MOUNTAIN RAIN OR SNOW: ENHANCING AVALANCHE FORECASTING WITH REAL-TIME PRECIPITATION PHASE DATA

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ABSTRACT: Both minor and major rain-on-snow events can create a weak layer in the snowpack or reduce snowpack stability, increasing the potential for avalanche conditions. Understanding and monitoring rain-on-snow events is crucial for avalanche forecasters to assess the stability of the snowpack. But for mountainous regions, forecasting rain vs. snow (precipitation phase) is not as simple as knowing whether the air temperature is above or below freezing. The atmospheric temperature profile, humidity, surface pressure, warm air advection, cold air damming, and other microclimate phenomena are some of the reasons that precipitation phase forecasting remains a challenge. These challenges are amplified in mountainous regions where terrain shapes local and regional weather patterns. To address these challenges, we developed the Mountain Rain or Snow participatory science project and recruited over 1,300 observers across the US to build a precipitation phase validation dataset focused on eight regions. Across these eight regions of the continental US, we have collected over 78,000 observations to-date. These observations show real-time changes in precipitation phase, which can help forecasters validate the occurrence of both minor rain-on-snow events and high-impact rain-on-snow events that can rapidly change snowpack conditions, increase snow load, and lead to snowpack instability. By providing real-time precipitation phase observations, the Mountain Rain or Snow dataset can help forecasters better understand and predict these critical changes in snowpack conditions, ultimately improving avalanche forecasting and safety. In this pilot study, we explore the application of Mountain Rain or Snow data for avalanche forecasting by comparing probabilistic forecast snow levels to observed precipitation phase, analyzing the correlation between precipitation phase observations and subsequent avalanche activity, and studying the effectiveness of using real-time precipitation phase data from the Mountain Rain or Snow application in the decision-making process.

Keywords: snow level, probabilistic forecast, precipitation phase, Sierra Nevada

1. INTRODUCTION

Accurate snow level forecasting is a critical component of avalanche and weather forecasting in mountains. The ability to predict snow levels allows for more reliable assessments of avalanche hazard and subsequent risk, which in turn enables better decision-making for those who live, work, and recreate in these areas. In recent years, the introduction of probabilistic forecasts into the available suite of forecast products in the United States from the National Weather Service (NWS) has added value to snow level predictions, offering a range of possible outcomes rather than a single deterministic prediction Joslyn and LeClerc (2012). This approach enhances the reliability of forecasts by providing a more nuanced understanding of potential snow and avalanche outcomes.

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However, despite these advancements, one of the ongoing challenges in hydrometeorology is the lack of comprehensive and high-quality observations to validate these forecasts. Traditional meteorological observation networks are often sparse and limited in coverage, particularly in remote and/or high-altitude regions where snow and avalanche risks are most pronounced. This gap in observational data hinders the ability to accurately verify and improve forecasting models.

Avalanches result from numerous formation and release processes causing the snowpack's load on a slope to exceed its strength (Schweizer et al., 2003). During winter storm events, precipitation and wind transport often produce rapid and/or gradual uniform loading. While snowfall and wind-driven transport are sufficient to produce natural or contribute to human-triggered avalanches, precipitation falling as rain or as increasingly dense snow ('upside down storms'; e.g., Hatchett et al. (2016)) can also lead to reduced snow stability. Under these warm or rapidly warming scenarios, knowledge of the location and trend of the rain-snow transition elevation aids haz-

ard assessment. However, a range of temperatures can result in rain or snow (Jennings et al., 2023) making it difficult for sparse observational networks to help forecasters identify precipitation phases.
To address this challenge, we leverage data collected by the Mountain Rain or Snow (MRoS) citizen science project (Collins et al., 2023; Jennings et al., 2023; Arienzo et al., 2021). This initiative harnesses the power of weather observers to monitor the phase of precipitation—whether it is rain, snow, or a wintery mix—at their locations. By engaging observers in data collection, the project aims to significantly expand the geographical coverage and frequency of precipitation phase observations. Here, we provide four examples of how this novel dataset can be used to validate for snow level forecasts, ultimately contributing to inform avalanche hazard forecasts. This study takes a unique approach to analyzing data from three different sources: NWS the National Blend of Models, avalanche observations, and observations of precipitation phase submitted through participatory science methods.

2. DATA AND METHODS

2.1 Study Area

This study focuses on the greater Lake Tahoe area of the Central Sierra Nevada in California and Nevada (western United States). More specifically, we constrain our study to include MRoS observations within and to the west and east of the Sierra Avalanche Center forecast area, located between 1,600-3,300 m. (Figure 1). We selected two 2.5 km forecast points from the National Digital Forecast Database near mountain passes: Donner Pass to the north of Lake Tahoe at 2,128 m and Echo Peak to the south at 2,499 m. The median precipitation at each location is 65.8 mm and 53.7 mm and the median peak SWE is 37.2 mm and 40.3 mm respectively (US Department of Agriculture, 2024). Generally precipitation increases with elevation and decreases with distance east of the crest due to rain shadow effects; the Carson Range (a sub-range of the Sierra Nevada on the eastern margin of the SAC forecast area) is higher, colder, and drier and thus is characterized by a more intermountain snow climate than the Sierra Nevada crest. The forecast area commonly experiences rain-on-snow events and median snow liquid ratios of 9:1, though variance in snow-liquid ratios occur both within storms and across the cool season (van Cleave and Rasch, 2013).

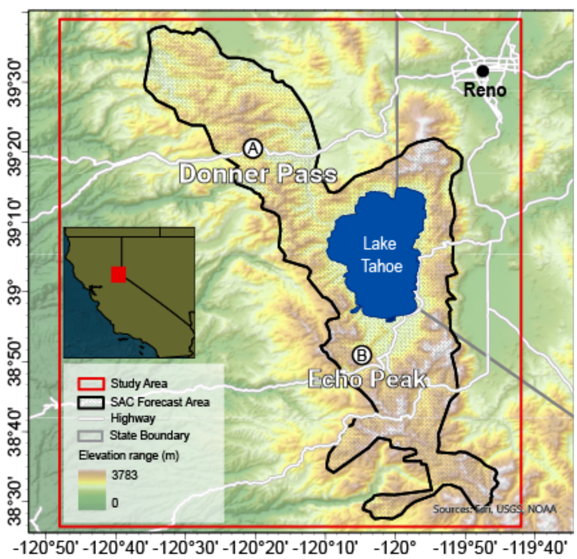


Figure 1: Project study area (red box) including the Sierra Avalanche Center forecast area (black outline) and two National Digital Forecast Database 2.5 km forecast points at Donner Pass (A) and Echo Peak (B).

2.2 Data

2.2.1 National Weather Service probabilistic snow level forecasts

We selected the National Blend of Models (NBM) probabilistic forecast data product to support the United States' National Weather Service (NWS) transition towards probabilistic forecast information to core partners. Snow level forecasts, based on the height of the 0.5°C wet bulb temperature, were downloaded from NOAA via the Amazon Web Services (`https://registry.opendata.aws/noaa-nbm`). We selected a 48-hour snow level forecast from two locations on the crest of the Sierra Nevada: 1) Donner Pass and 2) Echo Peak, located to the north and south of Lake Tahoe respectively (Figure 1). A portion of this work used code generously provided by Brian Blaylock's Herbie python package Blaylock, 2024.

2.2.2 Sierra Avalanche Center Avalanche Observations

Snow and avalanche observations are made by Sierra Avalanche Center forecasters and professional observers and contributed by members of the public. Observations are shared on the SAC

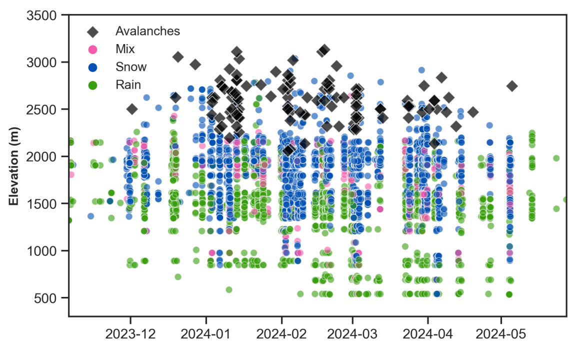


Figure 2: Comparison of the elevation of SAC archived avalanches and MRoS precipitation phase for mixed (pink), snow (blue), and rain (green) from 1 November 2023 through 30 May 2024.

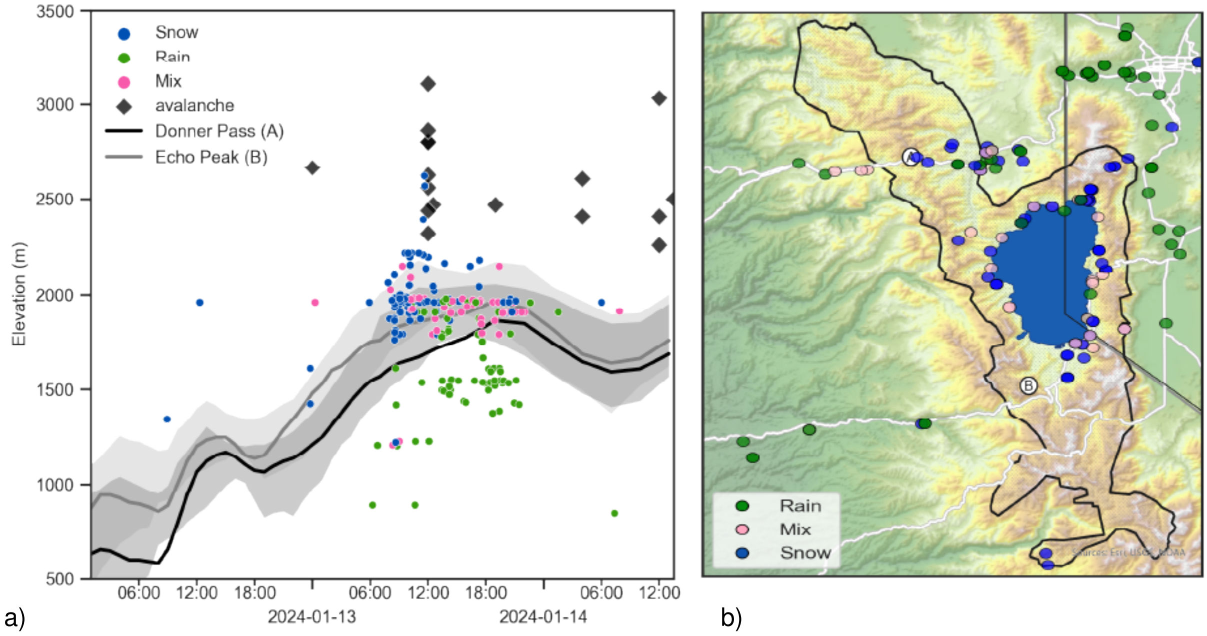


Figure 3: Case study plot for 12-14 January 2024. (A) Time series plot of the deterministic snow level forecast for Donner Pass (black) and Echo Peak (grey) with shaded 10^{th} and 90^{th} percentiles compared with SAC archived avalanches (black diamond) and MRoS precipitation phase for mixed (pink), snow (blue), and rain (green). (B) A map of all MRoS observations in the sudy area durign this even.

website (`https://www.sierraavalanchecenter.org`). A total of 111 avalanches were reported on 51 Days from 1 November 2023 through 30 May 2024 (Figure 2).

2.2.3 MRoS Observations

The MRoS dataset has over 78,000 observations across the United States from 2020-2024. The processed dataset used in this study includes the time stamped MRoS observation latitude and longitude and observed precipitation phase coupled with ancillary elevation and modeled meteorological outputs (Heggli, 2024). All observations are quality controlled using similar methods detailed in Jennings et al. (2023). In short, and for the purposes of this study, duplicate observations from the same user were flagged, and only the first observation of the duplicate set was kept in the dataset. Within the greater Lake Tahoe area, a total of 7,118 observations were reported from 1 November 2023 through 30 May 2024, ranging from 532 m to 3035 m in elevation.

3. RESULTS AND DISCUSSION

Our study focuses on four avalanche cycles during the 2023-2024 winter. Each case study will review the times series of the determistic snow level forecast, the 10^{th} and 90^{th} percentile from the NBM snow level forecast, the MRoS precipitation phase observations, and the location and timing of avalanches reported to the Sierra Avalanche Center.

3.1 Event 1: 12-14 January 2024

The first case study is an "upside down" storm (Hatchett et al., 2016) where snow levels rose during the storm, and 17 avalanches were reported above the snow level (Figure 3). The forecast snow levels were higher at Echo Peak than Donner Pass with peak snow level forecast at 1967 m and 1863 m respectively. However, when compared to the 200 MRoS observations during this event, the snow level forecast was lower than what was observed, with rain observed as high as 1977 m and mixed phase observed at 2144 m. Probabilistic 10^{th} and 90^{th} percentiles captured 96.7% observations correctly with only six outliers. The forecast captured the observed rise in snow levels during the storm. Rising snow levels indicate a sign of instability due to rapidly rising temperatures which, combined with continued snowfall and wind, facilitate the formation of storm slabs and density changes in newly deposited snow.

3.2 Event 2: 3-5 February 2024

The second case study is another "upside down" storm (Hatchett et al., 2016) and 13 avalanches were reported during the storm cycle. Of the 370 MRoS observations submitted during this storm, 364 were located on the leeside of the Sierra Nevada (Figure 4). Similar to the first case study, the forecast snow levels are slightly higher at Echo Peak compared to Donner Pass with a rapid rise in snow level to 2007 m and 1935 m respectively. However, around 1,500 m elevation the MRoS observations do not validate the snow level rise. Upon

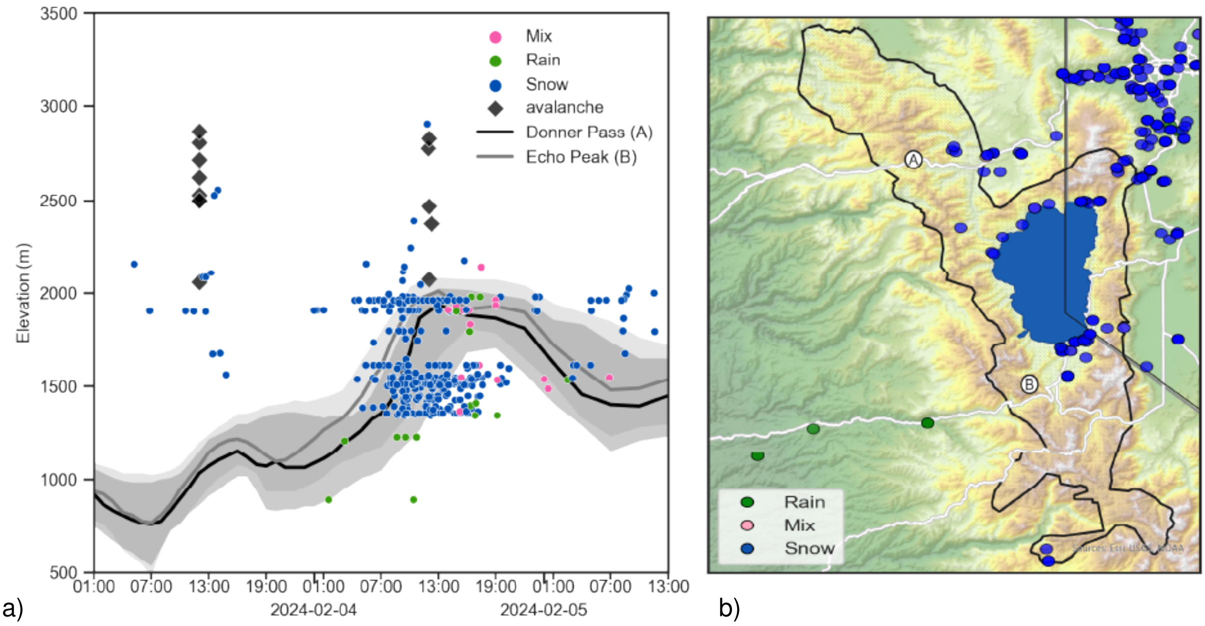


Figure 4: Case study plot for 3-5 February 2024. (A) Time series plot of the deterministic snow level forecast for Donner Pass (black) and Echo Peak (grey) with shaded 10^{th} and 90^{th} percentiles compared with SAC archived avalanches (black diamond) and MRoS precipitation phase for mixed (pink), snow (blue), and rain (green). (B) A map of all MRoS observations in the sudy area durign this even.

further inspection and with knowledge of the terrain we know that 1,500 m is below lake level, and with only 6 observations on the windward side of the Sierra Nevada, all of these other observations are on the leeside of the Sierra Nevada where cold air can be trapped in valleys. The overrunning warmer air can lead to rain at higher elevations while mixed or frozen precipitation occurs at lower elevations until the cold air is mixed out of the basins by wind. The MRoS observations around 2,000 m, which is slightly above the elevation of Lake Tahoe and where the communities are located, capture the transition from snow to rain with just a single mixed phase observation above the 90^{th} percentile.

3.3 Event 3: 17-20 February 2024

The third case study had snow levels that hovered around 2,000 m (Figure 5). In contrast to the previous event, the forecast snow levels for each location fluctuate above and below each other. A total of 6 avalanches were reported during this storm cycle, all at elevations well above the rain/snow transition elevation. There were 214 MRoS observations during this event. In the afternoon and evening of 17 February there is agreement between the forecast and observed snow levels that track the slight drop in snow level, with all but one mixed phase observation occurring within the 10^{th} and 90^{th} percentile range. During the next wave of MRoS observations, the snow level is forecast to be higher than the observed snow and mixed phase observations. The map in Figure 5 shows that the majority of the MRoS observations were made north of Lake Tahoe and the snow level tracks the 10^{th} percentile forecast from Donner Pass. In this case, rather than communicating a deterministic snow level forecast without any expression of uncertainty, the probabilistic forecast communicates the range of possible snow levels. When coupled with the MRoS observations the outcome can be validated in real-time.

3.4 Event 4: 29 February - 3 March 2024

The fourth and final case study contrasts the other three case studies with dropping, but still variable, snow levels during the storm. A total of 9 avalanches were reported from 29 February through 3 March (Figure 6). This classic Sierra Nevada snow storm generated 191 cm of snowfall at the UC Berkeley Central Sierra Snow Laboratory in Soda Springs, California which is located on the windward side of the mountain just 50 m below Donner Pass. Consistent with the first two case studies, snow levels at Echo Peak were forecast higher than Donner Pass. There were a total of 809 MRoS observations during the 48-hour period and 93% of the observations were made from the leeside of the Sierra Nevada, to the east of the forecast points. At the onset of the storm the observed snow level was within the 10^{th} and 90^{th} percentiles. This is illustrated by the cluster of mixed phase observations between 07:00 and 13:00 on 29 February. The snow level drops rapidly (640 m in 10 hours) but MRoS observations show that snow levels stayed higher than forecast, though still within the 10^{th} and 90^{th} forecast range. During the morning of 1 March, snow levels were forecast to rise and MRoS Observations showed that the snow levels did rise, but a little earlier than what was forecast. However, there appears

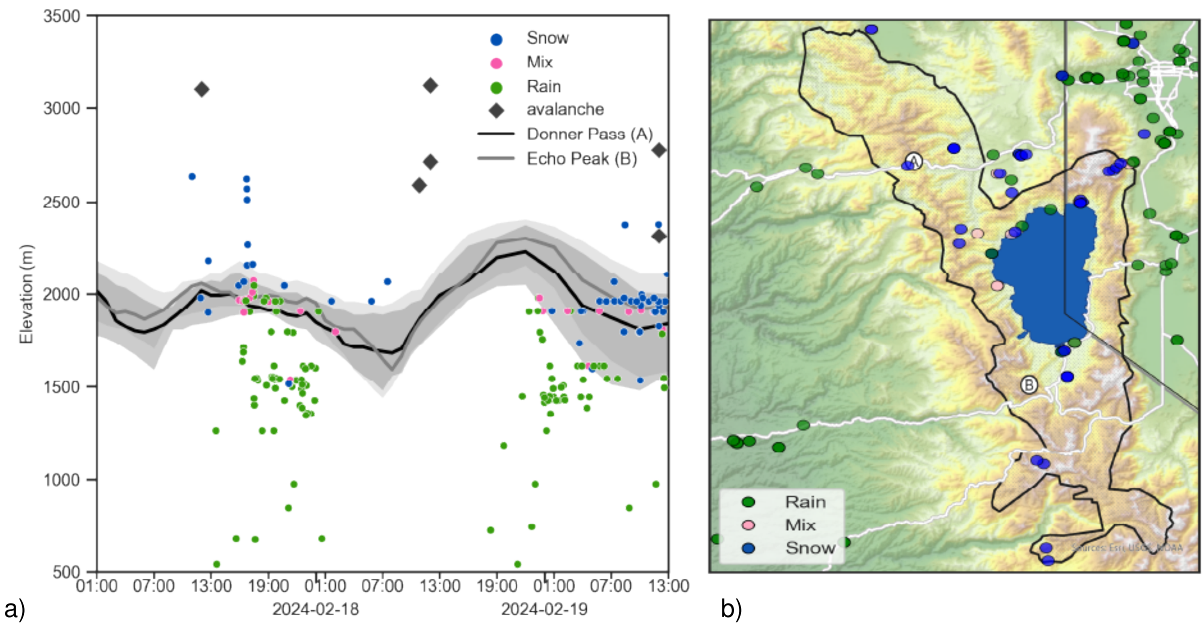


Figure 5: Case study plot for 17-20 February 2024. (A) Time series plot of the deterministic snow level forecast for Donner Pass (black) and Echo Peak (grey) with shaded 10^{th} and 90^{th} percentiles compared with SAC archived avalanches (black diamond) and MRoS precipitation phase for mixed (pink), snow (blue), and rain (green). (B) A map of all MRoS observations in the sudy area durign this even.

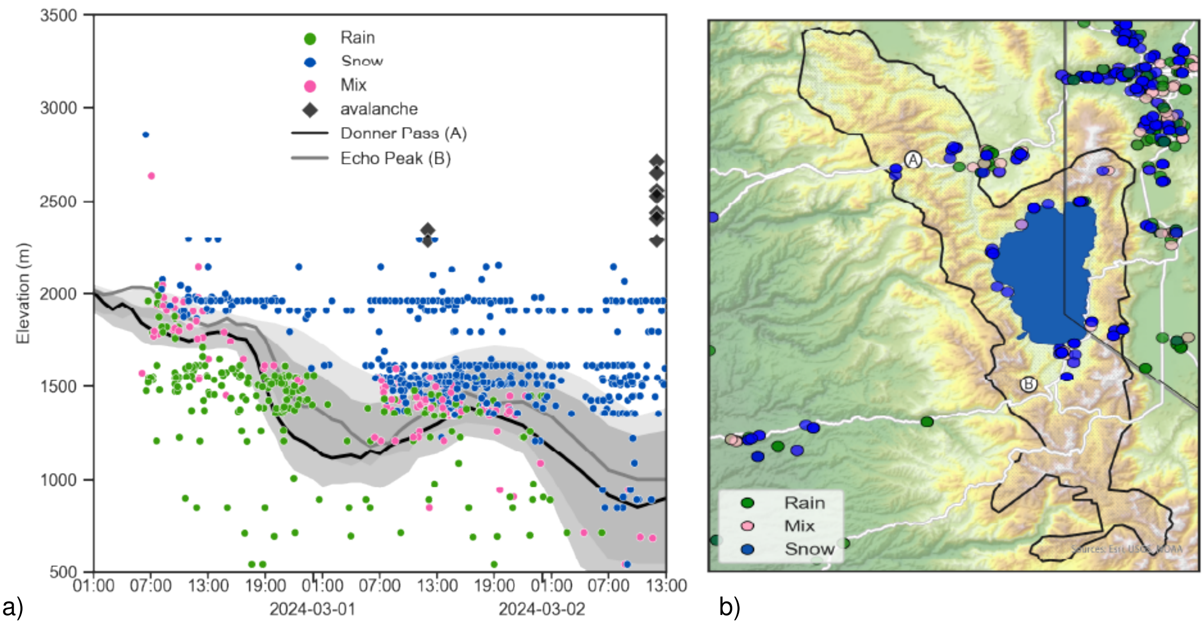
to be disagreement between MRoS observations on where exactly the snow level is as the system moves through. The MRoS observations highlight the importance of the topography for precipitation phase since 7% of these observations are on the windward side of the mountain and 45% are in the valley to the east of the Sierra Nevada, which could lead to disagreement in the rain-snow transition.

3.5 The value of MRoS observations

In these case studies the MRoS observations are typically made in the communities and mountain passes below avalanche terrain. For this region, the MRoS observations are beneficial to validate snow level forecasts that are used for avalanche forecasting. The value of the MRoS observations is amplified when coupled with probabilistic forecast information that provides additional detail about the range of snow level with the associated uncertainty. Providing probabilistic information can increase trust among users (Ripberger et al., 2022) and also allows decision makers to consider the true range of possible outcomes and their potential implications. Communicating the full range of uncertainties is especially important with avalanche forecasting when considering individual risk tolerances or perceived risk from a deterministic forecast that may not include any communication of a low-chance high-risk scenario like what is provided with probabilistic forecast information. When probabilistic forecast information is coupled with real-time observations to validate the forecast, there is an opportunity to adjust decisions on the fly or more confidently take action on the actual outcome, having prepared mentally for the full range of scenarios.

Observations of precipitation phase made at the elevation where avalanches occurred or are possible could inform avalanche forecasting when those observations are. For example, in a scenario where surface hoar is widespread but these observations can confirm that it rained at the elevation band of the surface hoar (thus destroying the surface hoar), it would lead to a very different avalanche forecast than if it was unclear what phase the precipitation was at that elevation. Another way these observations could provide additional insight to enhance avanche foecasting would be if the observations verify rainfall over fresh snow, indicating the likely formation of a denser surface layer where the density change (and change in crystal habit) creates a potential weak layer. If the rainfall results in preferential flow paths, liquid water can be routed to a buried crust where lubrication may reduce snowpack strength. Rain-on-snow can also re-freeze to produce a surface crust that can act as a bed surface or eventually form a weak layer upon subsequent burial by additional snow. Conversely, snowfall observations at elevations below the forecast snow level imply snow accumulation and increases in avalanche hazard at elevations that may not have been identified as problem areas.

Rising snow levels (upside down storms) indicate not only change of precipitation phase but also increasing snow density (liquid to snow ratios) and greater precipitation intensities (rain falls faster than snow falls) that elevate concerns for storm slab avalanche problems. The timing and location of



a) b)

Figure 6: Case study plot for 29 February - 3 March 2024. (A) Time series plot of the deterministic snow level forecast for Donner Pass (black) and Echo Peak (grey) with shaded 10^{th} and 90^{th} percentiles compared with SAC archived avalanches (black diamond) and MRoS precipitation phase for mixed (pink), snow (blue), and rain (green). (B) A map of all MRoS observations in the sudy area durign this even.

precipitation phase changes can alert forecasters to the onset (or delay) of frontal passage. Even short durations or trace quantities of rainfall can produce crusts that later form failure planes (bed surfaces) or weak layers and create difficult travel scenarios; knowing the elevations and/or regions where rain occurred can inform hazard forecasts and travel itineraries. Consider a scenario where 60 cm of new snow fell over a 24 hour period. Storm that produced 60 cm of new snow could produce widespread avalanche activity or none at all depending in part on changes in the snow level and precipitation intensity during the event. If the snow falls at a consistent temperature (no change in snow level) or if snow levels are droping throughout the event building up the snow "right side up" with the least dense snow on top, then perhaps there would be no storm slab layering within the 60 cm of new snow. However, if the storm begins with 15 cm of cold snow in the first 12 hours and then 45 cm of warmer, denser, heavier snow in the final 12 hours the 60 cm of new snow might have a problematic storm slab layering due to the "upside down" composition caused by rising snow levels.

While these case studies provide examples of how precipitation phase observations can be valuable to validate snow level forecasts, it will be important to compare observations that are representative of the forecast area to focus on the microclimates within complex mountain terrain. The snow level forecasts and MRoS observations can provide indications of changing new snow density but we cannot know what is happening everywhere. These observations rely on human observers, which reduces issues with data quality from sensors, but relies on community members to be traveling in diverse areas and actively reporting their observations. Fortunately, as the MRoS observer network grows, so will the diversity of observations across regions.

4. SUMMARY

Increasing the accuracy of weather forecast through the validation of precipitation phase, particularly for rain on snow and rising snow levels, can lead to a more precise avalanche forecast. This study takes a unique approach of employing the novel MRoS participatory science data set to validate probabilistic snow level forecast during periods of increased avalanche activity. The MRoS data set can enhance the value of probabilistic snow level forecast by validating the observed snow level in real-time and can verify elevation bands that experienced rain on snow, which in return provides additional insight for the avalanche forecast, benefiting NWS core partners and members of the community simultaneously.

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