Local Terrain Topography and Thermal Properties Influence on Energy and Mass Balance of a Snowcover

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ABSTRACT. Snow's interaction with the environment is an important area in environmental science, particularly as climatic conditions change. We consider the local influence at the slope or smaller scale. Near surface properties drive the dynamic interface with the atmosphere and with surrounding terrain. While accounting for topography, complex interactions involving energy and mass transfer at the snow surface are considered, using a computer simulation (Radtherm/RT). Digital elevation maps are used to numerically fabricate terrain features and vegetation, while applying appropriate thermal properties to specified terrain types. Conduction, convection, radiation and phase change (dry snow) are considered. Particularly relevant to this study are infrared (long-wave) and solar (short-wave) radiation, which in the model account for shadowing, multiple reflection and emissive contributions. An example of a north facing 30 degree, snow covered clearing bounded by trees is examined using measured meteorological conditions. Applying the same weather conditions, the model is used to examine the difference if the trees are assumed bare or covered with snow. Results indicate that, for the conditions considered, when trees are covered with snow, the open slope is cooler and the snow mass loss is less. Spatial variability across the slope is also noted. Differences are largely due to topographic radiation exchange.

INTRODUCTION

The reflective characteristics of snow are important in the atmospheric energy balance. Consequently the areal and temporal extent is of major consequence to the global climate. The interaction of terrain and vegetation with snow is significant. Therefore, the presence of a snow covered verses an exposed landscape interacting with snow may provide a feedback with respect to the retention of the snowcover itself. The global importance is well known (Armstrong and Brun, 2008). In this paper we quantitatively consider a theoretical example as a means to examine the influence that local surroundings may have on the energy and mass balance of snow on the slope and smaller scale. We use a modeled example to demonstrate how a snow covered slope might be affected by its surroundings with more or less snow cover in its view shed. We consider an open slope surrounded by trees and inspect the changes that might be expected if these trees are covered or replaced by snow. Changes in snow surface morphology will influence the energy balance. We briefly discuss the potential influence of near surface metamorphism.

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Energy Balance Model

A first principles energy balance model, RadthermRT, that accounts for topography and terrain type was the basis of this analysis. Within this model, thermal properties appropriate to terrain type are assigned and topography is constructed as an assemblage of surface elements (termed facets) which overlay subsurface nodes. Hemispherical rays emanating from each facet are defined, then, employing enclosure theory, geometric view factors with respect to all other surfaces and the sky are calculated. Meteorological data is applied and a 1-D energy balance is calculated for each of these facets. Conduction, convection, radiation and latent heat are accounted for in the model; however, its unique strength is the radiation component. Taking into account topography, global position and time, insolation relative to each facet at each time step is calculated, as are short wave reflection and long wave radiation exchange with the sky or other terrain surfaces. Surface temperature, temperature profiles and surface mass fluxes are calculated for each of these facet elements.

A commercial thermal modeling code, Radtherm/RT by ThermoAnalytics Inc, has its genesis in code originally developed to recognize the infrared/thermal signatures of vehicles based on their geometry and material composition. The same methods applied to vehicles were extended to topographically varied terrain and snow by Adams and McDowell (1991). RadTherm/RT and was further extended to analyze topographically complex terrain utilizing digital elevation maps (DEMs), in collaboration between Montana State University (MSU) and ThermoAnalytics, Inc. (Adams, 1999). It was operationally tested to calculate pavement temperatures using forecast meteorological data (Adams et al., 2004) where it was found to provide reasonably accurate results (McKittrick et al., 2004). Mass flux calculations have been used to model surface hoar growth in mountainous terrain (Adams et al., 2004). A recent iteration of the model accounts for visible radiation penetration into the snowpack and consequent subsurface heating. Spatial variability of surface temperature and near surface temperature gradients leading to surface hoar development and radiation recrystallization has been calculated based on meteorological conditions and coupled with observations (Adams et al, 2009).

STUDY LOCATION AND MODEL INPUT

The north facing ~30° slope utilized for the study is located in a generally wind protected location below timberline at an elevation of 2530 m, lat 45°14′52.3″N, long 111°27′21.8″W. The site, which is situated in the Yellowstone Club ski area in Montana, USA, has available meteorological data. It has been the focus of several previous studies (Cooperstein, 2004, Slaughter et al. 2008; McCabe et al., 2008; Slaughter et al. 2009; Adams et al., 2009). A DEM (125 m x 131m) for the site has been generated from remotely sensed light detection and ranging (LIDAR) data at a one meter planar resolution. Terrain “parts” for this site are resolved and defined as snow and coniferous trees in this model since they are the predominant winter features of this slope.

Meteorological data for one day (31 March 2010) was used in the analysis in this example; these data are shown in Figure 1. The input radiation values are provided from a weather station located on a ridge above the modeled slope. The location was used because of its unobstructed ridge-top view for measuring solar and sky radiation. The sun position is calculated based on geographical location and time. The DEM data allows the model to account for shadowing, reflection and surface to surface radiation exchange based on view factors calculated for all facets. All other environmental inputs are measured at the slope. This north facing slope was chosen for the study since we wanted specifically to examine how the interaction with different surrounding terrain properties would influence the snow on the slope. In particular, how might results differ if we consider the same conditions, but for the situation where the trees are covered with snow?

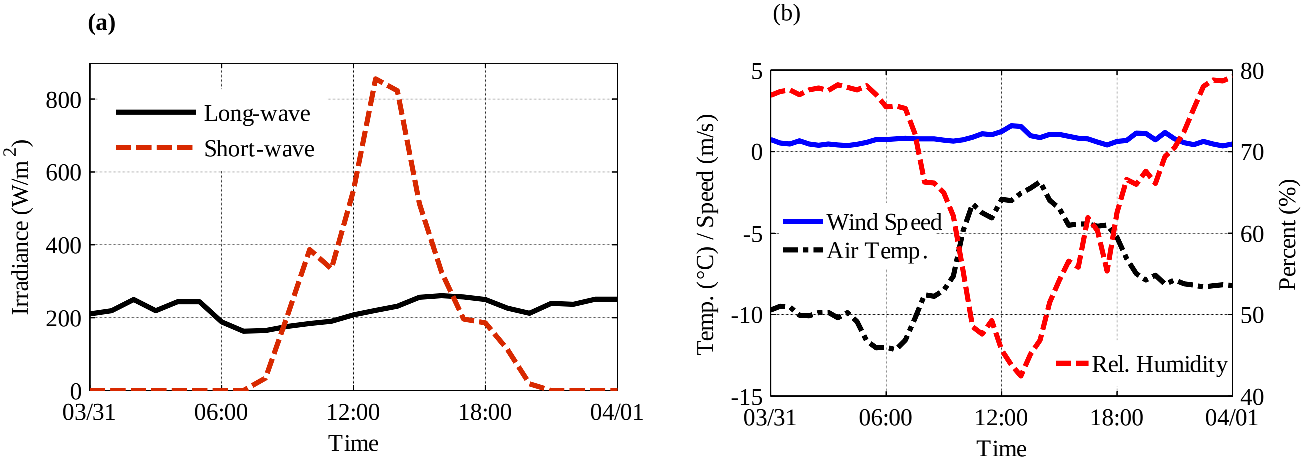


Figure 1: Recorded (a) radiation data from a ridge above the study location and (b) air temperature, wind speed, and relative humidity data from the north study location on 31 March 2010, which was used as input into the energy balance model.

Radiation was selected as the primary focus of this paper because it is understood to be one of the most import parameters influencing snow morphology near the surface. In a recent study, Slaughter (2010) considered an energy balance model which was similar to that used in the Radtherm/RT simulation, but essentially considering an individual facet. He applied Monte Carlo simulations to construct a sensitivity analysis, developed by Saltelli (2002), that allows the variance in the model output to be apportioned to each of the inputs. That is; how much of the change observed in the model output is due to the changes in each of the model inputs. Inputs included both environmental parameters (e.g., albedo and short-wave radiation) and snow properties (e.g., density and thermal conductivity). The model outputs addressed the formation of surface hoar and radiation recrystallization, both of which are faceted forms that affect the strength and likely alter the reflective properties of snow (Kokhanovsky and Zege, 2004; Jin et al., 2008).

In general, the work performed by Slaughter (2010) highlights and quantifies the importance of incident long-and short-wave radiation on the snow. His results indicate that the most critical energy component for the formation of surface hoar is incoming long-wave radiation. Approximately 57% of variance in the model output—mass deposition onto the snow surface—was directly related to absorbed long-wave radiation. When interactions with other inputs were considered, this value increased (e.g., changes in long-wave radiation coupled with changes in snow density and/or wind speed). In this case, approximately 74% of the output variance is in some fashion related to long-wave radiation absorption.

The topographic configuration of the site is such that the snow covered slope is a consistent at 30 – 35 degrees, has a northern exposure and is surrounded by trees as indicated in Figure 2. On this date in the spring, the sun is sufficiently high (maximum solar elevation angle 49°) to clear the obstruction presented by trees on the upper (south) section of the slope providing direct incident solar radiation to much of the slope. For the snow, measured albedo on this day of 0.94 came from slope normal upward and downward facing short-wave radiometers, the snow emissivity is assumed to be 0.98. The coniferous trees are assumed to have an emissivity is 0.95 and an albedo of 0.3.

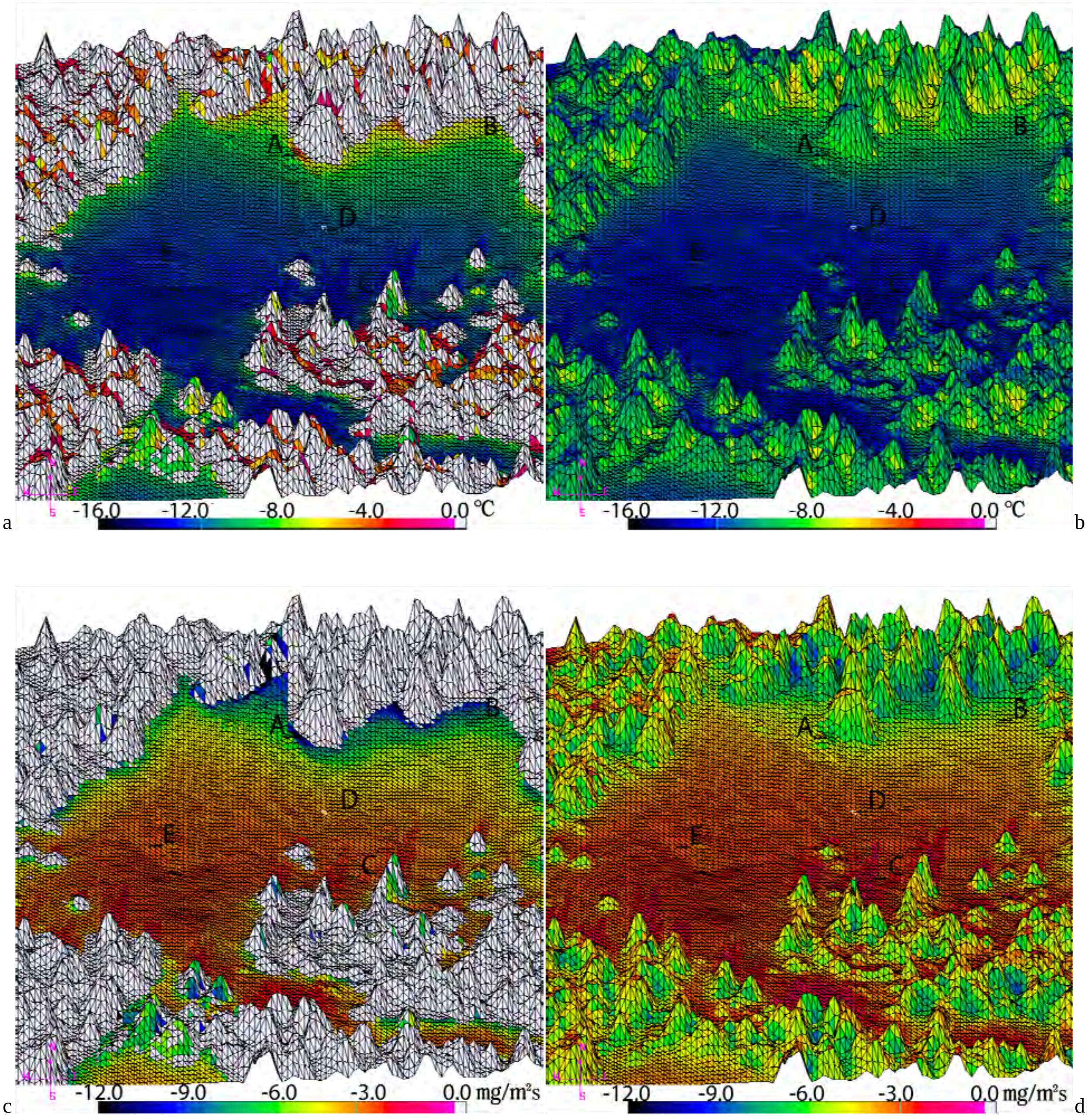


Figure. 2: Digital elevation map (~125m x 131m) demonstrating an instantaneous spatial temperature and mass flux distributions calculated for the snow on the slope at 13:00. (a) Temperature map for the snow slope surrounded by trees, (b) temperature map for the snow slope with the snow-on-trees scenario, (c) mass flux rate for the trees scenario and (d) the mass flux for the snow-on-trees case. The locations of selected points are labeled.

ANALYSIS

First, we consider results averaged across the open snow covered slope and compare the scenarios where the trees are free from snow and where the trees are covered with snow. For this document, the scenario in which the trees are covered with snow are referred to as “snow-on-trees”. Covering the trees with snow is implemented by replacing the tree thermal properties with thermal properties of fresh snow. Figure 3 displays the calculated temperature difference for the average temperature of the entire snow covered clearing and for a few selected facets. The location of these facet elements are labeled in figure 2. The calculations indicate that the snow on the slope for the snow-on-trees scenario is colder for the entire duration and reaches a maximum in the early afternoon. The difference at individual facets reveals this same trend; however there is a distinction depending on position relative to the surrounding terrain features.

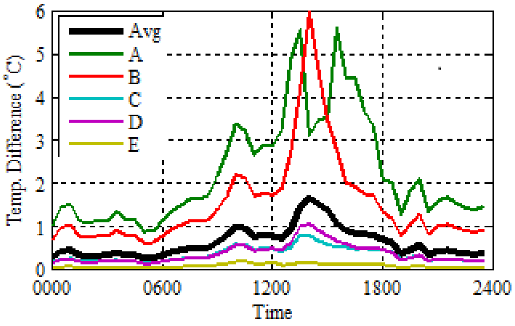


Figure 3: Difference of the calculated temperature (trees minus the snow-on-trees) for the two scenarios modeled; for selected elements and for the average of all elements on the snow slope. The case with the uncovered trees predicts the snow bordering is warmer everywhere. The locations of the individual facets are displayed on figure 2.

We next investigate the radiation incident on the snow covered slope (Figure 4), which is strongly influenced by the different materials and their topographic orientation. Radiation incident on the snow slope is the result of direct and reflected short-wave (solar) radiation and long-wave (infrared) radiation exchange between each snow slope facet, with its surroundings and with the sky (as defined by the view factors). Figure 4 provides a time history of the radiation averaged over all facets. Figure 4b provides a measure of the energy gain due to radiation for the snow for the two scenarios. Warming will result due to the short-wave gain (figure 4b) distributed through the depth with cooling at the surface resulting from the long-wave radiation loss (figure 4b).

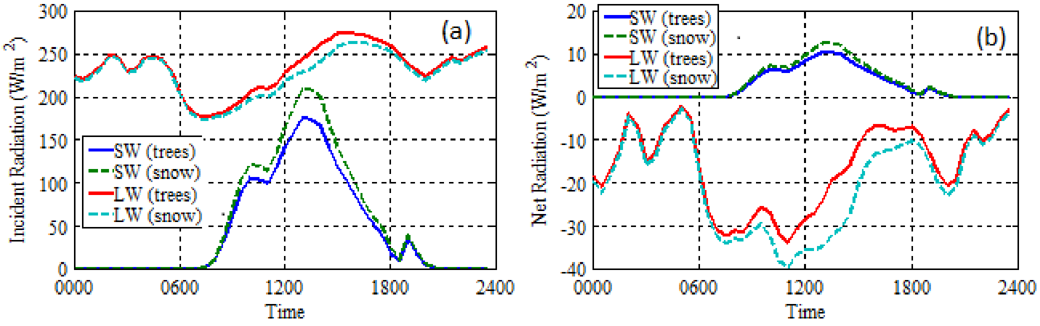
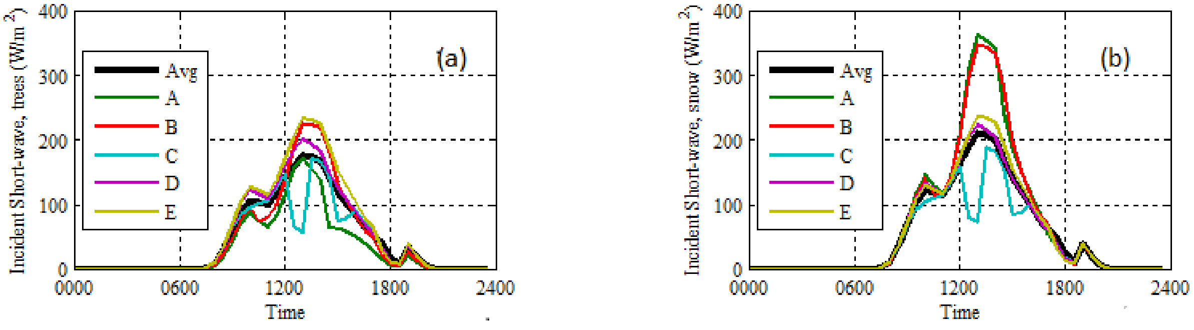


Figure 4: The average incident radiation across the snow slope for (a) incoming long wave (LW) and short wave (SW) and (b) net (absorbed) solar and infrared radiation for the snow and snow-on-trees settings. The "snow" in the legend indicates the snow-on-trees scenario.

The spatial variation of the slope snow temperature and the difference in this variation between scenarios is apparent in figure 2. This spatial variability is largely a response to the different forcing radiation induced by the surrounding terrain properties and the general topology. Clearly from figure 4 the short-wave (solar) incident to the slope snow is greater for the snow-on-trees condition. As shown in figure 5 , the difference at some locations is substantial. It is also apparent that there is a marked difference for the incident long-wave (infrared) for the different conditions. Here, again strongly dependant on location, the incident long-wave is adding more energy in the case of the trees.



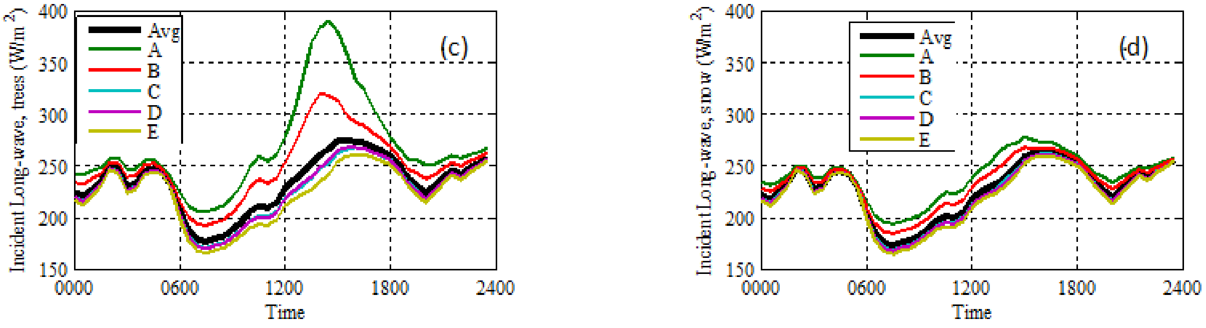


Figure 5: Selected facets for the calculated incident short-wave radiation for the (a) trees, and (b) the snow-on-trees. The calculated incident long-wave radiation for (c) the trees and (d) the snow-on-trees.

An extremely important aspect considered here is the mass gained or lost from the snowpack. Figure 6 displays the calculated rate of mass flux rate averaged for the entire snowpack surface area of 7500 m^2 for the two scenarios. Clearly there are periods of deposition (+) and periods of sublimation (-). During times of deposition, accumulation is greater for the snow-on-trees scenario, while during sublimation the rate of loss is less. During transition periods, the instantaneous individual directions of mass flux rate for each of the scenarios may differ, but yield the same overall effect on mass balance.

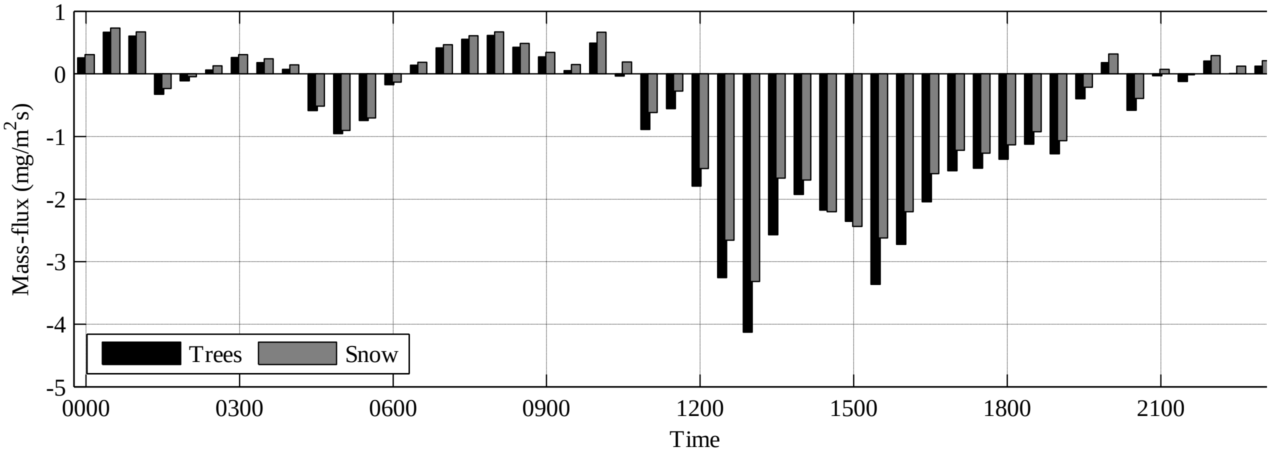


Figure 6: The rate of mass flux averaged for the entire snowpack for the snow-on-trees (snow) and the trees (trees) scenarios. Positive values indicate mass deposition onto the snow slope and negative values indicate sublimation.

Integrating calculated flux values for this entire day indicates that there would be a total mass loss for both cases. Overall, the analysis yields a loss of snow for the snow-on-trees condition that is 27% less than that of the trees. Considering the individual contribution for periods of accumulation, we see that the snow-on-trees is 32% greater than that of the trees and for periods of sublimation the loss is 18% of that of the trees. The accumulation-to-loss ratio of mass on the slope for the trees is 0.14 and for the snow-on-trees is 0.24.

DISCUSSION

In this numerical analysis, we examine the influence that topography and terrain thermal properties may have on snow. We consider the potential of what might be expected at the slope scale (or below) in the presence or absence of adjacent snow covered topographically complex terrain. Of particular relevance is the influence of short- and long-wave radiation interactions.

The short-wave albedo of bare trees is lower than for the snow-on-trees, which induces relatively greater heating of the trees when they are exposed to solar loading. This warmer temperature, apparent in Figure 2, results in greater long-wave emission from the trees to the snow on the slope. Conversely, there is less heating of the snow-on-trees due to solar loading, resulting in less incident long-wave radiation to the snow on the slope. As a consequence, the higher albedo of the snow-on-trees yields greater incident short wave to the snow slope when it is reflected from the snow-on-trees. Particularly noteworthy to this distinction is physically where these processes are most prominent. The influence is most pronounced at the bottom, northern edge of the snow slope (figures 2 and 5) near complex features in “view” of the snow.

Although direct sunlight is available to this north facing, tree bounded, ~30 degree open snow slope at this time of the year, it is at an oblique incident angle. This oblique orientation yields a smaller facet view factor to the sun. The facet view factor for the generally vertical trees that are subjected to direct solar loading (for example at the bottom northern edge of the open slope) will be greater. View factors between facets provide for radiative exchange resulting from relative orientation for the given topography. With this and the thermal properties of the two terrain types known, the radiation exchange is calculated.

The influence of energy exchange on the snow temperature is determined, to a large degree, by its high short-wave reflectivity and near black body emissivity. These factors are apparent in the net radiation displayed in figure 4. Although there is significant incident short-wave to provide heating, the net gain is not large when compared to the net long-wave energy loss. Also the net short-wave radiation gain to the snow is greater for the snow-on-trees than for the trees due to increased reflectivity of the snow encompassing the trees. With regard to the terrain radiation exchange, the long-wave net loss is still the more significant.

It should be noted that the long-wave exchange takes place at the snow surface, while a portion of the incident short-wave will penetrate the snow to be absorbed and attenuating with depth. It is this property that can, in certain instances, have a profound influence on the near surface snow morphology, producing a thin layer of faceted crystals at and just below the surface. While much of the incident short-wave energy may be reflected for certain snow types, the solar influence is very important. It should also be stated that the albedo of snow is variable, ranging from 0.80-0.95 for fresh dry snow; 0.70-0.80 for old, dry snow; 0.5-70 for wet snow and 0.25-0.8 for melting ice/snow (Armstrong and Brun, 2008). While these albedo values are useful in analysis such as this, the snow albedo is highly wavelength dependent (Armstrong and Brun, 2008).

New snow has one of the highest albedos in the visible spectrum of any natural material, with pure snow typically absorbing less than 10% of the incoming visible radiation. In the NIR (near-infrared), approximately 20-60% of the energy is absorbed depending on snow grain size. For the SWIR (short-wave infrared) and longer wavelengths, snow is essentially a blackbody absorbing nearly 100% of the energy (Armstrong and Brun, 2008). In the NIR, grain size is a primary variable in determining a snowcover albedo while the visible albedo is largely insensitive to grain size (Wiscombe and Warren, 1980; Dozier and Painter, 2004). An optically equivalent spherical grain size is normally calculated or measured when determining the NIR dependence. Since little energy penetrates the snow surface above the visible wavelengths, grain size has appropriately beenused as a principal parameter to predict the NIR albedo. With the highly active thermodynamic microstructure near the surface and the potential for surface penetration of visible radiation, rapid and dramatic changes in near surface morphology are frequently observed. Little consideration has been given to crystal habit in albedo effects but there are indications that morphology may be a significant contributor to visible reflectance, particularly if considered from variable directions. Jin et al. (2008) predicted that the equivalent spherical grain approach worked well when reflected energy was hemispherically averaged, but over predicted forward reflected and under predicted backscattered irradiances. They argue that reflected directional properties of snow depend upon snow particle shapes. The topographic influences discussed here may result in altered snow grain morphologies which, in turn, influence snow slope radiation exchanges. This provides a potential environmental feedback mechanism as alerted properties give rise to altered radiation exchanges.

Although no physical observation of the snow was made on this day, faceted surface hoar crystals likely developed during the night. This conclusion is based on a separate study carried out on this same slope when wide spread 5 mm surface hoar crystals were observed (Adams, et.al, 2009). Applying the Radtherm/RT model to the meteorological conditions in that instance, mass flux values similar to those calculated here were observed. In the present study, the onset of melt was also calculated at a few locations on the slope, which would indicate a change in morphology toward larger more rounded grains. This is relevant since changes in grain size and possibly shape will influence the snow albedo and consequently play an evolving role in the energy and mass balance. This is an area of research that is relevant to environmental snow science.

Furthermore, the resulting temperature differences displayed in figure 3 are also influenced by the convective atmospheric exchange and conduction in the snowpack, which are governed in part by the temperature of the snow surface itself. Phase change also contributes to the resulting snow temperature. We note that the modeling of phase change of the snow following the onset of melt is not adequately handled in this model due to the complex interactions that result from the phase changing in the three phase granular material.

CONCLUSIONS

Our interest in this study is to examine how differences in snow coverage, whether the result of annual variations or longer term climate deviation, may influence a snowcover. At the global scale, feedback to the atmosphere that accompanies the areal coverage of the snow generally implies that a reduction in extent will result in atmospheric warming. Consequently, adjusting the areal extent of snow for a given annual point in time can have important climactic ramifications as the result. We approach this concept from a local, that is at the slope scale or smaller, rather than the larger global or regional scale. This smaller size consideration when integrated to a larger area, naturally, contributes and adds detail to the bigger issue.

Changes in precipitation patterns may dictate modification of the seasonal extent of the snow cover, so that portions of the local landscape will have different distribution. In our analysis, we examine how different portions of the landscape with material specific thermal properties will interrelate. We examine a specific case of trees and trees that are assumed snow covered on a specific slope and at a particular time. However, conclusions and analysis techniques from this case study are applicable to other materials such as rock and to different topographies. For the scale we examined, a primary consideration of importance is the inter-surface and the surface to atmosphere and surface to sun view factors. If we had considered flat terrain with little or no inter-surface view factor association, then the influence of different thermal properties for different parts of this terrain would have little influence. This does not imply that less topographically complex terrain (which also has a mix of snow covered and non snow covered terrain) is not important on a larger or global as an influential factor in climate analysis. Nor does it imply that there are not important considerations at the local scale for snow with another material at the lateral interface, such as patches of bare ground interspersed with snow, where for example transverse conduction might be important.

The influence of snow covered verses non-covered topographically complex terrain has a significant spatially varied influence on both the energy and mass balance at the local slope and smaller scale. For conditions modeled in the example case presented for dry snow, when terrain (i.e. trees) were covered with snow, the adjacent snow covered slope always remained cooler and had less mass loss. Examination of these important balance considerations at the local scale accounting for topography and terrain properties is relevant to a comprehensive understanding at the global scale. Additional investigation is warranted.

It is important to examine variation at the small scale as well as at the global and regional scales. A robust evaluation governing environmental variation important at these smaller scale and modeling efforts such as this could be helpful to a deeper understanding of this complex system. It will also be important continue to examine more completely the changes that snow surface morphology play in feedback to snow retention and the resultant influence on to the global environment.

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