ABSTRACT: Predicting avalanche danger depends on knowledge of the existing snowpack structure and the current and forecasted weather conditions. In remote and data sparse areas this information can be difficult, if not impossible, to obtain, increasing the uncertainty and challenge of avalanche forecasting. In this study, we coupled the Weather Research and Forecasting (WRF) model with the snow cover model SNOWPACK to simulate the evolution of the snow structure for several mountainous locations throughout western Montana, USA during the 2014-2015 and 2015-2016 winter seasons. We then compared the model output to manual snow profiles and snow and avalanche observations to assess the quantitative and qualitative accuracy of several snowpack parameters (grain form, grain size, density, stratigraphy, etc.) during significant avalanche episodes. At our study sites, the WRF model tended to over-forecast precipitation and wind, which impacted the accuracy of the simulated snow depths and SWE throughout most of the study period. Despite this, the SNOWPACK-WRF model chain managed to approximate the snowpack stratigraphy observed throughout the two seasons including early season faceted snow, the formation of various melt-freeze crusts, the spring transition to an isothermal snowpack, and the general snowpack structure during several significant avalanche events. Interestingly, the SNOWPACK-WRF simulation was statistically comparable in accuracy to a SNOWPACK simulation driven with locally observed weather data. Overall, the model chain showed potential as a useful tool for avalanche forecasting, but advances in numerical weather and avalanche models will be necessary for widespread acceptance and use in the snow and avalanche industry.

KEYWORDS: snow cover models, weather models, snowpack, wrf, avalanche forecasting

1. INTRODUCTION

Avalanche forecasters use an assortment of data to predict avalanche danger including field observations of snow stratigraphy, structure, and stability (LaChapelle, 1980). Observed snow cover and stability data usually comes in the form of manual snow pit observations and stability tests from areas where the terrain is relatively safe and accessible. Therefore, observed snow cover information is not always available due to poor weather conditions, inaccessible terrain, avalanche danger, and/or the remoteness of a location, leading to a data gap for many backcountry avalanche forecast locations.

The 1-D numerical snow cover model, SNOWPACK, is a relatively new and evolving tool that has been used over the past 15-20 years to provide detailed and continuous snow cover information for operational avalanche forecasting, augmenting the necessity for manual snow cover observations (Lehning et al., 1999). SNOWPACK uses meteorological input data to simulate the structure and evolution of seasonal mountain snow cover. Typically, SNOWPACK is driven with locally observed weather data from remote weather stations. This in turn limits employment of SNOWPACK to locations with instrumentation that can measure all required meteorological data. Additionally, weather stations can be cost prohibitive and unreliable, which can degrade the effectiveness, timeliness, and reliability of SNOWPACK simulations for use in real world operations.

As an alternative to in-situ weather data, forecasted weather data from a numerical weather prediction (NWP) model can be used as input to drive SNOWPACK. The horizontal resolution of NWP models has dramatically increased in recent years,
making prediction of microscale weather phenomena in complex mountainous terrain viable. NWP models can provide all necessary meteorological parameters to run SNOWPACK with continual spatial and temporal coverage and require minimal cost and maintenance to operate. Several studies have coupled NWP models with SNOWPACK including Bellaire et al. (2011), Bellaire and Jamieson (2013), and Horton and Jamieson (2016), who all coupled SNOWPACK with the Canadian GEM model in southwestern Canada and evaluated the simulation of new snow amounts and critical weak layers.

To date, only one study has focused on using SNOWPACK in the U.S. (Lundy et al., 2001) and none have used a coupled NWP-SNOWPACK model chain. In this study, we coupled the SNOWPACK model with the U.S. developed Weather Research and Forecasting (WRF) model over the course of two winters to simulate snowpack structure and avalanche conditions for several locations across western Montana. The goal of this study is to assess the ability of a coupled NWP-SNOWPACK system to forecast avalanche potential in an intermountain U.S. snow climate and to determine whether or not the system would be a viable tool for operational avalanche forecasting in the future.

2. METHODS

We conducted this study over the course of two winters between 2014-2016. During the 2014/15 winter, we ran SNOWPACK for a single location using both observed and forecasted meteorological data. Our primary focus for this first season was on evaluating the quantitative accuracy of the SNOWPACK model against field observations as well as comparing the accuracy of a simulated snowpack using forecasted versus observed weather data input. During the 2015/16 winter, snow cover was simulated for 5 locations across western Montana using only WRF forecasted weather input. We used an event-based qualitative assessment and evaluated the ability of a coupled SNOWPACK-WRF model to simulate the observed snowpack structure and stability during several significant avalanche episodes across various mountain ranges.

2.1 Study Area and Field Data

During the 2014/15 season, the study was conducted at the Bridger Bowl ski area in southwest Montana, about 19 km northeast of the city of Bozeman, Montana (Fig. 1). A study plot was constructed at the ski area near the edge of a meadow at the top of the Alpine lift, adjacent to the Alpine weather station at an elevation of 2255 m a.s.l. Over the course of the winter, 19 full snow profiles were excavated at the site, which recorded density, temperature, hand hardness, and grain size and type at 10 cm intervals. Additionally, total SWE was measured at the study plot during each field day.

During the 2015/16 season, the study area expanded to include Lolo Pass in the Bitterroot Range (1597 m a.s.l), Stuart Mountain in the Rattlesnake Range (2255 m a.s.l), Noisy Basin in the Swan Range (1841 m a.s.l), and Big Mountain Summit in the Whitefish Range (2053 m a.s.l) (Fig. 1). Field data included public and professional snow and avalanche observations from 3 regional avalanche forecast centers, which covered each of the 5 locations.

Fig. 1: Map of Montana showing the location of the 5 study sites used during both seasons (white circles). Nearby cities are also included for reference (yellow diamonds).
2.2 Observed Meteorological Data Input

During the 2014/15 season, SNOWPACK was forced with observed meteorological data from two co-located weather stations at the Alpine study plot. A weather station (MSU weather station) was constructed at the edge of the study plot and provided hourly measurements of air temperature (TA), relative humidity (RH), snow depth (HS), 50 cm snow depth temperature (T50), incoming shortwave radiation (ISWR), outgoing shortwave radiation (OSWR), incoming longwave radiation (ILWR), and snow surface temperature (TSS). Bridger Bowl’s Alpine weather station, just 12 m north, provided hourly measurements of wind speed (VW) and gusts (VW Max) as well as liquid precipitation (rain or melted snow) (P). All parameters listed above were used as input to drive the SNOWPACK-OBS simulation during the 2014/15 season.

2.3 Forecasted Meteorological Data Input

For both seasons, a high-resolution version of the Advanced Research WRF (WRF-ARW) model was set-up and run by the National Weather Service Forecast Office in Missoula, Montana. WRF was run at a 2 km resolution during the 2014/15 season and at a 3 km resolution during the 2015/16 season. Each day at 1200 UTC, a 36-hour (2014/15 season), or 72-hour (2015/16 season), forecast was produced and the first 24-hours of each forecast were used to drive the SNOWPACK model. Output parameters used as input included hourly TA, RH, VW and VW Max, ISWR, OSWR, ILWR, TSS, and P. Since the elevation of the closest WRF grid point was usually different than that of the desired location, the forecasted air temperature was adjusted by -5 °C/km for each location to match the desired elevation. Unless otherwise noted, all other forecasted values remained uncorrected.

2.4 SNOWPACK Model Setup

In this study, we used SNOWPACK version 3.2, released in August 2014. The output time-step was set to 60 min in order to match the time-step of the measured and forecasted weather data. SNOWPACK was run beginning with the first snowfall, around Nov 1, through the snow melt-out date for each site, which varied for each location but was typically in early to mid June. Atmospheric stability was parameterized using the Monin-Obukhov bulk formulation with an aerodynamic roughness length of 2x10^-3 m. The energy exchange at the snow surface was calculated using the measured/forecasted snow surface temperature as a Dirichlet boundary condition for surface temperatures below -1°C. Otherwise, a Neumann boundary condition was utilized (Lehning et al., 2002). Other default SNOWPACK parameterizations included a fixed new snow grain size of 0.3 mm, and a rain/snow threshold of +1.2 °C.

2.5 Comparison of Forecasted and Observed Data

During the 2014/15 season, both the WRF and SNOWPACK models were validated quantitatively against observed data using several different statistical measures of model error (e.g., bias and mean absolute error) as well as accuracy. Accuracy was determined by a ratio method, where either the observed or modeled value (smaller value) was divided by the other (larger value). The ratio, bounded between 0 and 1, was then converted to a percentage to achieve the final accuracy score. In order to validate variables from the snow profiles (e.g., temperature, density, grain size and shape, and hand hardness), a normalization method was employed in order to match and compare specific layers where profiles had different depths. This was needed as the HS was typically over-forecasted at the study site. Layer heights were converted to a relative depth (i.e., percentage of total depth) and the layers in the observed profile were compared against the layers in the modeled profile that had the closest relative depth.

To compare modeled and observed grain type, an agreement score method was utilized, as described by Lehning et al. (2001). This method utilizes a grain type agreement matrix which provides an agreement score, bounded between 0 and 1, for all possible combinations of the 8 grain types used in SNOWPACK. The final agreement score for each layer is determined by taking into account the agreement between the primary and secondary grain types. For a full explanation of the calculations used in this method, please refer to Lehning et al. (2001).

3. RESULTS

3.1 2014/15 Winter – WRF Performance

WRF model output was compared against observed weather data at the Alpine study plot between 31-Oct-2014 and 2-Jun-2015. Throughout the season, WRF provided relatively accurate forecasts of air temperature, snow surface temperature, and relative humidity but over-forecasted
precipitation by 548 mm, or 69%, as seen in figure 3. Additionally, winds and ISWR were over-forecasted throughout the majority of the season as well.

3.2 2014/15 Winter – SNOWPACK Performance

Observed pit data, as well as other snowpack data gathered from the co-located weather stations and ski patrol end-of-day observations, were used to validate the two SNOWPACK simulations run during the 2014/15 season. Results in table 1 show the simulation forced with observed weather data (SNOWPACK-Obs) provided a slightly more overall accurate prediction of the snowpack than the simulation forced with forecasted weather data (SNOWPACK-WRF). Figure 4 shows the comparison of modeled (SNOWPACK-WRF) and measured snow depth during the season. Modeled snow depth was relatively accurate through the first part of the winter before higher than observed snowfall increased the snow depth well above the observed value, continuing through the spring before melting off more rapidly.

Tbl. 1: Accuracy of both SNOWPACK simulations for each of the measured field variables. The grain type agreement score was converted to a percentage for comparison purposes.

<table>
<thead>
<tr>
<th>Field Variable</th>
<th>SNOWPACK-Obs</th>
<th>SNOWPACK-WRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>85%</td>
<td>83%</td>
</tr>
<tr>
<td>Temperature</td>
<td>77%</td>
<td>76%</td>
</tr>
<tr>
<td>Grain Size</td>
<td>63%</td>
<td>65%</td>
</tr>
<tr>
<td>Hand Hardness</td>
<td>47%</td>
<td>52%</td>
</tr>
<tr>
<td>Grain Type</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>HS</td>
<td>98%</td>
<td>69%</td>
</tr>
<tr>
<td>SWE</td>
<td>93%</td>
<td>66%</td>
</tr>
<tr>
<td>50 cm Temperature</td>
<td>93%</td>
<td>79%</td>
</tr>
<tr>
<td>24HN</td>
<td>68%</td>
<td>58%</td>
</tr>
<tr>
<td>Total Snowfall</td>
<td>90%</td>
<td>84%</td>
</tr>
<tr>
<td>New Snow Density</td>
<td>80%</td>
<td>78%</td>
</tr>
<tr>
<td>Overall</td>
<td>79%</td>
<td>71%</td>
</tr>
</tbody>
</table>

3.3 2015/16 Winter

During the 2015/16 season, the WRF model varied in performance across the 5 locations, with precipitation generally being overestimated and temperature generally being underestimated throughout the winter (Tbl. 2).

Tbl. 2: WRF precipitation error and temperature bias for each location during the 2015/16 winter.

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Prec ( % Error)</th>
<th>Temp ( ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Mountain Summit</td>
<td>+32%</td>
<td>-1.46 ºC</td>
</tr>
<tr>
<td>Noisy Basin</td>
<td>+7%</td>
<td>-2.57 ºC</td>
</tr>
<tr>
<td>Stuart Mountain</td>
<td>+62%</td>
<td>-3.27 ºC</td>
</tr>
<tr>
<td>Lolo Pass</td>
<td>+4%</td>
<td>-1.79 ºC</td>
</tr>
<tr>
<td>Bridger Bowl</td>
<td>+17%</td>
<td>-1.70 ºC</td>
</tr>
</tbody>
</table>

Additionally, wind speeds were still systematically overestimated at each site. In order to produce a more realistic SNOWPACK simulation, forecasted winds were corrected by applying a numerical multiplier, either based off of available nearby wind data or estimated using recommendations from the NWS.

SNOWPACK simulations forced with WRF data for each location were produced for the entire 2015/16 season. Though full snow profiles were not routinely dug during this season, snow depth data was available for each site at nearby weather or SNOTEL stations. Observed snow depth was then compared to simulated snow depth for each location, with results shown in Table 3.
Snow depth was underestimated at each location with the exception of Stuart Mountain, which correlated to the heavily overestimated precipitation and underestimated temperatures at that location.

### 3.4 Case Studies

SNOWPACK-WRF simulations were analyzed during three significant avalanche events during the 2015/16 season; with two events in the Swan and Flathead Ranges in NW Montana (Fig. 5) and one at Saddle Peak in the Bridger Range in SW Montana (Fig. 6). The first event in NW Montana consisted of a potent early December storm system that brought rain levels up to 2100 m leading to a significant rain on snow event. This led to an early season wet slab avalanche cycle and the formation of a thick rain crust that persisted throughout the rest of the season. The second case study in NW Montana consisted of a significant mid-January avalanche cycle. During this event, a prolonged cold dry period, which led to faceting throughout most of the snowpack, was followed by a potent winter storm that deposited 13.7 cm of SWE and 114 cm of snow in parts of the Swan Range, leading to numerous natural and human triggered avalanches across the region. These events were compared against the Noisy Basin SNOWPACK simulation.

The Saddle Peak case study analyzed the conditions surrounding a human triggered avalanche in mid-January on Saddle Peak, a popular backcountry skiing area just south of Bridger Bowl. Here, early season depth hoar and facets were buried by successive storms in mid-January leading to a subsequent remotely triggered avalanche that happened to be captured by a time-lapse camera (Saly et al., 2016). This event was modeled with a SNOWPACK simulation forced with a combination of forecasted and observed weather data, where WRF forecasted radiation and precipitation values were used in conjunction with observed values of temp, RH, and winds from the nearby Schlasman’s weather station.

**Fig. 5:** Analysis of 2 significant avalanche events during the 2015/16 winter at Noisy Basin in NW Montana. (a.) SNOWPACK-WRF modeled grain type and (b.) observed snow profile for the Dec 9th rain on snow event. (c.) SNOWPACK-WRF modeled grain type and (d.) image of a crown line from a large avalanche that released during the mid-January avalanche cycle. (Photos: FAC, 2016)
4. DISCUSSION

4.1 2014/15 Winter

The snow cover during the 2014/15 winter was reasonably simulated by the SNOWPACK-WRF model but was limited by the quality of the forecasted weather data input. Specifically, the WRF model tended to over-forecast precipitation leading to higher than observed snow depths, though this was mitigated some by the over-forecasted wind speeds, which tended to densify and compact the simulated new snow. The main issue that likely led to these errors stemmed from limitations of model resolution in complex terrain. For example, the location of the WRF model grid point was on the windward side of the Bridger range while the study plot was on the leeward side, which likely led an overestimation of orographically enhanced precipitation throughout the winter. Additionally, the model resolution was not fine enough to resolve the micro-scale effects of topography and vegetation, which sheltered the study plot decreasing observed wind speeds and direct solar radiation due to friction and shading, respectively. This led to a systematic over-forecast of wind speeds and ISWR by the WRF model throughout the season.

Even though the WRF model struggled in certain areas, the SNOWPACK-WRF simulation was overall relatively accurate and compared rather favorably against the SNOWPACK-Obs simulation for most parameters. The difference in accuracy between the two models was small for variables associated with internal snowpack structure (e.g., density, temperature, grain size and type, and hand hardness) while greater differences were seen for variables influenced more by total precipitation (e.g., HS and SWE) (Tbl. 1). These results are encouraging because they suggest we can run SNOWPACK with relatively inexpensive model output instead of expensive weather station observations and get similar results.

4.2 2015/16 Winter

During the second season, the WRF precipitation forecast, on average, improved markedly over the
prior season but winds were still systematically over-predicted. This led to unrealistic snow cover simulations for most locations as the higher winds tended to either over-compact or strip the snowpack of new snow. The combination of higher winds and more realistic precipitation amounts resulted in shallower and colder snowpacks throughout most of the season, consisting mostly of faceted grains and depth hoar until spring. Bias correcting the wind forecast produced more realistic snow cover simulations with four out of five locations showing increased snow depth accuracies compared to the previous season at Bridger Bowl. This highlights SNOWPACK’s sensitivity to wind speed and precipitation inputs and the necessity of properly bias correcting these forecasted parameters before being used as input to drive SNOWPACK.

4.3 Case Studies

The snowpack conditions were generally simulated for each of the case studies, which highlighted the prominent snowpack features impacting stability and avalanche danger at the time. The Dec 9th rain on snow event in NW Montana was predicted by the Noisy Basin SNOWPACK simulation, with 0.82 cm of rain forecasted between the 8th and 9th, leading to rain water percolating halfway through the snowpack (Fig. 5a). Field observations revealed a 10 cm thick rain crust present throughout the region after the 9th, but the crust did not form in SNOWPACK until nearly 3 weeks later. Interrogating further, forecasted snow surface temperatures never dropped below 0 °C after the rain event and subsequent new snow insulated the wet snow, preventing refreezing of the wet snow layer. It wasn’t until a prolonged cold outbreak a few weeks later, where sub-freezing temperatures were able to penetrate deep enough into the modeled snowpack, that the wet snow layer finally refroze forming the rain crust.

The mid-January storm cycle was accurately simulated with facets developing in the upper half of the modeled snowpack in early January which were subsequently buried by 60 cm of snow between the 11th and 14th (Fig. 5c). The model did under-predict new snow amounts, which ranged between 75-115 cm throughout the region, but the persistent weak layers were seen across NW Montana. Using an improved stability classification method for SNOWPACK profiles (Bellaire and Jamieson, 2013a), the simulated avalanche danger was rated as high on the 14th, which corresponded to an avalanche warning issued by the Flathead Avalanche Center and the numerous natural avalanches observed around the region on the same day.

The Saddle Peak simulation modeled the persistent depth hoar that was observed throughout the Bridger range in January (Fig. 6a), which was the failure point for the human-triggered avalanche on the 14th. The model predicted 15 cm of new snow the day prior, which was right in the range of the 10-18 cm that was measured, though some additional wind loading was observed in the starting zone. The simulation predicted the most likely avalanche release point at 0.7 m below the surface where 1.75 mm depth hoar was modeled. This corresponded well to an observed crown line of 0.6 m that failed on depth hoar near the ground. The stability rating for the simulated profile was rated as low by SNOWPACK but increased to moderate using the improved Bellaire and Jamieson method. The simulation did predict a layer of 3.5 mm surface hoar 20 cm below the surface, which was not observed in the field, but was not deemed a critical weak layer by SNOWPACK.

The Saddle Peak simulation results highlight the potential of using a combination of locally observed and forecasted weather data to produce a SNOWPACK simulation, where only standard weather station data is available but the remaining input requirements can be supplemented using NWP output.

5. CONCLUSIONS

This study evaluated the performance of a coupled weather and snow cover model to predict snowpack structure and avalanche potential in the intermountain snow climate of western Montana. Snow cover simulations were forced with forecasted weather data from the WRF model over two seasons across several prominent locations and were validated against field data.

During the first season, precipitation, winds, and solar radiation were all over-forecasted but the model chain still had an overall accuracy of 71% for 11 different snowpack parameters, which was only 8% lower than a simulation driven with locally observed weather data. During the second season, the WRF model showed improvement but winds were still over-forecasted necessitating a bias correction prior to running through SNOWPACK. The coupled model simulated snowpack conditions and stability for 5 different locations relatively accurately during several prominent events, though some specific layers were either not modeled or were falsely predicted in the simulation.
Results from this study show the potential of a coupled weather and snow cover model as a valuable and inexpensive tool for avalanche forecasting, especially in remote and data sparse areas, but also show room for improvement in the SNOWPACK model, regardless of input type. Additionally, further study and understanding of NWP model biases are needed before using the coupled model in an operational capacity. Further analysis and detailed descriptions of the methodology will be presented in Van Peursem et al. (In Prep).

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