTI makes sense and that it would be useful for conveying information to key partners, but added: "*one thing that would be helpful would be a key that essentially says, if you're between 5.5 and 6.5 it's critical.,That way there is uniformity across all offices [for IDSS applications].*" This question also led to a line of discussion regarding how the RFTI is calculated, to which one participant explained that it is solely calculated by relative humidity and wind speed percentiles:

> *"Going back to how it's calculated, it's an observational period. Then you quartile rank those 1-5. Add scores 1-5 for RH to the wind, and that's how it's calculated - using surface winds. But it's more complex than just surface wind."*

Categorizations for RFTI are as follows: 1-2 is elevated; 3-4 is near critical; 5-6 are critical; all the way to 9-10, which is defined as "historic." We then asked about other types of variables that would be useful to include as part of the Rapidly Changing Fire Environment product (Scenario 3). Two participants explained that the inclusion of lightning fields–especially dry lightning–would be interesting and also critical for firefighter and fire personnel safety.

The third question the facilitator posed asked participants, "**How, if at all, would the availability of the three WoFS-Smoke products in real-time change what you do?**" He then rephrased to ask another forward-thinking question, "**Or how would their availability change what products you issue or decision support products you could provide?**" Responses among participants varied and led to follow-up questions for the developers. One shared that, for them and their key partners, the products would especially support prescribed burn planning and by being able to provide more direct, remote decision support for IMETS. Another participant shared that in addition to enhancing decision support for their key partners, these products can also be useful for communication to the general public:

> "*From a different perspective, on smoky days our phones do not stop blowing up from the general public…Social media-wise, being able to communicate any [smoke] relief people might have would be really helpful for us as well.*"

This response further highlights the value of the rapid forecast cycle for the cancellation of products. However, following this point, other participants cautioned the issue of "turf wars" (with other responsible agencies) and needing to be careful about whether/when outputs from products are disseminated to the public from NWS. As one participant explained, "*[We] ran into a sticky situation where we put out graphics from HRRR Smoke and were told from some of their core partners that 'that's our job'.*" This participant went on to describe that "*We still did it, but had to be careful with how we said it - that this is a trend or model, but not a forecast*." One participant expressed that the "*ability to put fire on the landscape in the model, see what it does and run it forward*" would be particularly useful for decision support. "*We would do a 10am conference call on prescribed fire days. [Having the] ability to run this forward and have visual output to show them would be valuable… and could help with go/no-go decisions.*" They later shared that, "*even having smoke visualization and seeing what smoke will do would be really helpful too.*"

Next, the facilitator asked, "**For each product, are the visualizations clear and understandable?**". This question sparked an especially iterative discussion between participants and members of the WoFS-Smoke team. One participant shared that "*[it] depends on the audience we are serving. No one size fits all. While we can clearly read some of this, it could be open to misinterpretation.*" They added that while it can be beneficial to standardize outputs, having the ability to take information and display or tailor it to our respective audiences "*would be best.*" Another echoed this sentiment, stating that "*everybody has a different way of viewing the data*" and suggested the inclusion of a cursor read out. Two additional recommendations and observations included a comment that "*for RFTI, above 8.5 is a pretty similar color. Something worth adjusting,*" and another suggesting the inclusion of an adjective category for RFTI alongside the graphic. To wrap up the focus group discussion, the facilitator asked, "**Is additional information or products that you would like to have leading up to fire weather**

events/days conducive to fire weather that would assist your decision support roles?" Two participants responded:

> "*Layering and compositing various parameters, even if it's just RH and wind speed. Different composite parameters like that…would [also] like to see fuels intelligence data in the background in one form or another.*"

> "*Would be interested in seeing vapor pressure. [I have] kind of been evaluating that at the state level here in [REDACTED] as a potential alternative to RH.*"

No participants provided comments when asked whether there were any remaining comments, suggestions, or questions that they may have at the end of the evaluation.

6. Assessment of Product's Capability to Meet User Needs

Broadly, the current WoFS-Smoke framework addresses a range of known user needs pertaining to fire environment forecasting before, during, and after fire. In particular, the rapid forecast cycling and high-time resolution output was frequently highlighted as valuable information by participants for identifying the likely timing of onset and cessation of critical fire weather patterns (e.g., wind shifts, abrupt changes in RH, and precipitation) that could directly inform situational awareness on the fireline, tactical decision making, and communication with core partners and the public. However, with regards to the timestep of output, the five-minute output was suggested as not necessary by four participants, however the value of 15-30 minute output was referenced throughout the evaluation.

Participants had several recommendations for visualizing information. Participants discussed the addition of a topographical map as a background to model output visualizations, which would be especially useful when paired with the capability to zoom on the web-viewer. Additionally, two participants requested indicators of critical assets (VARs; structures, roads, other infrastructure such as schools or airports) to help interpret how smoke may interact with topography and impact VARs, especially for IMETs deployed to regions they are unfamiliar with. For meeting needs of improved situational awareness on active fire incidents, participants requested the inclusion of relevant (i.e., last 1-2 years) and immediately available fire perimeter overlays.

Forecasting the range of potential timing and magnitude of smoke impacting public health or transportation (including air operations on wildfire incidents) is a major need of the NWS and partner agencies such as air quality managers. By introducing an output of visibility or AQI, the WoFS-Smoke system is well-posed to meet this need. Like many atmospheric models, WoFS-Smoke remains limited by physical parameterizations of smoke emission, transport, and fate, and further development of model physics and coupling with chemistry models will further enhance its capability to meet these needs.

The primary limitation of WoFS-Smoke in meeting needs is the fact that simulations are performed over small domains on demand. This sentiment was expressed by a participant, *"Will I be the chosen one today to have a WoFS-Smoke domain for my area?"* Identifying and acquiring the necessary computational and human resources to operate WoFS-Smoke in a reliable, robust, and consistent manner will be crucial to building trust in the operational user community. If the model is not reliably run over areas of interest, it will not address the suite of needs that it has shown the capability to meet. Lack of dependability will limit the ability to integrate this into a forecaster's workflow.

7. Reflections on the WoFS-Smoke Evaluation

7.1 What Went Well

This was the FWT's first pilot virtual evaluation, and the FWT is always looking to improve. Following the evaluation, the consensus among FWT staff was that the evaluation went smoothly and was successful, highlighting the return on investment of planning and preparation, with a particular value found in the facilitation guide (Appendix B). The value of planning and preparation amongst the FWT team and the WoFS-Smoke team was highlighted by the fact that the evaluation stayed on schedule: the time allotted for each activity was sufficient and no activities ended too early nor dragged on too long. One benefit was the additional scenario that was explored during the focus group time, which also was possible because this scenario was planned for. For data collection purposes, we found that asking participants to write their responses in the virtual meeting chat was a helpful data recording mechanism, and this data was used later when inductively identifying and developing participant response themes.

We found including a range of participant levels of experience with a product (i.e., at least one with substantial familiarity/experience) is beneficial to supplement training materials and topics provided by the product developers. A range of participant levels with a product–but also in terms of operational forecasting more generally–is beneficial to understanding how intuitive, clear, and useful a product is within a segment of end-user groups. Here, having a very familiar participant with WoFS-Smoke but also several participants familiar with the original WoFS system and a range of operational exposure from recently-certified IMETs to forecasters with decades of experience aided our assessment and added value to the evaluation to all involved.

7.2 What Could Be Improved

No evaluation will be perfect; there will always be areas for improvement. Based on lessons learned during the FWT's first virtual evaluation, several process improvements are noted for future evaluations. Early in the evaluation, acquiring participant background information through a simple survey would help assess participant responses over time and for evaluation-specific contexts. Further, having that information on the front end could also have helped us tailor questions/prompts as appropriate. For the training and scenario components, we need to ensure clear explanations from developers to the FWT and from the FWT to participants. The explanations should focus on why a scenario was chosen (fire of known origin and intent, Scenario 1) if not to highlight aspects of the physical outcome (given this was a relatively non-dispersive smoke event). When possible, include a variety of challenging ("edge") as well as classic example ("textbook") cases to demonstrate the capabilities and limitations of the framework and stimulate discussion on situations where the strengths and weaknesses of the product can be highlighted. In the future, a post-evaluation survey, ready for rapid deployment to participants and developers would allow us to gain additional feedback on the tool and our evaluation itself. Subsequent FWT evaluation designs will include a short (5-10 minute) post-evaluation survey with open- and closed-ended questions to be distributed to participants within two weeks following the evaluation (i.e., make available the business day following the evaluation and leave it open for two weeks). For evaluations where the intent is to check how well information was retained rather than product feedback, this survey could be released two weeks (or later) following the evaluation.

8. Summary and Recommendations

A one-day virtual evaluation of the postfireWarn-On-Forecast System for Smoke (WoFS-Smoke) was facilitated by the NOAA Fire Weather Testbed. The evaluation included seven operational forecasters, who are subject matter experts in wildland fire meteorology, and the WoFS-Smoke development team. Several hours of training were provided along with four example scenarios highlighting key products and followed by a focus group discussion. Due to the small participant sample sizes of this pilot study, numeric results may be limited in their generalizability to the broader population of U.S. meteorologists. Nonetheless, the evaluation finds the WoFS-Smoke system to demonstrate substantial capabilities to meet existing needs of operational forecasters working to provide probabilistic information for impact-based decision support (IDSS) to planned, ongoing, and following wildland fires. This can be summarized by the thoughts of one participant who suggested WoFS-Smoke is "*a pretty sophisticated tool to share with incident management teams*" in addition to being used for various other contexts to communicate probabilistic hazard information to NWS core partners in support of tactical decision making. The outputs and ensemble-based information provided by WoFS-Smoke were noted as being particularly valuable to support a range of applications. The FWT found that the WoFS-Smoke system is capable of addressing several needs of wildland fire forecasters and has the potential to substantially contribute to decision support services provided to fire management partners. Three key recommendations from the WoFS-Smoke Evaluation follow:

1. Inclusion of additional outputs pertinent to fire management such as vapor pressure deficit, visibility thresholds, air quality index thresholds, and indicators of dry lightning.

2. Addition of high resolution topography and key critical assets as well as the development of zoom functionality (both for the web viewer but also the ability to export figures).
3. Identifying and acquiring the necessary computational and human resources to operate WoFS-Smoke in a reliable, robust, and consistent manner is vital to build trust in the operational user community and their partners. Lack of dependability ("[When] the whole West was lit up by lightning, am I going to be the chosen one? Can I rely on ever having it? Don't want to invest time if I won't have it when I need it.") will limit the motivation and ability to integrate this into a forecaster's workflow.

Continued development, verification and testing, with focuses on use cases pertaining to tactical decision making and communication of high impact wildland fire-related events during all aspects of the wildland fire cycle (before, during, and following fire) will further elevate the technical readiness of WoFS-Smoke. However, the ultimate usability and ability to deploy WoFS-Smoke into operational environments will require addressing the challenge of acquiring sufficient computational resources necessary to produce consistent simulations in regions of need. The Fire Weather Testbed strongly encourages the WoFS-Smoke team to build upon the existing strengths and address the identified limitations to continue the progression of this product towards operational deployment.

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Appendix A: Agenda

Primary Goal and Motivation: Determine how useful WoFS-Smoke products are to both pre- and active fire decision making processes, and use that information to motivate future WoFS-Smoke development. There are several directions product development can go and WoFS Developers want ideas to help prioritize these.

Specific Questions

1. Pre-Fire: What benefits do high temporal resolution products (30 min update cycle, 5 min output) that indicate a favorable environment for wildfire ignition and spread provide to forecasters fire-weather products and decision support in a 0-6 hour time frame? For example, specifically how would these newly developed products (ensemble-based probability of smoke, lowest level RH, and Red Flag Threat Index) be useful in generating and/or improving a fire-weather based mesoscale discussion, decision support services or other NWS products?

2. Active Fire: Are ensemble forecast smoke plume characteristics useful in forecasting short-term air quality impacts of wildfires in the surrounding environment? Can WoFS output provide guidance for allocating wildfire response resources? Do WoFS forecast products support messaging to fire resources, other emergency managers, or to the public? Developers are interested if WoFS-Smoke forecasts could be used to determine if a significant population center or value-at-risk (e.g., airport, interstate highway, or stadium) is likely to see impacts in the 0-6 hour time from increased smoke production or changes in smoke transport.

Introductions	(Mountain Time)	0900-0920
Training Session		
WoFS model basics		0920-1000
WoFS-Smoke probabilistic output		1000-1020
WoFS-Smoke RFTI + other parameters		1020-1045
Break		1045-1100
Scenarios		
Probability of Smoke Scenario 1 (FASMEE) + Follow-up Discussion		1100-1145
Red Flag Threat Index (RFTI) Scenario 2 (potential fire/growth) + Follow-up Discussion		1145-1230
Lunch		1230-1315
Scenarios Continued		
Rapidly changing fire environment (RH, convection) Scenario 3 + Follow-up Discussion		1315-1400
Break		1400-1415
Focus Group Discussion and Wrap-up + Next Steps		1415-1600

Appendix B: Post-Scenario Discussion and Focus Group Facilitation Guide

Purpose: Determine how useful WoFS-Smoke products are to both pre-fire and active fire decision making processes, and use that information to motivate future WoFS-Smoke development. There are several directions product development can go and WoFS Developers want ideas to help prioritize these.

How useful are WoFS-Smoke products to Forecasters for both pre- and active-fire decision making, issuing NWS Products and providing decision support services?

Format: Virtual focus group discussions (post-scenarios and summative) in which Zach will facilitate and Ben and Jamie will take detailed notes to document responses to each question among scenario evaluation participants.

Attendees: NWS fire weather subject matter experts from a variety of NWS Regions.

Facilitators: Zach Tolby, Benjamin Hatchett, Jamie Vickery, Patrick Skinner, Thomas Jones.

Guests: Included members of the NWS Operations Proving Ground, GSL Weather Informatics and Decision Support Division, and the WoFS-Smoke team.

General Tips for Facilitation:

Ensuring equal time for participation and navigating the "big talkers" - a few ideas:

Round robin approach following each question (rather than letting organically)

Calling on (in a gentle way) participants who haven't talked or who have talked minimally (e.g., "Josh, I'm curious to hear your thoughts on X" or: "I'd like to hear from those of you we haven't gotten perspectives from.")

Clearly explaining the purpose of today's events and the questions we are asking of participants. It's helpful to remind them a couple of times to make sure everyone is on the same page, and that they have a clear understanding of why they were asked to participate.

While it can be beneficial to be conversational, try to let the participants speak as much as possible without providing your own thoughts/opinions.

When you can (especially if it's not a straightforward response), repeat back your understanding in your own words to make sure we are accurately capturing their feedback/insights.

Be mindful of time (Ben and Jamie will help with this), and use this as a motivator for everyone to get through the questions (e.g., "since we have a couple of minutes left, I want to make sure we get to the final question..").

Notes: The names of people responsible for each agenda item are in blue text. Italicized text represents facilitator script and notes for the team. Timing for each agenda item is in orange text. Ben and Jamie can assist with keeping track of the time to make sure we get to all questions.

Run-of-Show

9:00am - 11:00am

Introductions, Training Session, & Break #1 (Zach)

Good morning everyone, thank you for being here..

Brief outline of the day and introductions..

Note: Guests to be active listeners. Limited time..

We could spend all day on any of these questions, we want a short amount of feedback for each topic. If I cut you off, it's just that we need. If you see emojis that's your sign.

Introductions: Zach, Ben, and Jamie. WoFS-Smoke developers, participants, guests.

3 training sessions, time for questions between each training section.

11:00am - 11:45am

Presentation #1 (Pat): Probability of Smoke Scenario (FASMEE) [20 minutes]

Link: https://cbwofs.nssl.noaa.gov/forecast?model=WOFSRun20231010-143717d1&rd=20231010&rt=202310102000&product=totsmoke__ens_mean&sector=wofs

Group Discussion (Zach) [25 minutes] Ben and Jamie to put questions in the chat after each one is read by Zach.

As mentioned at the outset of today's workshop, following each presentation we have a few questions that we would like to put forward for group discussion to gather your thoughts and feedback about the products as well as to learn more about critical decisions you support and information needs you have that would better support you in your roles. We will ask many of the same questions following each scenario to capture your feedback.

To begin, we want to understand (based on your experience), what forecast timescales are often most critical for smoke decision support? OR: What are the most critical decision points or time frames for smoke products and decision support? Hours/Days?

How familiar were you with the WoFS Probability of Smoke product before today?

Does the Probability of Smoke exceedance product provide additional or more timely information then other existing products? In other words, does this fill an information gap?

Next we would like to ask specifically about timing of output release and updates to the product. What, if anything, is the utility of the following as it relates to issuing NWS smoke related products or providing decision support for smoke:

1) 5 min timestep of output?

2) 30 min update cycle?

3) How does the Probability of Smoke product align with decision timelines?

11:45 am - 12:30 pm

Presentation #2 (Thomas): Red Flag Threat Index (RFTI) Scenario (potential ignition/spread) [20 minutes]

Link:https://wof.nssl.noaa.gov/research/?model=wofs_research&case=20220422_smoke_3km&rd=20220422&rt=2100&product=rh_ll__ens_mean&sector=wofs

Group Discussion (Zach) [25 minutes] Ben and Jamie to put questions in the chat after each one is read by Zach.

Following the same format as the last discussion, we want to begin by asking you:

To begin, we want to understand (based on your experience), what forecast timescales are often most critical for Red Flag Watches and Warning decision support? OR: What are the most critical decision points or time frames for Red Flag Watches and Warning products and decision support? Hours/Days?

How familiar were you with the Red Flag Threat Index product before today?

Does the Red Flag Threat Index provide additional or more timely information then other existing products? In other words, does this fill an information gap?

Next we would like to ask specifically about timing of output release and updates to the product. What, if anything, is the utility of the following as it relates to issuing NWS Red Flag related products or providing decision support for elevated fire weather concerns:

1) 5 min timestep of output?

2) 30 min update cycle?

3) How does the Red Flag Threat Index align with decision timelines?

****LUNCH BREAK 12:30 pm -1:15 pm****

1:15 pm - 2:00 pm

Presentation #3 (Thomas): Rapidly changing fire environment (RH, convection) Scenario [20 minutes]

Link:https://wof.nssl.noaa.gov/research/?model=wofs_research&case=20220317_smoke_3km&rd=20220317&rt=2100&product=rh_ll__ens_mean&sector=wofs

Group Discussion (Zach) [25 minutes] Ben and Jamie to put questions in the chat after each one is read by Zach.

To begin, we want to understand (based on your experience), what forecast timescales are often most critical for rapid changes in RH or convection decision support? OR: What are the most critical decision points or time frames for rapid changes in RH or convection products and decision support? Minutes/hours?

How familiar were you with the WoFS RH and convection products before today?

Does the WoFS RH and convection provide additional or more timely information then other existing products? In other words, does this fill an information gap?

Next we would like to ask specifically about timing of output release and updates to the product. What, if anything, is the utility of the following as it relates to issuing NWS products or providing decision support for rapidly changing fire environment:

1) 5 min timestep of output?

2) 30 min update cycle?

3) How does the WoFS RH and convection align with decision timelines?

****BREAK 2:00pm - 2:15pm****

2:15pm - 3:45pm

Summative Focus Group Discussion (Zach):

For the remainder of today's WoFS-Smoke Evaluation Workshop, we have a set of questions we would like for you to reflect upon and discuss. As we explained at the outset of this workshop, your participation and responses will provide us with valuable feedback to inform the refinement, development, and application of WoFS-Smoke products to support you in your decision support roles. There will also be an opportunity to provide feedback via a Google form following the workshop about the training and any additional thoughts that may arise regarding the products we shared with you today.

[Note: Suggest repeating what participants shared following the first scenario to verify that their decision points/critical time frames are captured. Jamie and Ben to synthesize over lunch to give to Zach. Ben and Jamie to put questions in the chat after each one is read by Zach.]

1. To start off, we want to share back what you explained to us during the first group discussion to ensure that we appropriately captured your critical decision points/time frames.

   Have Ben/Jamie summarize findings from morning scenarios (e.g., levels of initial familiarity, what WoFS provides, timescales). Is this accurate? Or is there anything you would add or change?

2. In your roles as forecasters, what decisions or types of decisions, if any, does the product inform in the context of this scenario?
   a. Probability of Smoke exceedance
   b. Red Flag Threat
   c. RH/Convection
3. What is the WoFS system not currently capable of resolving or predicting as it relates to smoke forecasting? What capabilities could be added that would be helpful?

   a. Probability of Smoke exceedance
   b. Red Flag Threat
   c. RH/Convection
   d. Prompt: Could be model/forecast-related (forecast time horizon, ability to zoom on map) or technical (i.e., web-viewer crashes, slow responses, non-intuitive usability);

    e. [E.g., Add more critical assets/map options or focus on outputs (note thresholds will be next): what variables are missing?]

4. Across the products we shared with you today, we presented various thresholds and variables designed to inform decision support that you provide during wildfires or days conducive to fire weather. We would like to dig into these thresholds and variables to determine whether they are useful or actionable in your roles as forecasters providing decision support.

    a. For the Probability of Smoke Exceedance product, are the thresholds for smoke actionable? (>25 $\mu g/m^2$, $50\mu g/m^2$, etc)

    b. For the Red Flag Threat Index, does the index make sense, can it be useful in IDSS?

    c. Rapidly Changing Fire Environment: What other WoFS variables are most useful?

5. How, if at all, would the availability of the above WoFS-Smoke products in real-time change what you do, or what products you issue or decision support products you could provide?

6. [Time permitting] For each product: Are the visualizations clear and understandable? [Prompt: Ask about fontsize, colors, map layers and download capabilities]

    a. Probability of Smoke exceedance
    b. Red Flag Threat
    c. RH/Convection

7. Is there additional information or are there products that you would like to have leading up to fire weather events/days conducive to fire weather that would assist your decision support roles?

8. Before we conclude this focus group, are there any other comments, suggestions, or questions that you have?

3:40 pm - 4:00 pm

Wrap-up and Next Steps

Review the day (Zach), what we came to do, what we did, a few highlights, and now we'll hear a few thoughts from the WoFS Team

(Zach) Closing thoughts (thank everyone: participants, WoFS team, OPG, our WIDS/FWT team) and provide some guidance as to what to expect next.

Closing thoughts from WoFS Team (e.g., thank yous and appreciation shout-outs from Thomas, Patrick)