ESTIMATION OF NEW SNOW DENSITY USING 42 SEASONS OF METEOROLOGICAL DATA FROM JACKSON HOLE MOUNTAIN RESORT, WYOMING

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ABSTRACT: New snow density is a key parameter for daily forecasting of avalanche hazard. However, there is currently not a reliable automated measurement of new snow density to provide data for the daily avalanche bulletin issued by the Bridger-Teton National Forest Avalanche Center. Although precipitation gauges at automated weather stations provide water content data, the measurements can be inaccurate in certain conditions. In this study we use 42 seasons of manual daily snow density measurements along with air temperature and wind speed data to derive equations to estimate new snow density. We use linear least squares regression techniques to find best-fit second-order polynomial solutions for three on-mountain stations, and provide analysis of the statistical significance of solutions. This work has resulted in a new snow density calculator that allows avalanche forecasters to quickly estimate the water equivalent of new snow (SWE) for various locations by entering 24-hr mean air temperature and 24-hr total wind kilometers. This tool is specific to data collected at the Jackson Hole Mountain Resort but may be useful to other avalanche forecasting operations.

KEYWORDS: snow density, snow water equivalent, avalanche forecasting

1. INTRODUCTION

Providing reliable measurements of new snow density or the water equivalent of new snow (SWE) is a key component of avalanche hazard forecasting, where density can greatly affect snow stability. To report 24-hr new snow and SWE totals for the daily 7 AM forecast, the Bridger-Teton National Forest Avalanche Center primarily relies on automated measurements from four weather stations located at Jackson Hole Mountain Resort (Figure 1). As has been recognized in previous work (e.g. MacDonald and Pomeroy, 2007; Rasmussen, 2012), measurements from automatic precipitation gauges can be inaccurate in certain conditions. We find that high winds can induce undercatchment (particularly for elevated gauges), snow can drift and bridge into the gauge opening (then falling into the gauge after a storm has ended), and occasionally the gauge fluid can partially freeze in very cold conditions.

In this study we have developed an additional tool to aid in the estimation of SWE for new snow. Using 42 seasons of manual daily snow density measurements (1974 - 2016) along with daily air temperature and wind speed data, we derive equations to estimate new snow density.

Figure 1. Rendezvous Bowl study plot (2,920 m) at Jackson Hole Mountain Resort, showing the ETI precipitation gauge and Judd Communications ultrasonic sensors for total snow depth (upper left) and new snow (bottom right).

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2. METHODS

This study utilizes historical daily measurements of new snow density and air temperature from three snow study plots at Jackson Hole Mountain Resort: Mid-Mountain Plot (2,493 m), Raymer Plot (2,853 m), and Rendezvous Bowl Plot (2,920 m). We analyze the relationship between 24-hr new snow density and 24-hr mean air temperature for each station, and between 24-hr new snow density and total 24-hr wind kilometers at the Summit wind station (3,185 m). Using the Python module Statsmodels we calculate the ordinary least squares (OLS) regression (2nd-order polynomial), in addition to quantile regression, confidence intervals, and prediction intervals to quantify the variability of the data (Figures 2 - 5). We then extend the analysis to calculate the best-fit OLS surface to predict new snow density as a function of both wind speed and air temperature (Figure 6).

We use 24-hr new snow totals of 2.5 cm (1 in) or greater, and corresponding snow water equivalent (SWE) measurements taken with a SnowMetrics snow board sampling tube. Density is reported as a dimensionless fraction, following standard definitions (Greene et al., 2010). Date ranges are limited to December 15 – March 30 to reduce the number of estimated new snow measurements from periods outside the mountain operation season when mountain access is limited. However, we observe a large bias towards 0.10 (and 0.05) in the new snow density dataset, likely an artifact of days where SWE was estimated, rather than measured.

3. RESULTS

We find that changes in previous 24-hr mean air temperature and total wind kilometers correlate with changes in 24-hr new snow density for three study plots at Jackson Hole Mountain Resort (Figures 2 - 5). This relationship is statistically significant at all study plots for air temperature as a predictor variable (p-values < 0.05 for all polynomial terms), and is less significant for wind speed (some p-values > 0.05). Although the addition of wind improves the model fit compared to temperature alone, wind is a less-significant predictor of density than temperature (for all stations).

Using the model solution for both air temperature and wind speed as predictor variables (Figure 6), we have developed a web-based javascript calculator that allows users to enter previous 24-hr air temperature and wind speed data to estimate corresponding new snow density (Figure 7).

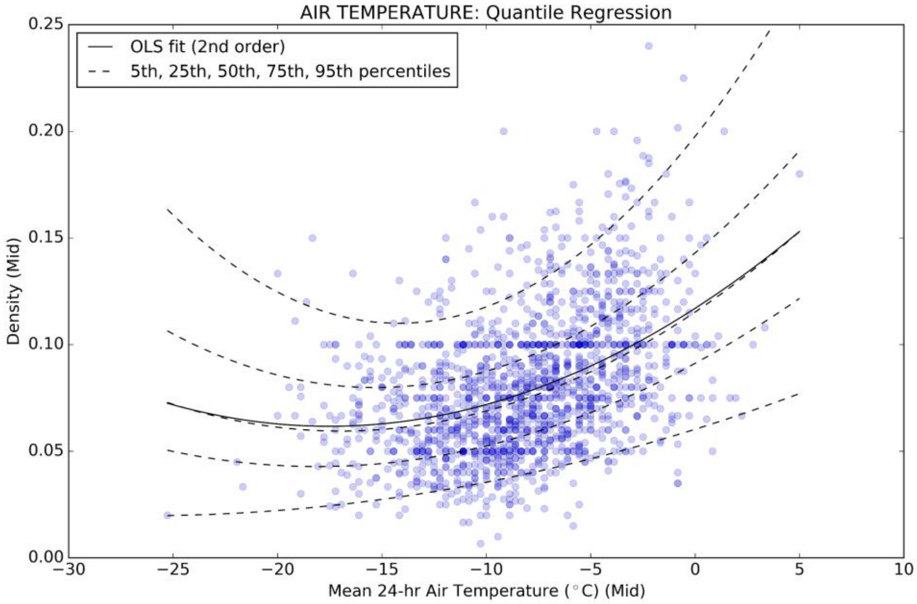


Figure 2. Quantile regression showing the distribution of new snow density vs. 24-hr mean air temperature for the mid-mountain study plot (N=1583). The best-fit ordinary least squares (OLS) regression line is shown in bold (2nd order polynomial, R^2=0.18).

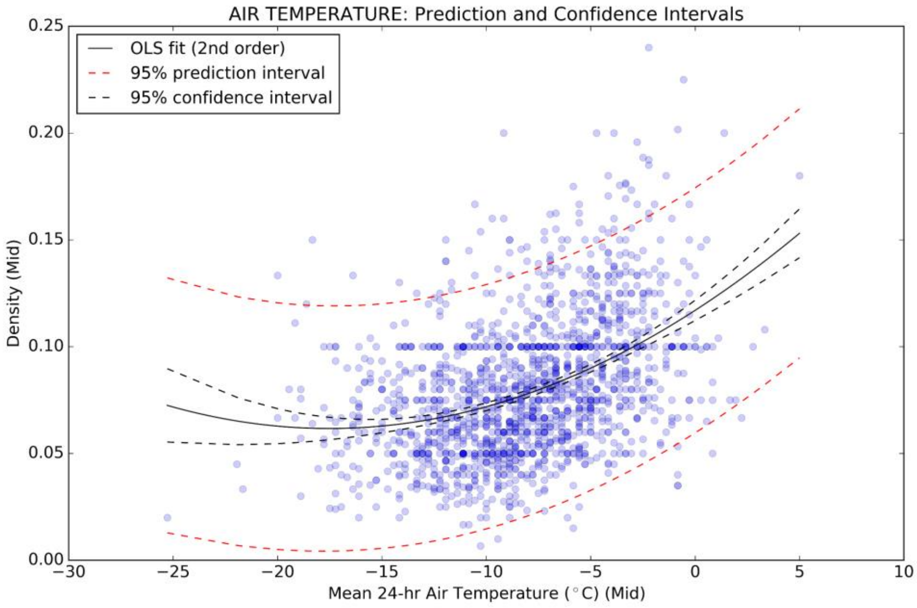


Figure 3. Prediction and confidence intervals for new snow density vs. 24-hr mean air temperature for the mid-mountain study plot (N=1583). The best-fit ordinary least squares (OLS) regression line is shown in bold (2nd order polynomial, R^2=0.18).

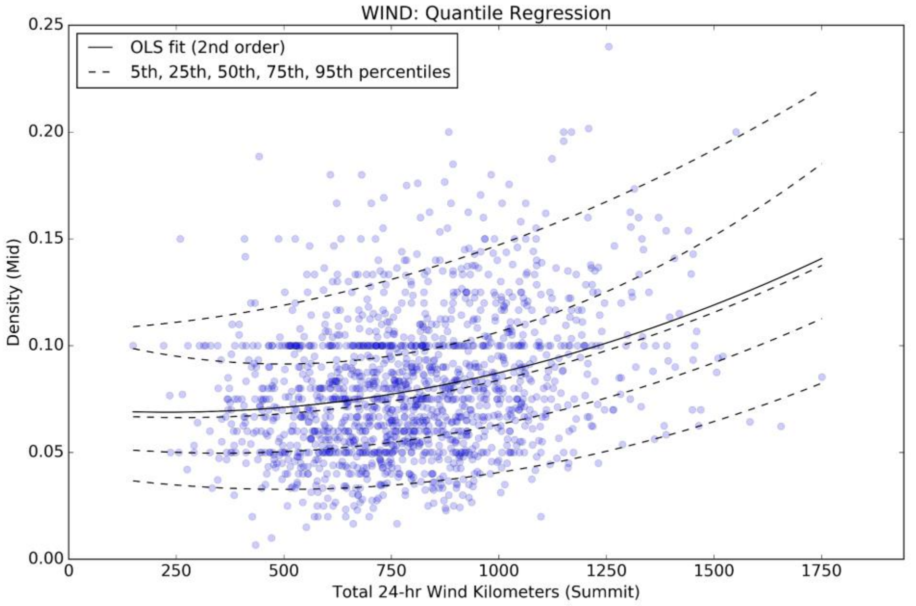


Figure 4. Quantile regression showing the distribution of new snow density at the mid-mountain study plot vs. total 24-hr wind kilometers at the summit (N=1583). The best-fit ordinary least squares (OLS) regression line is shown in bold (2nd order polynomial, R^2=0.08).

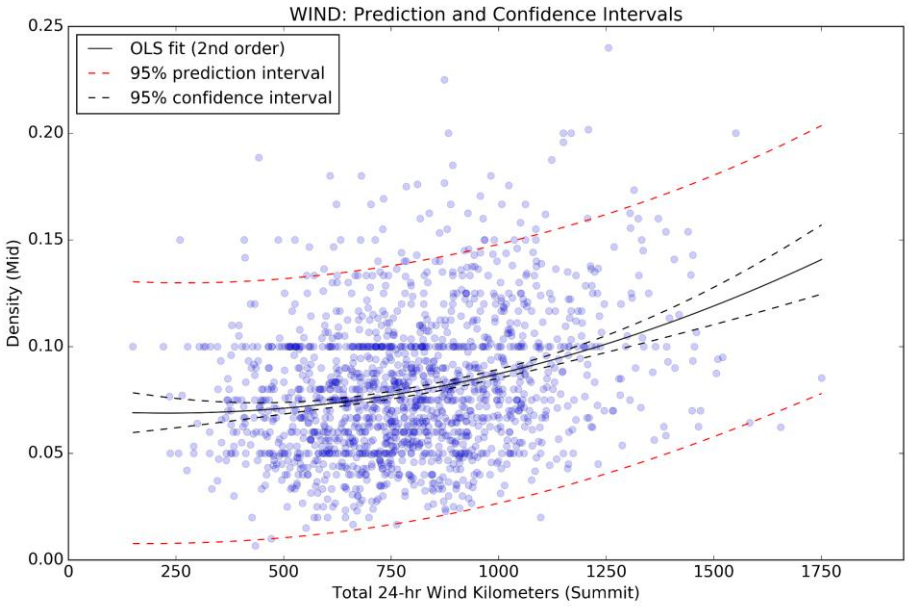


Figure 5. Prediction and confidence intervals for new snow density at the mid-mountain study plot vs. total 24-hr wind kilometers at the summit (N=1583). The best-fit ordinary least squares (OLS) regression line is shown in bold (2nd order polynomial, R^2=0.08).

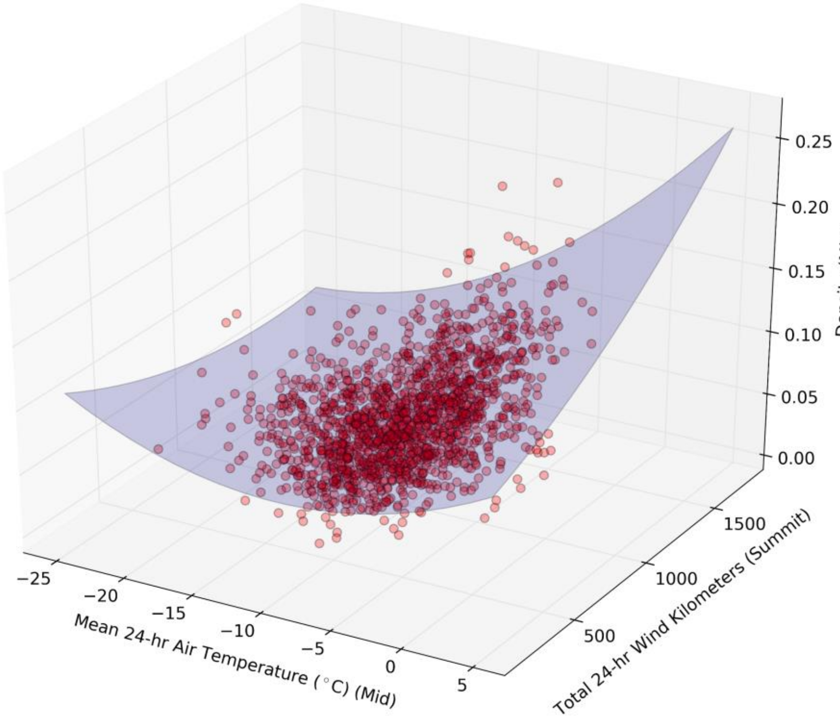
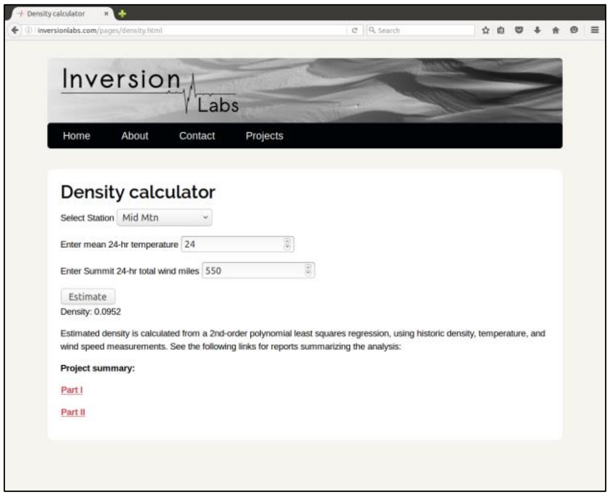


Figure 6. Best-fit surface (OLS 2nd order polynomial) for the mid-mountain study plot, used to estimate new snow density as a function of mean 24-hr air temperature and summit total 24-hr wind kilometers. The best-fit surface utilizes historical daily measurements (1974 - 2016) of new snow density, air temperature, and wind speed (N=1583).



Density calculator

Select Station Mid Mtn

Enter mean 24-hr temperature 24

Enter Summit 24-hr total wind miles 550

Density: 0.0952

Estimated density is calculated from a 2nd-order polynomial least squares regression, using historic density, temperature, and wind speed measurements. See the following links for reports summarizing the analysis:

Project summary:

Part I

Part II

Figure 7. Screenshot of the online density calculator tool, allowing rapid estimation of new snow density.

4. DISCUSSION

Our analysis is similar to previous work that provides SWE estimates based on the relationship between snow density and regional snow climates (e.g. Mock and Birkeland, 2000; Jonas and Magnusson, 2009; Sturm et al., 2010). However, our analysis is intended to represent variability within a single climate zone or forecast area, where new snow density can vary with air temperature and wind speed associated with individual storm events.

The density trends we observe likely arise from processes defined in previous work. The size and shape of snow crystal formation in the atmosphere is dependent on both air temperature and water vapor supersaturation (Whiteman, 2000; Libbrecht, 2005), which directly affects the density of new snow layers upon deposition. New snow can then further change in density as a function of surface air temperature over the 24-hr period. In addition, wind transport and re-circulation in the atmosphere can mechanically alter the size and shape of snow crystals before deposition and can create density changes through wind-packing during deposition (Whiteman, 2000; McClung and Schaerer, 2006). Although our analysis accounts for the physical mechanisms associated with air temperature and wind, our results are potentially limited by neglecting additional variables that affect new snow density such as settlement, wind redistribution after deposition, and solar radiation effects (warming and/or sublimation).

We also caution that although the best-fit model used to estimate new snow density is an accurate representation of the mean of the historical data, individual daily predictions using the model can vary widely within the range of density measurements (as shown by large prediction intervals, relatively large standard error, and low R^2 values).

5. CONCLUSIONS

An analysis of 42 seasons of meteorological data from study plots at the Jackson Hole Mountain Resort shows a relationship between air temperature, wind speed, and measured new snow density. This work has resulted in a density calculator tool that allows avalanche forecasters to quickly estimate the water equivalent of new snow (SWE) for three on-mountain locations by entering 24-hr mean air temperature and 24-hr total wind kilometers. This tool provides statistically-supported SWE estimates when conditions prevent reliable measurements from automated precipitation gauges. The tool is specific to data collected at the Jackson Hole Mountain Resort but may be useful to other avalanche forecasting operations.

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