Major Issues in Simulating Some Arctic Snowpack Properties Using Current Detailed Snow Physics Models: Consequences for the Thermal Regime and Water Budget of Permafrost

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Key Points:

- The detailed snow physics models Crocus and SNOWPACK do not simulate adequately physical properties of Arctic snowpacks such as thermal conductivity
- Incorrect thermal conductivities of snow layers do not affect ground temperature if the snowpack thermal insulance is correctly simulated
- Incorrect thermal conductivities of snow layers however modifies the simulated soil water budget, the soil thermal conductivity, and the snow surface temperature

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Major Issues in Simulating Some Arctic Snowpack Properties Using Current Detailed Snow Physics Models: Consequences for the Thermal Regime and Water Budget of Permafrost

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Abstract Accurately simulating the physical properties of Arctic snowpacks is essential for modeling the surface energy budget and the permafrost thermal regime. We show that the detailed snow physics models Crocus and SNOWPACK cannot simulate critical snow physical variables. Both models simulate basal layers with high density and high thermal conductivity, and top layers with low values for both variables, while field measurements yield opposite results. We explore the impact of an inverted snow stratigraphy on the permafrost thermal regime at a high Arctic site using a simplified heat transfer model and idealized snowpacks with three layers. One snowpack has a typical Arctic stratification with a low-density insulating basal layer, while the other (called *Alpine-type snowpack*) has a dense conducting basal layer. Snowpack stratification impacts simulated ground temperatures at 5 cm depth by less than 0.3 °C. Heat conduction through layered snowpacks is therefore determined by thermal insulance rather than by stratification. Ground dehydration caused by upward water vapor diffusion is 4 times greater under Arctic stratification, leading to a larger latent heat loss, but also to a lower soil thermal conductivity caused by ice loss, so that the overall effect of dehydration on ground temperature is uncertain. Snowpack stratification is found to affect snow surface temperature by up to 4 °C. Lastly, different snow metamorphism rates lead to a lower Alpine snowpack albedo, contributing to a warmer ground. Quantifying all these effects is needed for adequately simulating permafrost temperature. This requires the development of a snow and soil model that describes water vapor fluxes.

Plain Language Summary Many detailed snow physics models were developed mostly for alpine conditions. They do not reproduce the strong upward water vapor flux between the lowest snow layers in contact with the warmer ground and the upper snow layers in contact with the colder atmosphere, which occurs in the Arctic. As a consequence, snow density and thermal conductivity are not adequately simulated for Arctic conditions. Models predict high density, high thermal conductivity basal snow layers, while the opposite is observed in the Arctic. We show that, if the total insulating capacity of the snowpack is simulated correctly, having an incorrect layering of thermal conductivity in the simulated snowpack has little impact on ground temperature. However, since current models do not simulate the upward water vapor flux, the water vapor loss of the ground in winter cannot be simulated either. This affects the soil water budget and therefore its physical properties, and this may modify its temperature. Incorrect snow layering is also found to affect snow surface temperature by up to 4 °C.

1. Introduction

Accurately simulating the ground thermal regime is critical for permafrost because these frozen soils contain about twice as much carbon as the atmosphere (Hugelius et al., 2014) and their thawing could lead to the release of part of this carbon to the atmosphere, representing a strong positive feedback to climate warming (Schuur et al., 2015). Since permafrost is snow covered most of the year, an accurate simulation of snow

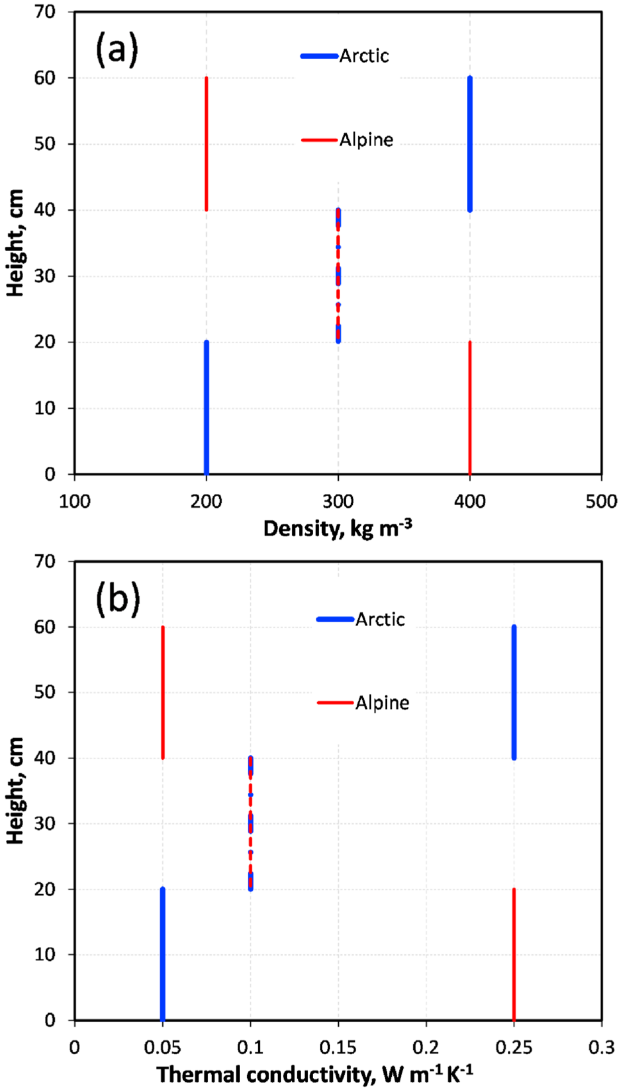

Figure 1. Physical properties of the 60-cm Arctic and Alpine snowpacks arbitrarily assigned to minimal firn model (MFM) runs. (a) Density and (b) thermal conductivity. The 30-cm snowpacks also used just have half as thick layers.

physical properties, and in particular, its thermal ones, thermal conductivity and density, is essential. Current climate models use snow schemes that are simplified (Burke et al., 2013; Chadburn et al., 2015; Decharme et al., 2016; Dutra et al., 2012; Lawrence & Slater, 2010; Paquin & Sushama, 2015) relative to available sophisticated snow models such as Crocus (Vionnet et al., 2012) and SNOWPACK (Bartelt & Lehning, 2002), and their ability to simulate snow thermal properties is not always optimal (Barrere et al., 2017) so that efforts are needed to improve these schemes. Before resorting to more sophisticated snow models, it is necessary to evaluate their performance and detect possible deficiencies before defining a strategy to improve the ability of climate models to simulate the thermal regime of frozen soils and hence related climate feedbacks.

Snow thermal properties are also important to simulate the temperature of the snow surface. Brun et al. (2011) showed that a correct snow density profile was required to simulate snow surface temperature accurately. In their model, thermal conductivity was parameterized as a function of density only so that thermal conductivity was also an important variable. Freville (2015) attempted to retrieve surface snow density and thermal conductivity from measurements of surface temperature and found that an error of just 1 °C in surface temperature lead to an error of 100 kg/m^3 in snow density. These studies demonstrate that snow thermal properties and its surface temperature are strongly coupled and that accurately simulating snow thermal properties is critical not only for simulating permafrost temperature but also the temperatures of the snow surface and of the near-surface air. Domine et al. (2016) simulated the snowpack at Bylot Island (73°N, 80°W) in the Canadian high Arctic using Crocus and found that the density and thermal conductivity vertical profiles were inverted relative to field measurements. Low values of both variables were measured at the base of the snowpack and high values at the top, while simulations found the opposite. An online discussion of that paper also indicated that SNOWPACK had a similar defect (http://www.the-cryosphere-discuss.net/tc-2016-107/tc-2016-107-AC2-supplement.pdf). Reasons given were that the strong thermal gradient present in Arctic snowpacks generates an upward water vapor flux that transfers mass from the lower to the upper snow layers. Such a flux has been first described and measured by Trabant and Benson (1972) and numerous subsequent studies that confirmed its significance (e.g., Sturm & Benson, 1997), and it leads to low-density lower layers and high-density upper layers. Since both Crocus and SNOWPACK calculate thermal conductivity only (Crocus) or mostly (SNOWPACK) from density, the thermal conductivity profiles were not simulated adequately either. With erroneous thermal conductivity values, temperature gradients are also erroneous and therefore all the snow metamorphism as well, which govern snow physical properties. Among other terms of the energy budget, heat fluxes between the atmosphere and the ground through the snow may therefore not be represented adequately, possibly leading to errors in the simulation of the surface energy budget and of the ground thermal regime.

Here we recall Crocus tests at a high Arctic site presented by Domine, Barrere, and Sarrazin (2016) and Barrere et al. (2017) and report additional tests of Crocus and new tests of SNOWPACK to further evaluate their ability to simulate Arctic snowpack properties. As expected, both models produce inverted thermal conductivity and density profiles. The main objective of this work it to determine the impact of these inverted profiles on the permafrost temperature. We therefore explore using a simplified heat transfer model where conductivity and density can be fixed, whether at constant thermal insulance, inverting the stratification leads to errors in the simulations of the permafrost thermal regime. Indeed, atmospheric temperature variations of finite duration do not propagate through the snow in a similar manner in snow layers of

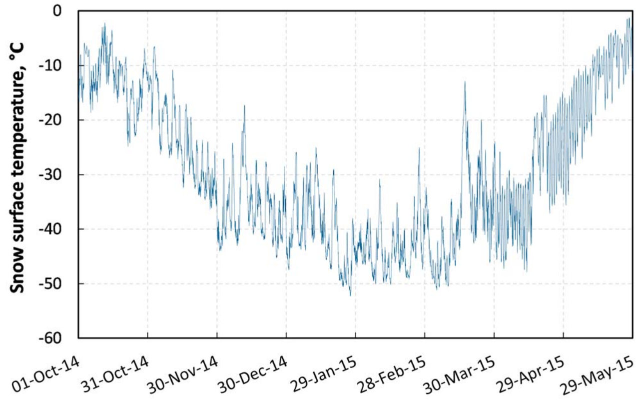

Figure 2. Snow surface temperature measured at Bylot Island for the simulation period.

different diffusivities and in particular, the thermal properties of the top layer will affect the penetration depth of thermal waves. Finally, we discuss other possible consequences of the incorrect snow simulations on the ground water budget, snow albedo, and snow surface temperature.

2. Methods

2.1. Experimental Site

Our study site is located on Bylot Island, Nunavut, Canada (73°08′N; 80°00′W) in Qarlikturvik valley. Its northern latitude means that the solar flux is essentially zero between late October and late February, so that diurnal temperature fluctuations disappear during that time. The average annual temperature, based on monitoring since 1989, is −14.5 °C (Gauthier et al., 2011). Currently, air temperature and relative humidity, wind speed and direction, ground temperature, liquid water content and thermal conductivity, surface temperature, snow temperature and thermal conductivity at several depths, and snow depth are monitored (Domine, Barrere, & Sarrazin, 2016). Logistics permitting, field trips have been performed in mid-May since 2013 to study snow properties. Snow depth was then measured at several hundred spots, and 15 to 20 vertical profiles of snow density, thermal conductivity, and specific surface area (SSA) were performed (Domine, Barrere, & Morin, 2016; Domine, Barrere, & Sarrazin, 2016). These data, together with complementary data from ERA-interim reanalyses (Dee et al., 2011), have been used as driving and testing data for previous model simulation of snow and soil properties, as detailed by Barrere et al. (2017). Similarly, snowpack simulations using Crocus driven by ERA-Interim at the scale of Eurasia and North America were previously shown to adequately correspond to measured snow depth and snow water equivalent (Brun et al., 2013; Mudryk et al., 2018).

2.2. Models to Simulate Snow Properties at Bylot Island

The Crocus snow model was used coupled to the ISBA (Interactions Soil-Biosphere-Atmosphere) land surface scheme within the SURFEX interface version 7.3 (Vionnet et al., 2012). Modifications described in Barrere et al. (2017) were used here, namely, that the effect of wind on snow density has been enhanced to fit observations and literature values of Arctic wind slab densities. Outputs variables considered here are snow density, snow thermal conductivity, and ground temperatures. For ground temperatures, simulation results are those of Barrere et al. (2017). We focus on the most complete run reported by Barrere et al. (2017), which takes into account the presence of a soil litter layer and of soil organic carbon. Given the difficulties in measuring and simulating precipitation, the amount of precipitation taken from ERA-Interim was adjusted to match observed snow depth. Simulated snow depth reached 32 cm in 2014 and 54 cm in 2015.

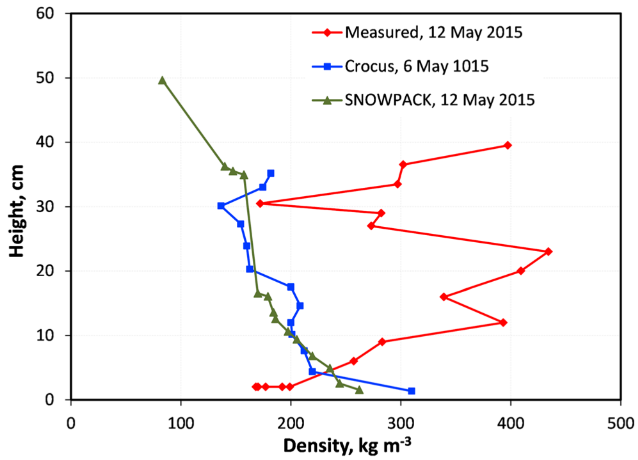

Figure 3. Comparison of measured snow density profiles at Bylot Island in May 2015 with those simulated using the detailed snow models Crocus and SNOWPACK. Crocus runs of 6 May are shown because Crocus simulates melting on 7 May, and this extra process makes comparisons irrelevant on 12 May.

The SNOWPACK simulations were conducted with version 3.4 (https://models.slf.ch/p/snowpack/). We used the meteorological forcing data of Barrere et al. (2017), as for Crocus. The height of the snowpack was driven by new precipitations and settling rates (i.e., snow height measurements were thus not used to force the simulations). Multiple soil layers were used to simulate the ground temperatures. The initial temperatures used for those layers were those measured at the beginning of the simulation.

2.3. Model to Simulate Heat Fluxes Through Simplified Snowpacks

Since a major objective of this work is to investigate the impact of snow stratification on heat fluxes through the snowpack, we used idealized snowpacks and the multilayer heat transfer model from Picard et al. (2009) called *minimal firn model* (MFM). Briefly, this model solves the surface energy budget using the minimal snow model (Essery & Etchevers, 2004) every 60 s to compute the heat flux entering the

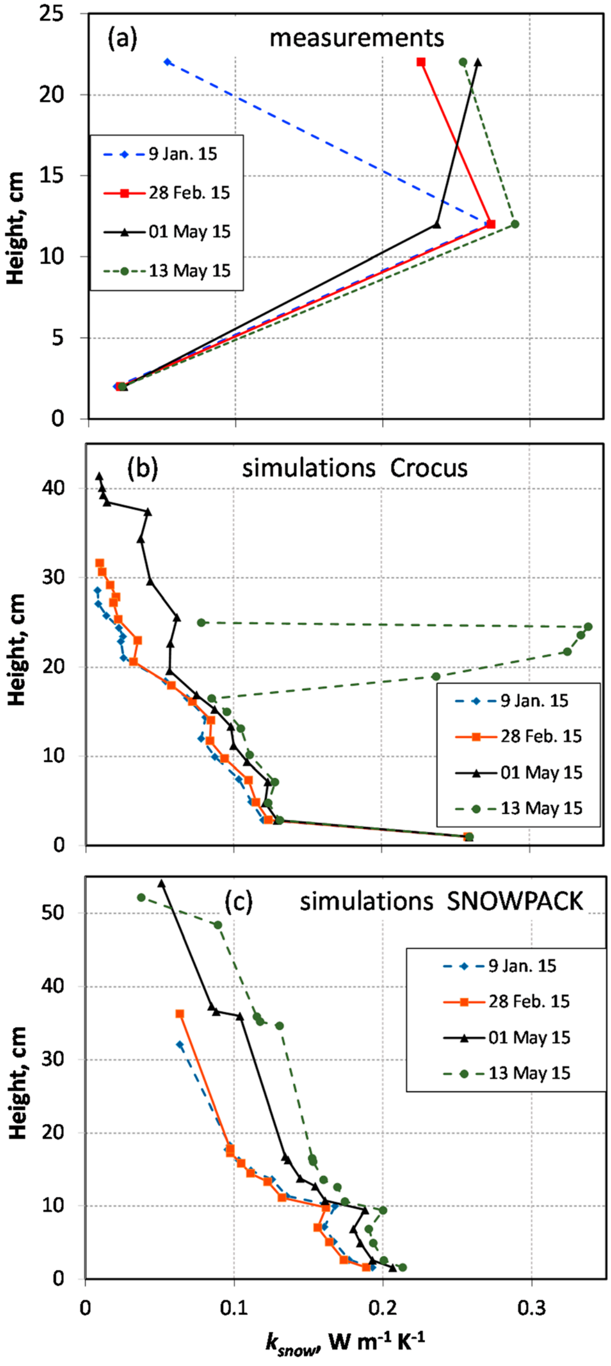

Figure 4. Comparison of measured and simulated snow thermal conductivity profiles at Bylot Island in winter and spring 2015. (a) Automatic measurements at three heights, (b) Crocus simulations, and (c) SNOWPACK simulations. Panels (a) and (b) are after (Domine, Barrere, & Sarrazin, 2016).

snowpack. The heat diffusion equation through a layered medium is then solved using a Crank-Nicholson scheme to propagate this surface flux downward, thus yielding temperature in every layer along the profile. The boundary conditions at the bottom interface of the model domain, here taken 10 m below the snow/ground interface, is a fixed temperature of −10 °C. Numerical layers thickness is constant (1 cm) throughout the snow and soil profile, and each layer (snow or soil) is assigned thermal conductivity, heat capacity, and density values. In the configuration implemented for this particular study, the model proceeds using a fixed snow stratification (no accumulation, no settling, no metamorphism, and no phase change) and is only used to perform numerical sensitivity experiments, keeping most variables and parameters fixed except the stratification of snow properties within the snowpack. The file for input meteorological variables used is that available at (Barrere & Domine, 2017). Data use a time step of 3 hr and were downsampled using linear interpolation to the model time step of 60 s. Other parameters of the surface scheme are constant and include the following: the aerodynamical roughness (1 cm), the albedo (0.85), and the correction for calm conditions (V = 3 W m^{-2} K^{-1}; see Essery & Etchevers, 2004).

Under steady state, the one-dimensional heat flux F (W/m^2) through a medium is simply described by Fourier's law:

$$F = -k\frac{dT}{dz} \tag{1}$$

where k is the snow thermal conductivity (W m^{-1} K^{-1}) and dT/dz (K/m) is the vertical temperature gradient in the snowpack.

For a layered medium, we consider its thermal insulance R_T (m^2 K W^{-1}):

$$R_T = \sum_i \frac{h_i}{k_i} \tag{2}$$

where h_i and k_i are the height and thermal conductivity of layer i. R_T can be used to relate simply F to the temperature difference between its surface and its base, T_{top}-T_{base}:

$$F = -\frac{T_{top} - T_{base}}{R_T} \tag{3}$$

Under these conditions, the stratification of the medium does not affect heat conduction. Under a time-variable forcing, however, the heat flux may depend on stratification because as stated in the introduction the thermal diffusion distance of a time-limited surface temperature variation depends on snow thermal diffusivity and therefore on stratification.

To test this, we used two types of idealized snowpacks 30 and 60 cm thick, each comprised of three snow layers of equal thickness, numerically split into 1- and 2-cm-thick layers, respectively. The Arctic snowpack has layers with increasing thermal conductivities toward the top, while the reverse is true for the snowpacks simulated by Crocus and SNOWPACK, hereafter referred to as *Alpine snowpack*, because Alpine snowpacks often have such a stratification in thermal properties (Morin et al., 2010) (Figure 1). Both types have exactly the same thermal insulance.

To illustrate climatic conditions, we report in Figure 2 the snow surface temperature measured between 1 October 2014 and 29 May 2015, during which period we are certain that there was snow on the ground.

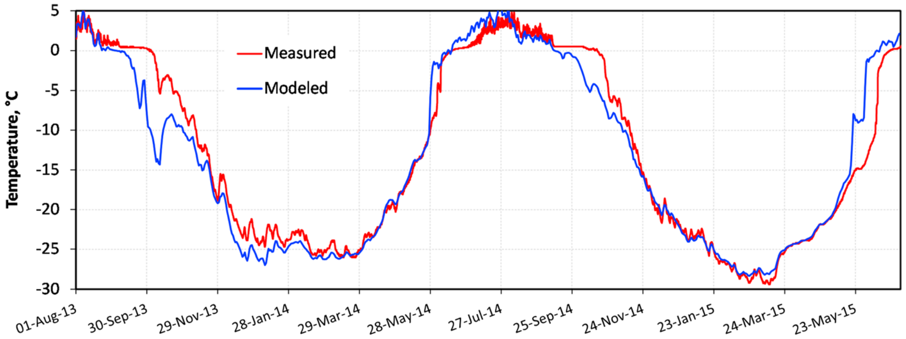

Figure 5. Measured and simulated ground temperature at 10-cm depth with Crocus.

Data indicate negative snow temperatures throughout this period. Even when there was no sun, the time variations of temperature were important in winter. Diurnal variations become important in mid-March. Air temperature and other environmental data have been reported in Domine, Barrere, and Sarrazin (2016).

3. Results

3.1. Snow Properties

Figure 3 compares density profiles simulated with Crocus and SNOWPACK with measured profiles. Clearly both models simulated basal densities that are too high and densities of higher layers that are too low compared to measurements.

Figure 4 compares simulated snow thermal conductivity profiles with values measured automatically at 2, 12, and 22 cm above the ground surface. As for density, measurements indicate low values for the basal layer and high values for the overlying wind slabs. On the contrary, simulations show high basal values and low values in upper layers.

3.2. Ground Temperature Simulations

Both Crocus and SNOWPACK can also simulate ground temperature, which is a main concern of this paper. Since Crocus and SNOWPACK simulate snow properties essentially in a similar manner and in particular, both produce inverted density and thermal conductivity profiles, this inversion has similar effects on ground

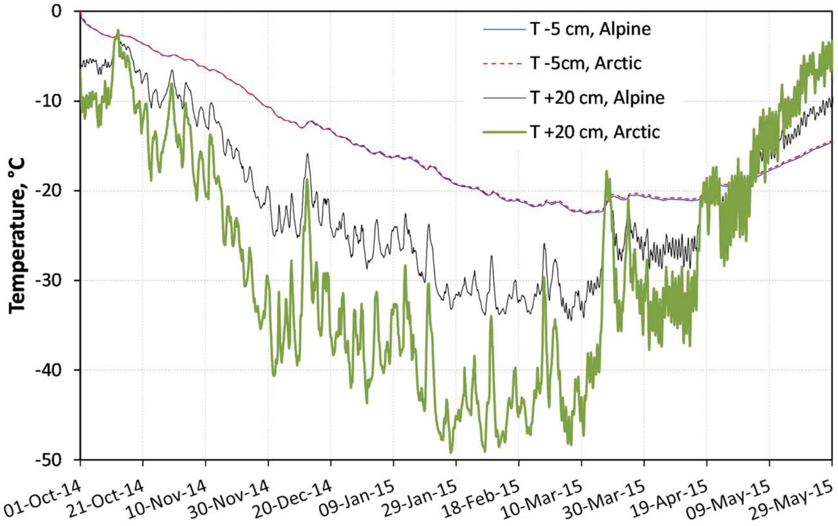

Figure 6. Simulated temperatures in the snow at 20-cm height and in the ground at 5-cm depth with the idealized 30-cm-thick Alpine and Arctic snowpacks of Figure 1.

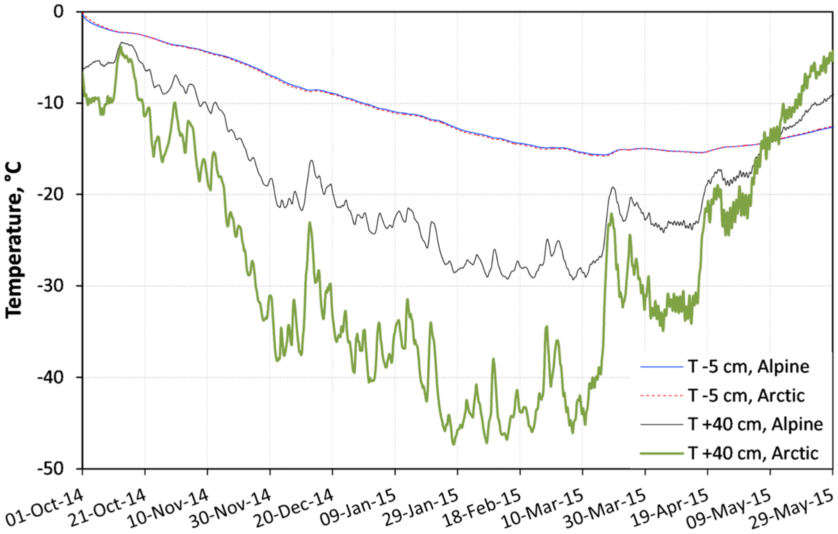

Figure 7. Same as Figure 6 for 60-cm-thick snowpacks, at 40-cm height and 5-cm depth.

temperature in both models. Because Crocus is coupled to a sophisticated land surface scheme, ISBA (Barrere et al., 2017), we focus below on ground temperatures simulated by Crocus/ISBA.

Figure 5 shows measured and simulated ground temperature at 10 cm depth. Crocus coupled to ISBA is able to simulate the soil temperature well except during freezing and thawing, both processes being much faster in the simulations. The difference during freezing is simply explained by the higher simulated thermal conductivity of the lower layer, which causes faster heat transfer when only that lower layer is present. Likewise, thawing is much faster in simulations, also because the top layers which are the insulating ones in simulations melt first, leaving only the most conductive basal layer.

3.3. Impact of Snowpack Stratification on the Ground Thermal Regime

To focus on the impact of stratification, we use the MFM heat transfer model described above. We first examine the temperature regime of the snow and ground in the case of a 30-cm-thick snowpack. Figure 6 shows the seasonal evolution of the temperature in the snow at 20 cm height and in the ground at 5 cm depth. The temperature is much colder near the top of the Arctic snowpack than in the Alpine one. This is expected because the top snow layer in the Arctic snowpack is 5 times as conducting as that in the Alpine one. The effect of the cold Arctic winter is therefore better transmitted to the top snow. However, the temperature in the ground is essentially the same under both snowpacks: The highest absolute difference is 0.281 °C, and 60.0% of the 5,784 absolute hourly differences are <0.15 °C. The Arctic ground temperature is almost always higher that the Alpine one.

When the snowpack thickness is increased to 60 cm, the situation is not significantly changed as shown in Figure 7. As expected, the base of the top layer is colder in the Arctic snowpack because it is more conducting, but the ground temperatures are still fairly similar, with a largest absolute difference of 0.278 °C and 89.2% the 5,784 absolute hourly differences are <0.15 °C. In this case the Alpine ground temperature is higher than the Arctic one, except before 20 October and after 24 April.

3.4. Impact of Snowpack Stratification on the Snow Surface Temperature

It is also interesting to consider the differences in snow surface temperature between both snowpack types, shown in Figure 8a. Averaged over a period of several days the surface temperatures are essentially the same. The amplitude variations are greater in the Alpine snowpack (Figure 8b) because the insulating layer at the top does not allow damping the air temperature variations by heat exchanges with the snowpack. This effect is more important in April and May, when daily temperature variations reach 20 °C, sometimes more. The absolute temperature differences reaches 4.7 °C on 8 February, when the temperature suddenly increases by 15 °C in 5 hr, and the surface temperature of the Alpine snowpack increases more rapidly. Overall, however, surface temperatures for both snowpacks are fairly close, with 73.3% of 5,784 absolute hourly differences

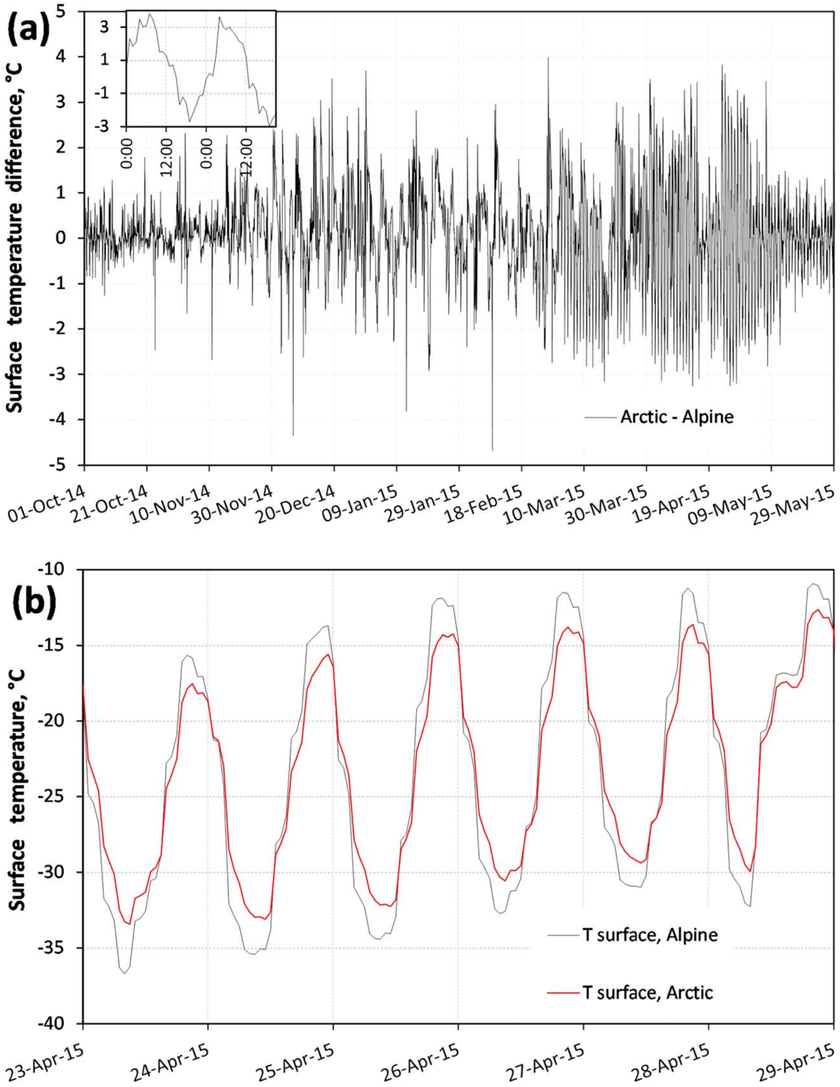

Figure 8. Impact of snowpack stratification on snow surface temperature. (a) Temperature difference (Arctic T − Alpine T) between the surfaces of the 60-cm Arctic and Alpine snowpacks. (inset) Detail of the daily variations on 23 and 24 April 2015. (b) Comparison of surface temperature variations in spring.

lower than 1 °C. For the 30-cm snowpack, temperature differences are similar. The highest temperature difference is 4.40 °C, also on 8 February and 75.2% of 5,784 hourly differences are lower than 1 °C.

4. Discussion

4.1. Heat Fluxes and Ground Temperature Regime

Considering heat fluxes through the snow clearly helps understand temperature variations. Figure 9 shows that heat fluxes in the top part of the 60-cm snowpack are more time variable in the Arctic snowpack than in the Alpine one. This is expected since the top layer of the Arctic snowpack is more conducting and therefore responds faster to air temperature variations. However, over the snow season, heat fluxes in both snowpacks show similar behaviors and the Alpine snowpack essentially damps heat flux variations rather than limits heat fluxes. At the snow-ground interface, heat fluxes are essentially the same for both snowpacks. This and the data of Figures 6 and 7 demonstrate that when conductive heat exchanges alone are considered, the thermal insulance of the snowpack is the only variable required to adequately simulate the ground

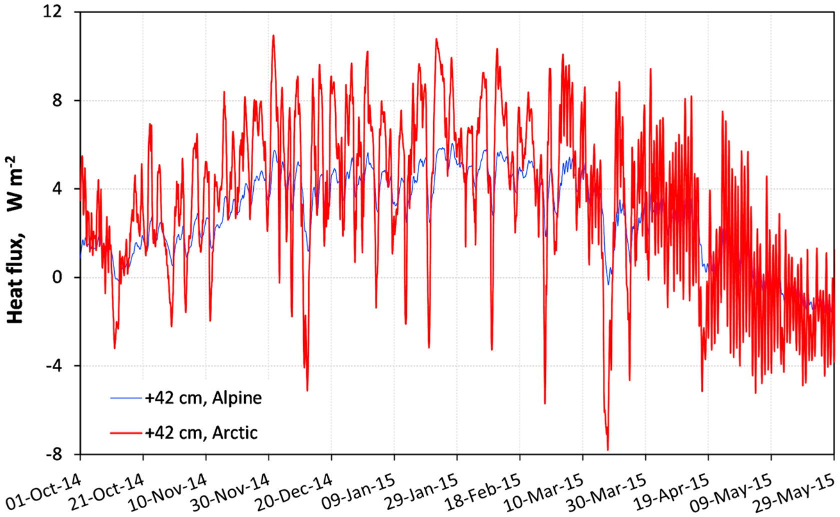

Figure 9. Heat fluxes in the Alpine and Arctic 60-cm snowpacks at a height of 42 cm, that is, near the base of the top snow layer.

thermal regime. Effects of the thermal stratification are negligible. This may allow considerable simplifications in snow models, if the objective is just to simulate conductive heat fluxes through the snowpack.

4.2. Water Vapor Fluxes

Even though this study is focused on thermal effects, we feel it is important to discuss the impacts of snowpack structure on the ground water budget. The autumn and winter temperature gradient between the warm ground and the cold snow leads to a water vapor flux between the ground and the snow, and to very significant ground dehydration (Domine, Barrere, & Sarrazin, 2016; Sturm & Benson, 1997). Figure 10 clearly shows that the temperature gradient between the ground and basal snow is much greater in the Arctic snowpack, which will therefore dehydrate much more than the Alpine one.

The data of Figure 10 and the dependence of ice vapor pressure on temperature (Marti & Mauersberger, 1993) were used to calculate the mass of water lost by the ground between 1 October and 30 May. Using a

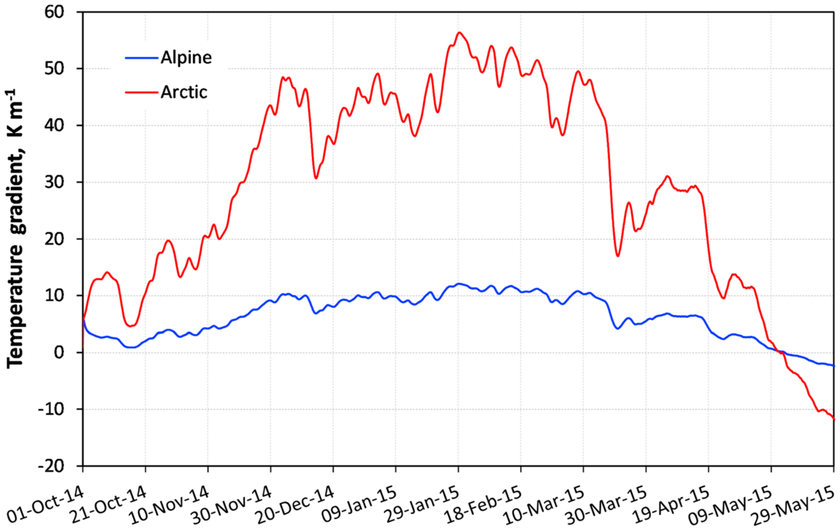

Figure 10. Temperature gradient at the snow-ground interface, calculated from snow temperatures at 0- and 1-cm heights, for the 60-cm-thick Arctic and Alpine snowpacks.

water vapor diffusion coefficient of 2×10^{-5} m^2/s, we calculate that the ground water loss was 0.45 kg/m^2 for the Alpine snowpack and 2.01 kg/m^2 for the Arctic one. As discussed for snow (Colbeck, 1993) and soils (Ho & Webb, 1998), the actual water diffusion coefficient in porous media may be much higher, possibly by a factor of 5 or even more. This issue is however controversial (Calonne et al., 2014), but air convection in the highly permeable depth hoar further enhances the water vapor upward flux (Benson & Trabant, 1973; Sturm & Benson, 1997) so that the soil dehydration computed here for the Arctic snowpack is most likely a lower limit and could be 5 to 10 times greater. Taking the latent heat of sublimation of ice as 51 kJ/mol (Marti & Mauersberger, 1993), we calculate that for the 60-cm Arctic snowpack, the ground heat loss due to sublimation is 5.7 MJ/m^2, while the time-integrated conductive heat flux at the snow-ground interface is 30 MJ/m^2. The cooling effect due to the sublimation of soil ice under the Arctic-type snowpack is therefore not negligible. In fact, it might even be the most important soil heat loss term if soil dehydration is more extensive than calculated with the value of the water vapor diffusion coefficient used here. Under the Alpine-type snowpack on the other hand, dehydration is much less and ground heat loss due to ice sublimation is only 1.3 MJ/m^2, that is, 4.3% of the conductive heat flux and therefore almost negligible. However, counteracting this latent heat effect, the thermal conductivity of the more dehydrated soil will be lower than when dehydration is moderate (Karra et al., 2014), resulting in reduced conductive heat loss under the Arctic snowpack, which counteracts the latent heat loss. Determining the overall effect would require hypotheses on soil type and a better understanding of vapor diffusion and convection in snow and soils.

4.3. Albedo Effects

Snowpack albedo is obviously an important aspect of the surface energy budget (Flanner et al., 2007). It is determined by snow SSA (Domine et al., 2007) and impurity content (Warren & Wiscombe, 1980), mostly of the snow surface layer. Our work has no implication for the snow impurity content, but SSA evolves as a function of wind speed and snow drift (Cabanes et al., 2003) and of the temperature gradient in the snowpack (Flanner & Zender, 2006; Taillandier et al., 2007). Wind effects are not considered here. Since the temperature gradient is most of the time higher in the surface layer of the Alpine snowpack because of its lower conductivity, SSA decreases faster and the albedo of this snowpack is then lower. Detailed snow physics models such as Crocus and SNOWPACK, which simulate SSA and hence albedo as a function of metamorphic conditions, will therefore simulate a lower albedo for the Alpine snowpack and therefore a warmer ground. Quantifying this effect is beyond our current scope, but this will also add to the latent heat effect.

5. Conclusion

Two detailed snow physics models, Crocus and SNOWPACK, are not able to simulate correctly the density and thermal conductivity profiles of Arctic snowpacks because they do not describe the upward water vapor mass transfer induced by the high temperature gradient in the snowpack. As a result, the density and thermal conductivity stratifications of the simulated snowpack are inverted. Using a simplified model with 30- and 60-cm snowpack of constant thickness throughout the season, we calculate that inverting the stratification results in negligible errors in thermal diffusion, with differences in ground temperature between both snowpack types always <0.3 °C, and < 0.15 °C most of the winter. This shows that the thermal stratification of the snowpack does not impact heat flux through the snowpack, and only its thermal insulance needs to be considered for heat flux calculations. We stress here that under real conditions where the snowpack builds up over time, the initial formation of conducting layers in the Alpine-type snowpack will lead to faster ground cooling than when the insulating basal layer of an Arctic snowpack is present, as already discussed by Barrere et al. (2017).

Other effects of the inverted stratification are discussed. Because the temperature gradient at the base of the snowpack is a function of stratification, we calculate that the ground under an inverted stratification dehydrates much less than under a normal one, leading to a lower latent heat loss. Dehydration also leads to a reduced thermal conductivity, so that the modification of the conductive fluxes in the soil due to dehydration will be opposite to the latent heat effect.

Detailed snow physics models that simulate grain size and albedo will simulate a lower SSA and lower albedo when the stratification is inverted. Of the four effects discussed here for a fully developed snowpack, two of them (water vapor diffusion in soils and albedo) have effects in the same direction, which all lead to ground warming for an inverted (Alpine) stratification. Thermal diffusion has no significant effect. The fourth effect (thermal diffusion in soil) leads to a warmer soil under an Arctic stratification, so that we cannot here predict the overall impact of an inverted stratification on ground temperature. In any case, most models aimed at simulating the ground thermal regime do not describe all these effects so errors due to incorrect stratification are likely. The very good simulation of the soil thermal regime during most of the winter at Bylot Island by Barrere et al. (2017; Figure 5) is probably partly due to fortunate error compensations, as already suggested by those authors. We stress here that errors in the water budget may also be significant.

Lastly, on timescales of the order of 1 day, surface temperature is affected by the stratification, and the difference between both snowpack types reaches 4.7 °C. However, averaged over several days this effect is negligible, and most of the time calculated surface temperature differs by less than 1 °C between both snowpack types. This may be relevant to numerical weather prediction, but a thorough evaluation of this impact, which is clearly beyond our current scope, would have to investigate other energy exchange processes such as turbulent fluxes in the context of the stable boundary layer often found in the Arctic (e.g., Boylan et al., 2014).

Crocus and SNOWPACK were developed for Alpine conditions where upward vapor fluxes in the snowpack are negligible. Given our considerations on soil dehydration and on albedo, developing a snow physics model coupled to a soil scheme that integrates water vapor fluxes in snow and soil that could be applied to Arctic conditions therefore appears as a worthwhile goal to understand and project the evolution of both permafrost and Arctic climate.

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