Landsurface Thermodynamic Response to Snow Depth Variability

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ABSTRACT

The presence of a snow cover is generally understood to produce an energy deficit at the surface-atmosphere interface, due to the high albedo of snow. Increasing snow depths are expected to augment this surface energy deficit, due in part to other thermodynamic processes such as conductive heat exchanges with the atmosphere and underlying soil. However, the specific effects of this snowpack thermal insulation property on snowpack and soil column temperatures are not well understood. This study isolates the landsurface thermodynamic response to snow depth variability using the SNTHERM one-dimensional snowpack energy and mass balance model, driven by meteorological observations for a station in Minneapolis, MN. Six simulations of a repeated winter day and a single winter season, with varying initial snow depths of 0.0 to 0.5 m, indicate that thicker snowpacks result in notably warmer average snowpack and soil column temperatures that are less reactive to air temperature fluctuations. Ground heat flux decreases and sensible heat flux increases, but radiative and latent heat fluxes are unaffected. These features respond nonlinearly to snow depth, but the overall response to increasing depth (0.1 m to 0.5 m) is comparable to the response to snow presence (0 m to 0.1 m). The results demonstrate that deeper snowpacks enhance the insulation of the atmosphere from the ground, so that more heat from the ground is retained below the surface-atmosphere interface. This insulative property provides a mechanism whereby increased snow depth can result in widespread diabatic cooling of the overlying atmosphere, and initiate remote climate teleconnections via dynamical processes.

Keywords: snow, insulation, soil, temperature, thermodynamics

INTRODUCTION

A considerable body of research has explored the atmospheric response to anomalous land surface snow cover (e.g., Ellis and Leathers, 1999; Bamzai and Shukla, 1999; Watanabe and Nitta, 1999; Cohen and Entekhabi, 2001; Gong et al., 2002). These local and remote climatic consequences are of course initiated by a more immediate snow-forced change in the land surface energy balance, i.e. energy fluxes acting on the surface, and temperatures within the snowpack and soil column. Therefore a detailed understanding of the thermodynamic impact of snow on the energy balance and thermal states within the land surface itself is of interest, and serves as a foundation for characterizing, attributing and quantifying the subsequent atmospheric and climatic response. The goal of this study is to provide a more detailed understanding of the land surface thermodynamic response to snow cover.

The shortwave radiation response to snow cover due to surface albedo changes is traditionally accepted as the dominant mechanism of snow-forcing at the land surface (e.g. Cline, 1997;

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Marshall et al., 2003). Other studies suggest that the insulating effects of snow cover on diffusive heat fluxes, and the latent heat flux associated with snowmelt, may also contribute to the overall surface energy balance response (Cohen, 1994). The potential influence of multiple processes is more apparent when the depth of snow on the ground is considered as well as its presence or absence. The presence of a thin snow cover will dramatically influence the surface albedo but may not provide substantial insulation or snowmelt. Conversely, a thicker snow cover will likely have a more modest effect on surface albedo (due primarily to increased fractional snow coverage on vegetated surfaces), whereas the insulation provided and the amount available for snowmelt can increase dramatically.

This study focuses on the insulative property of varying snow depth, in an effort to establish this specific relationship as a substantial contributor to the overall land surface energy balance response to snow cover. The scientific literature on heat diffusion through a snow-covered land surface deals primarily with snow cover presence or duration (Goodrich, 1982; Gosnold et al., 1997; Schmidt et al., 2001; Ling and Zhang, 2003), although some studies have recognized a measurable influence of snow thickness and its insulative capability (Smith and Risborough, 1996; Gong et al., 2004; Grundstein et al., 2005). A modeling approach is employed here to gain further insight by isolating the heat diffusion response to varying initial snow depths including snow-free conditions, and assessing the magnitude of associated temperature and insulative energy flux anomalies within the entire snowpack – soil column system.

APPROACH

Modeling experiments are conducted using SNTHERM (Jordan, 1991), a one-dimensional mass and energy balance snowpack model developed by the US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory (CRREL). Snow and soil layers are divided into horizontally infinite control volumes with vertically homogeneous physical properties. Each layer is controlled by the governing equations for mass, momentum and heat balance, subject to meteorological boundary conditions at the snow – air interface such as air temperature, wind speed, relative humidity, precipitation and cloud cover, and a temperature boundary condition at the lowest soil layer. Initial conditions consist of temperature, density, grain size and water content for various snow and soil layers. Outputs are thickness, temperature, phase, density, grain size, effective specific heat and thermal conductivity for each model layer, and the energy fluxes acting on the snowpack. SNTHERM has been shown to accurately estimate energy fluxes and represent physical processes within snowpacks (e.g. Cline, 1997; Ellis and Leathers, 1999).

Two experiments are conducted to evaluate the land surface insulative response to snow depth, over diurnal and intra-seasonal timescales. The specific atmospheric boundary condition applied in each of experiment represents a different degree of atmospheric complexity. However, both experiments isolate the insulation process response to snow depth from other processes. SNTHERM does not account for spatial heterogeneity due to vegetation cover, so the surface albedo response to snow depth via fractional snow coverage is minimized. Also, both experiments focus on the winter season where temperatures are consistently below freezing, so the latent heat flux response to snow depth is minimized. For each experiment, a set of six simulations under idealized boundary conditions is performed to isolate the energy and temperature responses due to initial snow depth perturbations. The initial snow depths (0.0, 0.1, …, 0.5 meters, hereafter denoted as SND0, SND0.1, …, SND0.5), reflect a realistic range of snow depths at the study site.

Experiment 1: In these simulations the hourly meteorological conditions of January 7th, 2008 are repeated for 50 days, representing a typical cold and dry winter day. The controlled and repeated atmospheric boundary conditions in Experiment 1 facilitate an analysis of the diurnal cycle response to snow depth. Precipitation is fixed at zero throughout the simulations, so that no more snow is added besides the prescribed initial snow depths. Hence the SND0 simulation remains snow-free throughout, allowing for an explicit comparison of the effects of snow depth vs. the presence of snow. The six simulations can be placed into three categories, with absent (SND0), thin (SND0.1) and thicker (SND0.2-SND0.5) snowpack.

Experiment 2: These simulations are run from December 1st, 2007 to February 29th 2008. The same 91-day observed meteorological timeseries (e.g., air temperature, humidity, wind conditions, precipitation) are applied as boundary conditions for each of the six simulations. The inclusion of observed precipitation inputs throughout the simulations means that even the SND0 scenario will have a snowpack, since air temperatures are consistently below zero during this winter simulation so that precipitation falls as snow. The 91-day winter season duration of Experiment 2 captures the intra-seasonal variability in atmospheric conditions, in addition to hourly variations.

RESULTS

Experiment 1 – Repeated-Day Simulations with Different Initial SND

Snowpack temperature, surface snow temperature, soil column temperature and topmost soil temperature are averaged from day 41-50 and plotted with respect to the six different initial SND conditions in Figure 1. The results of the final ten days of the simulation (day 41 to 50) are presented to allow the model to reach a pseudo-equilibrium state for the simulated days. The snowpack (soil column) temperature is computed as the thickness-weighted average of snow (soil) temperature at each layer. The topmost soil temperature is the temperature at the topmost soil layer, which extends to 3 mm below the land surface.

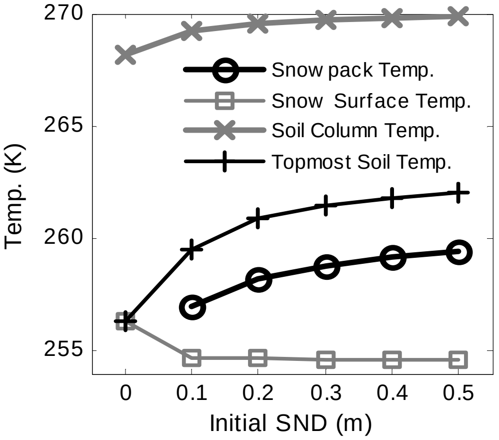

Figure 1. Ten-day averages (day 41 to 50) of temperatures within the snow-soil system for Experiment 1. The x-axis represents six different initial SND conditions (SND0 to

Figure 1 shows that snow and soil temperatures warm nonlinearly with snow depth throughout the system except for at the snow surface where temperatures cool slightly. Increased SND translates into greater insulative capacity, allowing more of the upward heat conduction from the lower soil boundary to be retained in the snow-soil system. This results in warming throughout the snowpack and soil column except at the snow surface.

Note in Figure 1 that the topmost soil temperature difference varies substantially across the six simulations (TSND0.5-TSND0=5.7 °K). Furthermore, the difference between thick and thin snow (TSND0.5-TSND0.1=2.5 °K) is close to the difference between thin snow and bare ground (TSND0.1-TSND0=3.2 °K). The soil temperature difference induced by snow depth changes is attributable primarily to added insulative capacity, whereas the temperature discrepancy caused by snow presence/absence is attributable primarily to the high albedo of snow-covered ground. A similar observation holds for the soil column average temperature. Therefore, snow thickness exerts an insulative influence on soil temperature that is considerable and comparable in magnitude to the radiative influence of snow presence.

Ten-day averages of ground and sensible heat transfer from day 41 to 50 are plotted with respect to different initial SND in Figure 2. A thicker snowpack nonlinearly reduces the rate of ground heat transfer from underlying soil and increases the rate of sensible heat transfer from the atmosphere. The change in ground heat flux induced by SND anomalies is substantial in magnitude, i.e. GHSND0.1-GHSND0.5=6.6 W/m^2 which represents a roughly 60% decrease from the GHSND0.1 value (10.6 W/m^2). The change in sensible heat flux is more modest, i.e. SH SND0.5-SH SND0.1=1.7 W/m^2 which represents a roughly 5% increase from the SHSND0.1 value (35.9 W/m^2). Shortwave radiation, longwave radiation and latent heat changes with SND are negligible in comparison (not shown), indicating the predominant roles of ground heat and sensible heat in the SND-driven land surface thermal response. Note that SND0 is not included in Figure 2 since the energy exchange for this simulation does not occur within the snowpack.

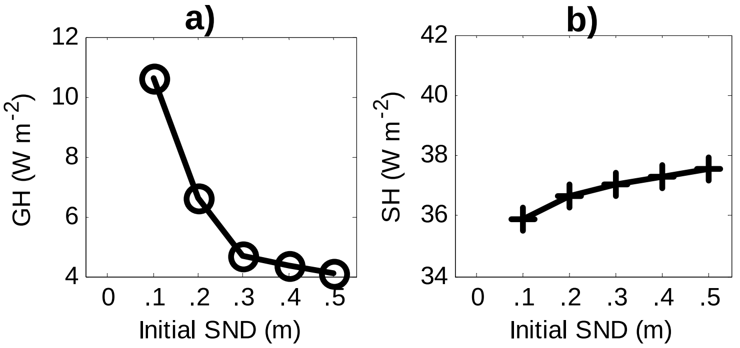

Figure 2. Ten-day averages (day 41 to 50) of a) ground heat flux (GH) and b) sensible heat flux (SH) for Experiment 1. The x-axis represents six different initial SND conditions (SND0 to SND0.5).

Hourly variations of topmost soil temperature and snowpack temperature are plotted in Figure 3. For each hour within a day, values are averaged over a ten-day period from day 41 to 50. Topmost soil temperature (Figure 3a) exhibits clear diurnal cycle for bare ground, in response to the atmospheric boundary, i.e., air temperature and incoming solar radiation changes. The existence of a snowpack warms up the soil, dampens the amplitude of the soil temperature's diurnal oscillation, and delays the afternoon peak temperature. Thicker snowpacks further warm the soil, and suppress and lag its diurnal temperature cycle. For SND0.5, the topmost soil layer exhibits only a slight diurnal cycle. Figure 3a also shows that the diurnal temperature response to a thicker snowpack (SND0.5 vs. SND0.1) is comparable to the diurnal response to the presence of snow (SND0.1 vs. SND0).

Figure 3b shows that the snowpack exhibits a diurnal temperature cycle for all snow depths. As for the soil, thicker snowpacks exhibit warmer temperatures, and more suppressed and lagged diurnal cycles (Figure 3a). However the sensitivity of snowpack's diurnal cycles to SND is far less than that for the soil, due to the relatively large thermal conductivity of snow. Even for SND0.5, the snowpack still exhibits an appreciable diurnal cycle. Hence the presence and thickness of snow progressively decouples the atmospheric boundary forcings from the underlying soil, so that the snowpack responds to the diurnal forcing more so than the soil.

Figure 3 suggests a second insulative function of a snowpack, namely a mitigation of the thermal responsiveness of the soil to atmospheric boundary conditions (e.g., the shortwave radiation and air temperature variability). This suppression of surface influence helps to facilitate the primary insulative function of the snowpack, i.e. warming from the lower soil boundary condition by retaining more upward heat transport within the snow-soil system. Thicker snow contributes to both the overall warming and diurnal suppression, to a comparable degree as snowpack presence.

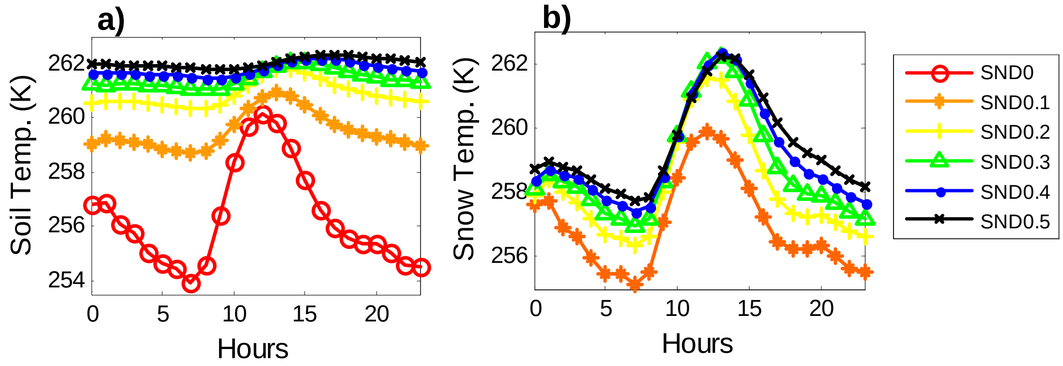

Figure 3. Diurnal variation of a) topmost soil temperature, and b) snowpack temperature for Experiment 1. For each hour, temperatures are averaged from day 41 to 50.

Experiment 2 – Intra-seasonal Simulations with Different Initial SND

An entire 91-day winter season is simulated in Experiment 2, rather than a single dry winter day repeated 50 times as in Experiment 1. This allows for an analysis of the intra-seasonal variability of snow depth's influence on the insulation process, e.g. the maximum extent of the surface temperature response that can be expected over the course of a season. Ten-day running means of air, snowpack and topmost soil layer temperature are plotted in Figure 4. Thicker snowpacks yield higher temperatures in both the snow and soil, consistent with Experiment 1. Snowpack temperature follows the same temporal pattern as air temperature variations (Figure 4a), but values are consistently higher than the overlying air temperature because of ground heat supply from the underlying soil. Meanwhile the range of snowpack temperatures over the course of the season is less than that for air temperatures, and this range decreases with increasing snow depth due to snowpack's insulative heat capacity. Similarly, thick snow has warmer and less variable soil temperature at the topmost soil layer (Figure 4b).

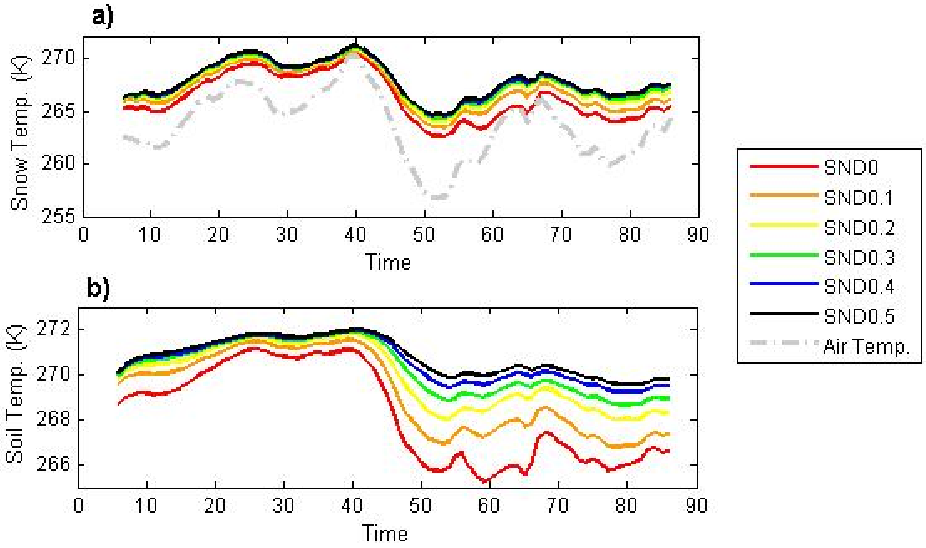

Figure 4. Ten-day running means of a) snowpack temperature, and b) topmost soil layer temperature at z=-3mm for Experiment 2, for six simulations with different initial snow depth conditions (SND0 to SND0.5).

The temperature changes across the six simulations vary considerably over the course of the season, reaching magnitudes of TSND0.5-TSND0=2.9 °K for the snowpack temperature, and TSND0.5-TSND0=4.8 °K for the soil temperature. Note that these differences cannot be directly compared to those for Experiment 1, since the SND0 scenario is not "snow-free" in Experiment 2. Likewise the response to snow depth vs. snow presence cannot be distinguished in Experiment 2. However, TSND0.5-TSND0 for Experiment 2 does capture the full temperature response to snow depth changes via insulation, and indicates that the surface soil temperature can increase by nearly 5 °K during the course of the snow season solely as a result of added insulation. As can be seen in Figure 4b, this response magnitude is approximately the same as the temporal range of temperature values that occur over the course of the snow season for the SND0 simulation.

Figure 5 shows ten-day running means of ground heat and sensible heat fluxes, which decrease and increase respectively with initial snow depth. Ten-day running means of shortwave radiation, longwave radiation and latent heat fluxes (not shown) do not show any appreciable difference between different initial snow depth conditions. These results are consistent with Experiment 1. However, note that in Figure 5 the ground and sensible heat flux change across the six simulations varies considerably over the course of the season, reaching magnitudes of GHSND0-GHSND0.5=15.7 W/m^2 for ground heat, and SHSND0.5-SHSND0=8.9 W/m^2 for sensible heat. These changes due solely to snow depth insulation are appreciable, since the ground and sensible heat fluxes themselves are on the order of 10 W/m^2, and vary by roughly 10-20 W/m^2 over the simulated season.

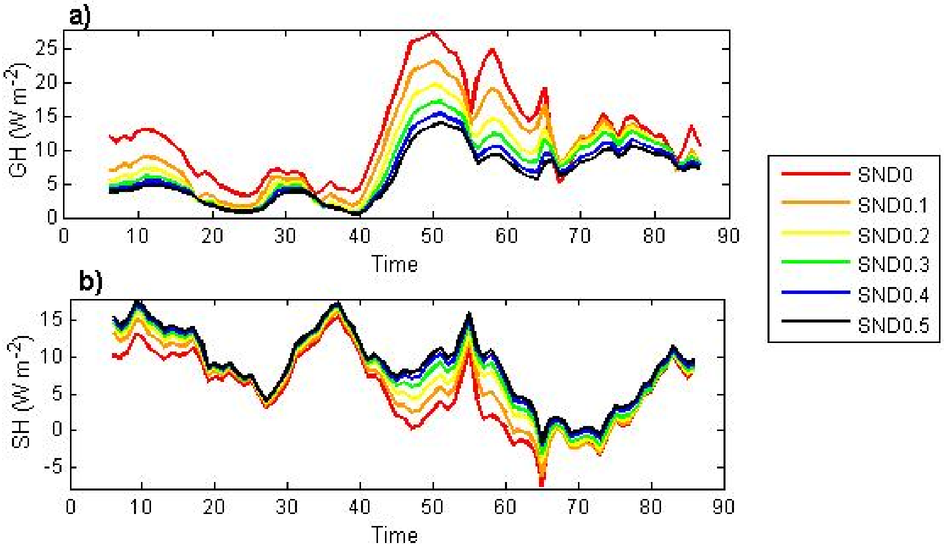

Figure 5. Ten-day running means of a) ground heat flux (GH), and b) sensible heat flux (SH) for Experiment 2, for six simulations with different initial snow depth conditions (SND0 to SND0.5).

CONCLUSIONS

This study describes the land surface insulative response to increasing snow depth. Perturbation experiments with varying initial snow depths indicate that with increasing SND, the overall snow – soil system warms, but the surface snow layer cools slightly. The soil column also exhibits a suppressed diurnal cycle. The warmer land surface thermal state in turn generates decreased ground heat flux and increased sensible heat flux responses. The model simulations are designed so that this land surface thermal response is attributable to the increased insulative capacity of deeper snowpacks, which makes the underlying soil less responsive to solar radiation and air temperature fluctuations, and facilitates sustained warming by the bottom soil layer boundary.

The magnitude of the surface temperature response over a 0.5 m range of snow depths is generally on the order of 3 to 5 °K. The corresponding ground and sensible heat flux responses are more variable, ranging from roughly 2 to 40 W/m^2. Compared to the typical values that occur during repeated-day simulations (Experiment 1) and the temporal ranges that occur during single-season simulations (Experiment 2), the modeled response to snow depth is quite substantial. Furthermore, although the thermodynamic response is asymptotically nonlinear with increasing snow depth, the overall effect of increasing depth due to insulation is comparable to the effect of snow presence vs. absence due to albedo.

The warming of the snow-soil system that occurs for deeper snowpacks can have a direct consequence on the overlying atmosphere. The additional heat retained within the snow-soil system due to a deeper snowpack represents energy that would otherwise be released to the atmosphere, so air temperature is likely to decrease as the snowpack gets thicker. This is consistent with the general understanding of surface air temperature response to snow cover reported in the literature (e.g., Baker et al., 1992; Ellis and Leathers, 1999; Gong et al., 2004), although the local air temperature suppression is usually attributed to albedo increases due to anomalous snow extent, which can be spatially and temporally fleeting. The insulation process identified here involves anomalous snow depth, which can occur over broad regions and sustained periods, regardless of snow extent anomalies. Hence the results of this study offer an alternative mechanism whereby increased snow depth can potentially result in widespread diabatic cooling of the overlying atmosphere, and initiate remote climate teleconnections via dynamical mechanisms. Snow depth perturbation modeling studies which include an interactive atmosphere are required to confirm this mechanism, and are the subject of ongoing research.

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