PATROLLING THE SNOW SURFACE ENERGY BALANCE

Austin Finnell*[1]

[1]*Keystone Ski Patrol, Summit County Rescue Group, Dillon, CO, USA*

ABSTRACT: Avalanche professionals usually build snowpack intuition from weather cues they can directly observe, including sun, cloud cover, air temperature, and wind. This study asks whether those cues account for what actually controls snow surface temperature. A minimal one dimensional snow surface energy balance model was developed and forced with observations from the Senator Beck Basin Study Plot in Colorado from 1 January to 28 February 2026. The model was tuned with measured station data to create a baseline simulation.

The baseline model reproduced observed snow surface temperature well, with MAE = 1.05 °C, RMSE = 1.53 °C, and $r = 0.962$. To test the model's response, downwelling longwave, absorbed shortwave, sensible heat, and latent heat were independently changed by $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ in separate runs. At every perturbation level, scaling downwelling longwave produced the largest increase in RMSE. A 10% reduction in downwelling longwave increased RMSE by 1.09 °C, compared with 0.05 °C for sensible heat, 0.04 °C for absorbed shortwave, and 0.01 °C for latent heat. Within this model and record, snow surface temperature RMSE was most responsive to proportional changes in downwelling longwave radiation. A simple air temperature proxy for snow surface temperature performed far worse than the energy balance model, with RMSE = 7.21 °C, about 4.7 times the baseline error.

These results suggest that practitioners may underestimate the contribution of longwave radiation to snow surface conditions, not because other variables are unimportant, but because longwave acts continuously without a visible signal and is therefore easy to omit from a mental model. In this two month record at one station, changing $LW_{\downarrow}$ by a given percentage produced a larger response than changing absorbed shortwave, sensible heat, or latent heat by the same percentage. As snow modeling becomes more common in avalanche forecasting, understanding longwave influence can help users interpret model results and reconcile differences between snow surface temperature, air temperature, and visible weather conditions.

KEYWORDS: Snowpack Properties, Instrumentation and Remote Sensing, Weather Forecasting

1. INTRODUCTION

Avalanche professionals build much of their weather intuition from conditions they can see and feel. A patroller standing on a ridge can judge whether the sun is out, clouds are increasing, the air is warming or cooling, and the wind is strengthening. These observations help us anticipate how the snow surface may change. Not every part of the snow surface energy balance is this easy to observe. Downwelling longwave radiation, $LW_{\downarrow}$, is thermal energy emitted toward the snow by the atmosphere, clouds, and surrounding terrain. It arrives day and night and cannot be seen or quantified directly without an instrument.

This creates a gap between the weather variables practitioners naturally notice and the full set of energy exchanges that control snow surface temperature. Standard avalanche observations emphasize sky cover, air temperature, wind, precipitation, and surface conditions, while downwelling longwave is rarely measured at operational weather stations (Raleigh et al. 2016). Previous studies have shown that errors in incoming longwave radiation can strongly affect modeled snow surface temperature (Lapo et al. 2015; Raleigh et al. 2016). This study translates that established result into a simple experiment for avalanche practitioners using measured radiation and surface temperature at a high alpine Colorado station at 3706 m. Model performance is reported as root mean square error (RMSE), a single number that summarizes how far the modeled surface temperature typically falls from the observed value.

The study asks a narrow question: For a simple one dimensional model, which of four energy terms produces the largest change in model-versus-observation RMSE when each term is changed by the same percentage?

1.1. A Ski Patroller Analogy for Radiation

The radiation balance can be pictured as two ski patrollers.

Corresponding author address:
Austin Finnell, Keystone Ski Patrol,
Summit County Rescue Group,
Dillon, CO, USA;
email: austin.finnell@gmail.com

Patroller Shortwave is everyone's favorite employee. Everyone knows them, sees their work, and can usually tell how hard they are working. Their schedule changes throughout the year, but it is predictable. They clock in at sunrise, warm up gradually, work hardest around midday, taper off, and clock out at sunset. They never work at night. Even when Shortwave is working hard, most of their effort is reflected before it enters the resort's energy budget. They are less productive when it is cloudy or stormy. Shortwave gets attention because the work is easy to see and understand without tools to monitor their effort.

Patroller Longwave is different. Longwave never goes home. They work 24 hours a day, including all night, and do not need sunlight to work hard. Their incoming contribution is much harder to see and can change as clouds and humidity change. They can work harder when it is cloudy or humid. We often talk about how they work less hard on a clear night, but forget that they continue working throughout the night.

Patroller Shortwave may get more attention because they are the most visible employee, but Patroller Longwave is always working and can contribute more effort to the operation over an entire day. This comparison highlights the importance of accounting for every patroller, as both are essential for maintaining a functional operation.

1.2. Surface Energy Balance

Snow surface temperature changes when incoming and outgoing energy are out of balance. When the surface gains more energy than it loses, it warms. When it loses more than it gains, it cools. These energy transfers are called fluxes and are measured in W m^{-2}. The main processes can be summarized with a conceptual surface energy balance:

$$\text{Net Energy} = SW_{\text{net}} + LW_{\text{net}} + H + LE + G \quad (1)$$

The terms are absorbed shortwave (SW_{net}), net longwave (LW_{net}), sensible heat flux (H), latent heat flux (LE), and conductive heat flux (G). Positive net energy adds energy to the snow, negative net energy removes it, and zero indicates no instantaneous net energy gain or loss. Together, absorbed sunlight, net thermal radiation, heat exchanged with the air and water vapor, and conduction with the snow below determine the net energy entering or leaving the snow surface. The temperature change also depends on the snow's heat capacity and the time over which these fluxes occur. Each flux can add or remove energy in W m^{-2}, and the sign and size can change through the day.

2. OBJECTIVES

Sensitivity studies have already established that errors in downwelling longwave are among the most damaging forcing errors for modeled snow surface temperature and snowpack evolution (Lapo et al. 2015; Raleigh et al. 2015; Raleigh et al. 2016), and that weather input uncertainty propagates into modeled uncertainty (Richter et al. 2020). The goal is to illustrate this established sensitivity in a form that avalanche practitioners can follow using measurements from one station and a simple heat transfer model that can be described concisely. Three objectives help meet that goal.

1. Establish whether a minimal 1D heat transfer model, forced by measured station meteorology and radiation data, can reproduce observed snow surface temperature closely enough to be worth interpreting.
2. Compare how surface temperature RMSE responds when $LW_{\downarrow}$, absorbed shortwave, sensible heat, and latent heat are independently changed by equal percentages, and quantify the energy-flux change represented by each change.
3. Compare the model with air temperature used as a proxy for snow surface temperature.

3. DATA AND METHODS

3.1. Station Data

The Senator Beck Basin Study Plot near Red Mountain Pass, Colorado, is a research weather and snow station at 3706 m operated by the Center for Snow and Avalanche Studies (Center for Snow and Avalanche Studies 2026). Data was accessed through the U.S. Geological Survey National Water Information System (U.S. Geological Survey 2026). Hourly observations from 1 January through 28 February 2026 were used. Model forcing consisted of air temperature, relative humidity, wind speed, snow depth, $SW_{\downarrow}$, $SW_{\uparrow}$, and $LW_{\downarrow}$. Snow surface temperature from the non-contact infrared sensor was used as the evaluation target. Upward and downward facing pyranometers measured incoming and reflected shortwave radiation. An upward facing pyrgeometer measured incoming longwave from the sky. Station reported

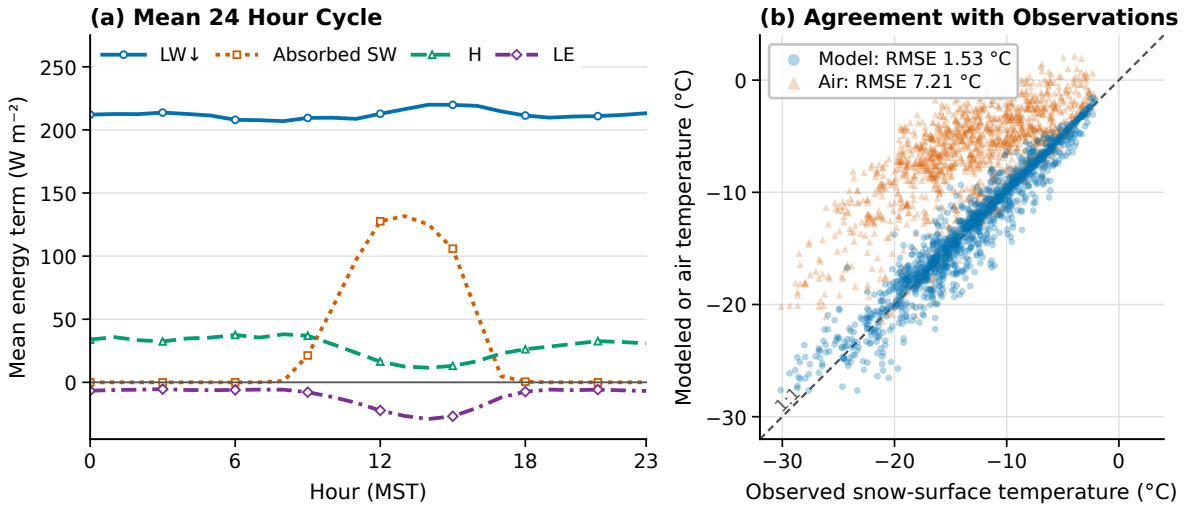


Figure 1: (a) Mean 24 hour cycles of the four terms changed during the experiment. Daily weather variability is not shown. (b) Agreement of the baseline model and air temperature with observed snow surface temperature across 1,404 hours. The dashed line denotes 1:1 agreement.

$LW_{\uparrow}$ values were derived from the infrared surface temperature measurement rather than measured directly by a downward facing pyrgeometer (Center for Snow and Avalanche Studies 2026). The record contained 1,412 hours with eight excluded because of missing fields, leaving 1,404 hourly observations.

3.2. *Simple Snow Model*

The model tracks how energy entering the snow changes temperature through 35 horizontal layers. It follows four steps:

1. Read and interpolate the measured weather and radiation for the current model time.
2. Calculate net longwave, sensible, and latent heat exchange at the surface.
3. Distribute absorbed shortwave radiation through the upper layers and move heat between neighboring layers by conduction.
4. Update the temperature of every layer and estimate snow surface temperature from the upper two layers.

The resulting hourly surface temperature estimates were then compared with the infrared observations.

This is a heat transfer model rather than a complete operational snowpack model. At each time step, the measured snow depth was divided into 35 layers, and hourly forcing was interpolated between observations. Each layer warmed or cooled according to heat conducted into or out of it and sunlight absorbed within it. Snow density and heat capacity determined how much the layer temperature changed for a given amount of energy.

At the upper boundary, outgoing longwave radiation was calculated from the upper layer temperature as $LW_{\uparrow} = \epsilon\sigma T_{\text{top}}^4$. Net longwave was then calculated by subtracting this modeled $LW_{\uparrow}$ from measured $LW_{\downarrow}$. Sensible and latent heat exchanges were calculated from air temperature, humidity, wind speed, and upper layer snow temperature. As the upper layer warmed or cooled, these surface fluxes were recalculated and used to determine its next temperature. Absorbed shortwave radiation was divided into visible and near infrared bands and absorbed progressively with depth.

Layer temperatures were advanced with an adaptive numerical solver (RK45) using steps no longer than 30 minutes. Temperatures were not allowed to exceed 0 °C because liquid water and melt energy were not explicitly represented. The model assumed a snow density of 200 kg m^{-3}, heat capacity of 2100 J kg^{-1} K^{-1}, thermal conductivity of 0.20 W m^{-1} K^{-1}, and emissivity of 0.99.

In summary, surface fluxes add or remove energy, absorbed sunlight warms snow at and below the surface, and conduction redistributes energy between layers.

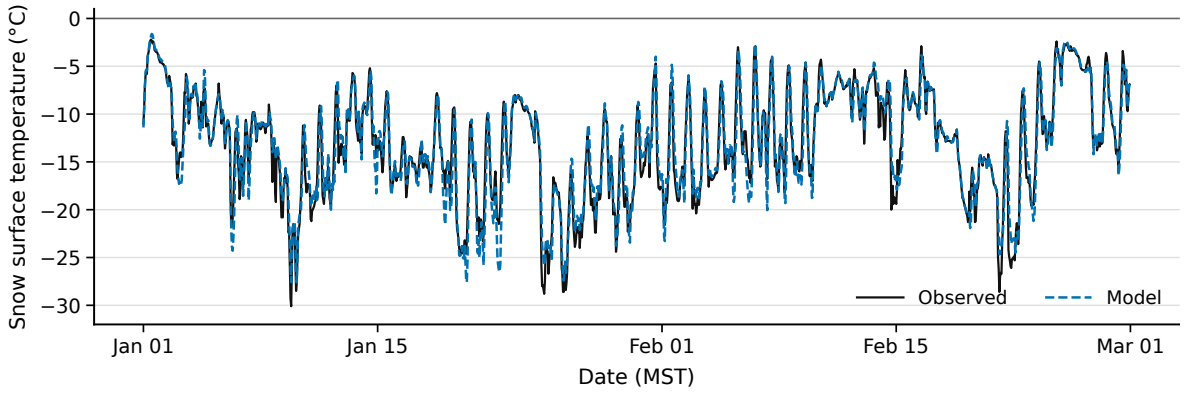


Figure 2: Hourly observed and modeled snow surface temperature from 1 January through 28 February 2026 ($n = 1{,}404$). The baseline produced MAE = 1.05 °C, RMSE = 1.53 °C, bias = +0.04 °C, and $r = 0.962$.

3.3. *Percentage Change Experiment*

A baseline model was tuned to the two month period with unmodified inputs, then one term was changed at a time from 30% below to 30% above baseline in 10% steps. For each run, one term—$LW_{\downarrow}$, absorbed SW, H, or LE—was multiplied by a factor from 0.7 to 1.3 in increments of 0.1. While one term was changed, all other measurements and model settings remained unchanged, but modeled temperature and temperature dependent fluxes were allowed to respond dynamically.

Equal percentage changes are not equal energy-flux changes in W m^{-2}. Ten percent of a large or continuously active flux is more energy than 10% of a smaller flux. The experiment tests proportional changes, not equal energy flux changes. Larger ± 20% and ± 30% changes are stress tests, not realistic error distributions.

Each run was compared with the observed surface temperature using RMSE. The reported value is perturbed run RMSE minus baseline RMSE. Positive values indicate a worse fit.

4. RESULTS

4.1. *Energy Fluxes*

Figure 1a shows the average daily cycles of the four energy terms changed during the experiment. Downwelling longwave radiation was present throughout the day and night. The mean diurnal cycle varied from approximately 207 to 220 W m^{-2}, with a record mean of 212.4 W m^{-2}. This average conceals substantial variability: individual hourly $LW_{\downarrow}$ observations ranged from 120 to 312 W m^{-2}, and 7% of consecutive observations changed by at least 10% from the preceding hour.

Total absorbed shortwave fell to zero at night, reached a mean hourly peak near 132 W m^{-2} at 13:00 MST, and averaged 30.3 W m^{-2} across all hours.

Integrated over the 24-hour cycle, incoming longwave supplied 18.35 MJ m^{-2}, compared with 2.62 MJ m^{-2} of total absorbed shortwave. Together, these positive radiative inputs averaged 242.7 W m^{-2}, equivalent to 20.97 MJ m^{-2} over the day. $LW_{\downarrow}$ supplied 87.5% of this combined input and absorbed SW supplied 12.5%. Downwelling LW was approximately seven times the absorbed SW. These are comparisons of gross positive inputs, not assessment of net radiation, because the snow simultaneously emitted longwave radiation.

The shortwave exchange can be expressed as:

$$SW_{\text{net}} = SW_{\downarrow} - SW_{\uparrow} \tag{2}$$

Shortwave radiation is sunlight retained after reflection. Its relative changes are often apparent in the field because observers can see the moving sun, passing clouds, terrain shadows, and the brightness of the snow surface. Exact values still require measurements, but the direction and timing of shortwave changes are usually recognizable during daylight. At Senator Beck, 79.7% of incoming shortwave was reflected during the study period. Approximately one-fifth remained available to warm the snowpack, corresponding to an effective albedo over the period near 0.80. Thus, even when incoming sunlight was large, most of that energy was reflected rather than absorbed.

The longwave exchange can be expressed as:

$$LW_{\text{net}} = LW_{\downarrow} - LW_{\uparrow} \tag{3}$$

The atmosphere and clouds provide downwelling

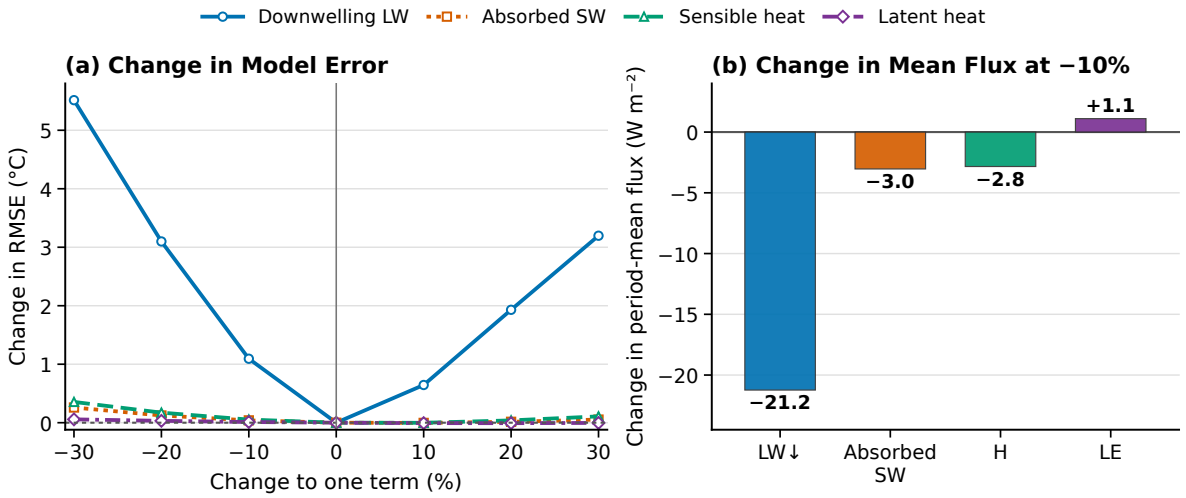


Figure 3: (a) Change in snow surface temperature RMSE relative to the baseline after independently scaling one term from -30% to $+30\%$; positive change in RMSE indicates a worse fit. (b) Change in each term's two month mean flux for the -10% perturbation highlighted in the text.

longwave radiation, while the snow surface continuously emits its own longwave radiation. Practitioners can observe some of the conditions that influence longwave radiation, but determining the actual energy exchange requires a measurement or model estimate.

This distinction is important because incoming longwave and net longwave describe different quantities. $LW_{\downarrow}$ averaged 212.4 W m^{-2}, but modeled net longwave averaged −46.3 W m^{-2}. The negative net value means the snow surface emitted more longwave radiation than it received and therefore experienced a net longwave energy loss. At the same time, the incoming contribution remained substantial and was present during every hour of the study period.

Radiative cooling occurs when $LW_{\uparrow}$ is greater than $LW_{\downarrow}$. Clouds do not prevent the snow from emitting longwave radiation. Instead, they commonly increase $LW_{\downarrow}$ and reduce the difference between the energy emitted and received. Atmospheric temperature, moisture, cloud properties, and surrounding terrain can therefore change how quickly the surface cools. A particularly clear sequence occurred on 13 February. With no incoming shortwave, $LW_{\downarrow}$ decreased from 282 W m^{-2} at 00:00 to 197 W m^{-2} at 02:00, then returned to 280 W m^{-2} by 05:00. The observed snow surface cooled from −7.6 °C to −13.1 °C and then returned to −7.6 °C, while air temperature remained near −7 °C. The 85 W m^{-2} decrease was four times the mean energy scale represented by the 10% $LW_{\downarrow}$ perturbation. This sequence is consistent with a temporary change in sky emissivity, such as a change in cloud cover, but cloud cover was not measured independently.

Air temperature, humidity, and wind were measured at Senator Beck, but sensible, latent, and conductive heat fluxes were calculated by the model. Positive values added energy to the upper snowpack, while negative values removed it. Sensible heat, H, transfers energy between the air and snow because of their temperature difference. It averaged 28.4 W m^{-2}, indicating that the air generally supplied energy to the colder snow surface during this period. Latent heat, LE, transfers energy through water vapor phase changes at the surface. It averaged −11.0 W m^{-2}, indicating that sublimation removed more energy than deposition supplied over the full record, although the direction changed during individual periods.

Conductive heat, G, transfers energy between the surface and the snow below. It averaged 18.1 W m^{-2}, indicating that subsurface snow generally supplied energy to the colder surface in the model. This result partly reflects the model's fixed lower boundary temperature and should therefore be interpreted as a modeled heat flux rather than a direct measurement.

Together, these results show that the snow surface was not controlled by a single energy source. Shortwave varied strongly through the day, longwave continued through day and night, and the turbulent and conductive fluxes added or removed energy according to atmospheric and snowpack conditions.

4.2. Baseline Model Fit

Within the 1,404 hour record used to configure the model, the baseline closely tracked the observed snow surface temperature pattern (Figure 2). The mean absolute error (MAE), or the average size of the model error, was 1.05 °C. The root mean square error (RMSE), which gives more weight to larger errors, was 1.53 °C. In practical terms, the modeled surface temperature differed from observations by about 1.05 °C on average, while occasional larger misses increased the RMSE to 1.53 °C. Mean bias was 0.04 °C, and the Pearson correlation was 0.962.

4.3. Air Temperature Substitute

Using air temperature alone as a simple substitute for snow surface temperature performed much worse. The air temperature proxy had an RMSE of 7.21 °C, about 4.7 times the baseline model error. Figure 1b compares the baseline model and air temperature with observed snow surface temperature. The full energy balance model generally tracked the observed surface temperature closely, while air temperature alone often missed it by several degrees. This shows that snow surface temperature does not simply follow air temperature. Radiation and other surface energy exchanges strongly influence how warm or cold the snow surface becomes. Net longwave loss can cool the surface well below air temperature, while absorbed shortwave and other energy inputs can warm it toward 0 °C even when the air remains below freezing.

4.4. Response to Percentage Changes

At the -10% level, reducing $LW_{\downarrow}$ produced the largest increase in model error. Reducing $LW_{\downarrow}$ by 10% increased RMSE by 1.09 °C. The same percentage reduction changed RMSE by 0.05 °C for sensible heat, 0.04 °C for absorbed shortwave, and 0.01 °C for latent heat. At the $+10$% level, increasing $LW_{\downarrow}$ raised RMSE by 0.64 °C, while the RMSE changes for the other terms were each less than 0.01 °C. The same overall pattern continued through the ± 20% and ± 30% tests, with $LW_{\downarrow}$ producing the largest RMSE response at every nonzero percentage change (Figure 3). At -30% $LW_{\downarrow}$, the RMSE reached 7.04 °C, which is almost as inaccurate as using air temperature as a proxy for surface temperature.

The response was directionally biased. Reducing $LW_{\downarrow}$ produced a larger error than increasing it by the same percentage. This behavior is consistent with the model's upper temperature limit of 0 °C. Additional energy could move modeled snow toward the melting point, but could not raise its temperature above that limit. No equivalent constraint limited cooling over the temperatures encountered in this study.

These results do not demonstrate that longwave radiation always controls snow surface temperature or is universally more important than shortwave, sensible heat, or latent heat. They show that, within this model and two month record, surface temperature error was most responsive to proportional changes in incoming longwave radiation. If $LW_{\downarrow}$ is underestimated because of measurement bias, an imperfect parameterization, or weather-model error, the modeled snow surface will tend to be too cold.

4.5. Measurement Implications

This sensitivity has practical importance for avalanche forecasting because $LW_{\downarrow}$ works continuously but cannot be judged directly by sight. Reducing $LW_{\downarrow}$ gave the model less incoming energy and produced a colder modeled surface. Shortwave changes are often apparent from sunlight and shading, while sun, clouds, air temperature, and wind do not by themselves reveal how much $LW_{\downarrow}$ reaches the snow. When longwave is not measured directly, users should know whether it comes from a weather model or parameterization and treat that estimate as uncertain. If modeled snow surface temperature disagrees with air temperature, visible weather conditions, or field expectations, the $LW_{\downarrow}$ source should be checked alongside shortwave, air temperature, wind, and humidity.

Shortwave and longwave radiation measurements provide different information, and both deserve consideration when weather stations are being built or upgraded. Shortwave radiation is essential for understanding daytime solar impacts and melt. Longwave radiation is less visible, but it reaches the snow throughout the day and night and helps control how quickly the surface cools and warms. In the patroller analogy used earlier, both the flashy daytime patroller and the patroller who works around the clock deserve consideration for monitoring.

Snow, Weather, and Avalanches: Observation Guidelines for Avalanche Programs in the United States (SWAG) recognizes the value of both com-

ponents but suggests that incoming shortwave may be the most useful when only one can be measured (American Avalanche Association 2022). Previous research provides a strong reason to give LW greater emphasis when building a weather station. Lapo et al. (2015) found that comparable longwave errors generally had greater effects on modeled snow surface temperature than shortwave errors. Raleigh et al. (2016) also found that replacing measured longwave with estimates frequently caused substantial differences in modeled surface temperature and snow water equivalent. This analysis reinforces the same sensitivity to longwave error in a form intended for practitioners.

These results show that both measurements serve important purposes in the energy balance. Operations that are building or upgrading automated weather stations should consider measuring both incoming shortwave and incoming longwave radiation, particularly when those stations will provide forcing for snowpack models. In a study of 1,318 automated weather stations across multiple networks in the western U.S., only 24% measured incoming shortwave and only 1.4% measured incoming longwave (Raleigh et al. 2016). The limited measurement coverage leaves many models dependent on estimated radiation inputs.

5. LIMITATIONS

This controlled experiment used one high elevation station and two midwinter months of data. Several model settings were adjusted to improve the baseline fit; therefore, that fit does not demonstrate predictive skill or constitute validation. Equal percentage changes were not equal energy flux changes. The model used constant snow properties, a fixed lower temperature boundary of 0 °C, simplified turbulent exchange, and no liquid water or grain evolution. Only surface temperature was evaluated. The experiment supports conceptual understanding of model forcing, not direct conclusions about current operational snowpack modeling output.

6. CONCLUSION

Avalanche workers spend a lot of time watching Patroller Shortwave. We notice when the sun comes out, when clouds move in, and when a slope starts receiving direct radiation. We also feel the air temperature and wind. These observations are useful, but they represent the visible employees whose work can be seen and felt across the resort. Patroller Longwave works mostly out of sight. Their shift continues through clear nights, cloudy days, storms, and periods when Shortwave has already gone home.

During January and February 2026, the simple model reproduced the observed surface temperature with an RMSE of 1.53 °C. Using air temperature as a substitute produced an RMSE of 7.21 °C. This difference reinforces the basic point that snow surface temperature does not simply match air temperature and develops from the combined surface energy balance and the movement of heat through the snowpack.

This is operationally important because many snowpack models rely on radiation inputs that are estimated rather than measured. Practitioner mental models and snowpack intuition also rely on estimated inputs. Both scientific models and practitioner mental models need to account for variables like longwave radiation, so the value must come from a measurement, a parameterization, an estimate, or a weather model. When model output and field observations disagree, forecasters should ask not only, “What is the model saying?” but also, “Where did the model get the energy it used to make that answer?”

The broader teaching point is not that avalanche practitioners need to measure longwave radiation while digging every snow pit. It is that understanding the surface energy balance makes model output easier to question intelligently. Patroller Shortwave may be the patroller everyone sees, but Patroller Longwave’s work deserves a closer look.

7. DATA AND CODE AVAILABILITY

Analysis scripts, cached USGS inputs, the model configuration, and percentage test results are available upon request.

ACKNOWLEDGEMENTS

The author thanks the U.S. Geological Survey and the Center for Snow and Avalanche Studies for maintaining and sharing the Senator Beck Basin observations used in this study; the ISSW Whistler team for developing the Practitioner Mentorship Opportunity; Erich Peitzsch for his time and mentorship during the development of this paper; and members of Keystone Ski Patrol and Summit County Rescue Group for developing the ideas and reviewing the paper.

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