Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

Biogeosciences
Discussions
Open Access

The growth of shrubs on high Arctic tundra at Bylot Island: impact on snow physical properties and permafrost thermal regime

Florent Domine[1,2,3,4], Mathieu Barrere[1,3,4,5,6], Samuel Morin[5]

[1]Takuvik Joint International Laboratory, Université Laval (Canada) and CNRS-INSU (France), Pavillon Alexandre Vachon, 1045 avenue de La Médecine, Québec, QC, G1V 0A6, Canada
[2]Department of Chemistry, Université Laval, Québec, QC, Canada
[3]Centre d'Etudes Nordiques, Université Laval, Québec, QC, Canada
[4]Department of Geography, Université Laval, Québec, QC, Canada
[5]Météo-France – CNRS, CNRM-GAME UMR 3589, CEN, Grenoble, France
[6]LGGE, CNRS-UJF, Grenoble, France

Correspondence to: F. Domine (florent.domine@gmail.com)

Abstract. With climate warming, shrubs have been observed to grow on Arctic tundra. Their presence is known to increase snow height and expected to increase the thermal insulating effect of the snowpack. An important consequence would be the warming of the ground, which will accelerate permafrost thaw, providing an important positive feedback to warming. At Bylot Island (73°N, 80°W) in the Canadian high Arctic where bushes of willows (Salix richardsonii) are growing, we have observed the snow stratigraphy and measured the vertical profiles of snow density, thermal conductivity and specific surface area (SSA) in over 20 sites of herb tundra and in willow bushes 20 to 40 cm high. We find that shrubs increase snow height, but only up to their own height. In shrubs, snow density, thermal conductivity and SSA are all significantly lower than on herb tundra. In shrubs, depth hoar was observed to grow up to shrub height, while on herb, depth hoar developed only to 5 to 10 cm high. The thermal resistance of the snowpack was in general higher in shrubs than on herb tundra. More signs of melting were observed in shrubs, presumably because stems absorb radiation and provide hotspots that initiate melting. When melting was extensive, this increased thermal conductivity and reduced thermal resistance, countering the effect of shrubs in the absence of melting. Preliminary simulations of the effect of shrubs on snow properties and on the ground thermal regime were made with the Crocus snow physics model and the ISBA land surface scheme driven by in-situ and reanalysis meteorological data. These predicted that the ground at 5 cm depth at Bylot Island during the 2014-2015 winter would be up to 13°C warmer in the presence of shrubs.

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

1 Introduction

Climate warming leads to shrub growth on Arctic tundra (Tape et al., 2006;Ropars and Boudreau, 2012). Shrubs are known to limit snow erosion by wind and to trap blowing snow, therefore increasing snow depth and perhaps snowpack duration (Liston et al., 2002;Lawrence and Swenson, 2011;Essery et al., 1999). Snowpack properties such as density, thermal conductivity and albedo are also known or suspected of being modified by shrubs (Liston et al., 2002;Ménard et al., 2014;Sturm et al., 2005). These modifications have many potentially important consequences, including: (1) Snow physical properties affect air temperature and climate through the energy budget of the snow surface, which involves snow albedo and snow thermal conductivity; (2) Snow thermal properties (thermal conductivity, height, density) determine heat exchanges between the ground and the atmosphere in winter, and hence are a key factor in the thermal regime of permafrost. Permafrost thaw is recognized as an important positive climate feedback, because it could lead to the mineralization of organic matter stored there for millennia, leading to the emission of poorly quantified but potentially enormous amounts of greenhouse gases (Koven et al., 2011). Illustrating the reality of this second consequence, Gouttevin et al. (2012) modelled the changes in permafrost thermal regime due to changes in snow thermal conductivity caused by the replacement of tundra by taiga and found ground temperature increases exceeding 10°C. While shrubs are not trees, this result does indicate the interest of investigating the impact of vegetation growth on snow physical properties.

Typical snowpacks on Arctic herb tundra first consist of a basal depth hoar layer which in general has a low density (200 to 280 kg m^{-3}) and a low thermal conductivity (0.03 to 0.08 W m^{-1} K^{-1}) (Domine et al., 2002;Domine et al., 2012;Sturm and Benson, 2004;Derksen et al., 2014). However, depth hoar can be indurated, i.e. formed by the metamorphism of a dense wind slab, and its density can then exceed 400 kg m^{-3} and its thermal conductivity 0.3 W m^{-1} K^{-1} (Domine et al., 2012;Sturm et al., 1997). Above that, one or several hard wind slabs made of small rounded grains are generally found (Domine et al., 2002;Domine et al., 2012;Sturm and Benson, 2004). These have densities from 300 to above 500 kg m^{-3} and thermal conductivities above 0.15 W m^{-1} K^{-1}, reaching 0.6 W m^{-1} K^{-1} (Sturm et al., 1997).Other types of snow layers may also be observed above the basal depth hoar, such as layers of faceted crystals or other layers of depth hoar, sometimes located in between two wind slabs (Domine et al., 2002;Domine et al., 2012;Sturm and Benson, 2004). However a simplified and representative description of Arctic snowpacks on herb tundra is that they consist of a basal depth hoar layer of low density and low thermal conductivity, overlaid by a hard wind slab of high density and high thermal conductivity.

Several studies document some aspects of how snow properties are affected by shrubs. Liston et al. (2002) modelled the effect of shrubs growing on Arctic tundra on snow height and energy fluxes. They took into account changes in snow depth and thermal conductivity. These last changes were made by assuming that the depth hoar layer was thicker in shrubs. They assigned a depth hoar layer thickness and did not observe or simulate metamorphism and depth hoar growth in shrubs.

Euskirchen et al. (2009) modelled changes in vegetation under different climate evolution scenarios. They considered snow cover duration and its effect on albedo. They did not consider changes in snow properties. Lawrence and Swenson (2011) considered the effect of shrub expansion on active layer depth. They included some snow effects such as how shrubs affect snow redistribution by wind. One effect of shrubs on snow albedo is taken into account: its decrease due to stems protruding above the snow in spring. One of their conclusions was that blowing snow processes need to be incorporated in model projections of future Arctic climate change. However, they did not consider changes in snow properties other than albedo and it is possible or even likely (Gouttevin et al., 2012) that their conclusions would be significantly modified if they had.

Myers-Smith and Hik (2013) observed that on Arctic tundra, snow was much thicker in low shrubs than on herb tundra (typically 30 vs. 10 cm). They also measured that winter ground temperature was up to about 8°C higher (typically 4 to 5°C warmer) under shrubs than under herb. They did not, however, observe snow properties. Ménard et al. (2014) performed a very detailed study of shrub bending by snow and how this affected albedo. They focussed on tall shrubs and concluded that many other studies needed to be performed to better understand snow-shrubs interactions.

These few investigations are very useful, but to our knowledge there is no extensive study of the impact of shrubs on snow physical properties. These are required to quantitatively understand and model the relationship between shrubs and ground temperature, especially in the context of shrub growth and expansion. Questions that deserve further or novel investigations include: Is the depth hoar in shrubs different from that on herb tundra? To what height does depth hoar form in shrubs? What is the snow density profile in shrubs and how is this related to stem density? How does the profile of snow specific surface area (SSA) in shrubs differ from that on grass? Since SSA, together with density and impurity content, governs snow albedo and also the light absorption profile and therefore the radiative energy input to the snowpack, this is a critical question affecting metamorphism and all snow physical properties. How do shrub stems, which strongly absorb shortwave radiation, affect the irradiance profile in snow? How do these light-absorbing stems increase the likelihood of snow melting events?

This work attempts to contribute to some of these questions. We have performed field observations and measured snow properties at Bylot Island (73°N, 80°W), a high Arctic site where willow shrubs (*Salix richardsonii*) 10 to 40 cm high are growing on herb tundra featuring mosses and graminoids. Our measurements include snow height and vertical profiles of density, thermal conductivity and specific surface area. We compare data over grass and in shrubs and use our data to perform numerical simulations intended to evaluate the impact of willow shrubs on the ground thermal regime.

2 Methods

2.1 Site selection

Bylot Island is a high Arctic site (see map on Fig. 1) with rare erect vegetation. The geomorphology of the site has been detailed by (Fortier and Allard, 2004). Meteorological monitoring started in 1994 at our research site in Qarlikturvik valley (around 73°10’N, 80°00’W). The mean annual air temperature for the period 1998-2013 is -14.3°C. Temperatures barely exceed 10°C in summer and drop down to -50°C most winters (Allard and Gauthier, 2014). More data are available from Pond Inlet, the nearest community, 84 km to the south-east, where the average measured snowpack height is 15 cm (Gauthier et al., 2013). The glacial valley of our study is roughly oriented E-W. It features wetlands at the bottom of a valley, consisting mainly of tundra polygons, thaw lakes and ponds. Vegetation is dominated by sedges (*Eriophorum sheuchzeri*, *Carex aquatilis*) and graminoids (*Dupontia fisheri*, *Pleuropogon sabinei*). Further upland, drier mesic habitat dominate, with forbs (*Saxifraga* spp., *Potentilla* spp., *Ranunculus* spp.) and graminoids (*Arctagrostis latifolia*, *Alopecurus alpinu*s, *Poa* spp., *Luzula* spp.) and mosses, as detailed by (Bilodeau et al., 2013). This is also where shrubs are found. These consist exclusively of willows (*Salix richardsonii* and to a much lesser extent *Salix arctica*), which rise 10 to 40 cm above the ground. During our field investigations in 2014 and 2015, most shrubs were encountered in the south (north facing) side of the valley. Since signs of shallow underground water flow were observed in many shrub spots in summer, this observation is consistent with the observation of Frost and Epstein (2014) that “rates of shrub […] expansion were not strongly correlated with temperature trends and were better correlated with mean annual precipitation”. Shrubs were either isolated, or more often regrouped in bushes whose largest dimension was at most a few meters. One site fairly far up the valley was almost entirely covered with shrubs over a distance of several hundred meters, but such extensive coverage appears exceptional.

2.2 Experimental methods

Field work took place around mid-May in 2014 and 2015, just before the onset of snow melt. It consisted in the measurement of snow depth at several hundred sites, the observation of snow stratigraphy in snow pits, and in the measurement of vertical profiles of snow density, thermal conductivity and specific surface area in these pits. Snow depth was measured with an avalanche probe. Density was measured with a 100 cm^3 metal box cutter 3 cm high, therefore providing a vertical resolution of 3 cm. Snow thermal conductivity, k_{eff}, was measured by inserting a heated needle probe (TP02 model from Hukseflux) into the snow (Domine et al., 2012). The needle was connected to a data logger. The principle is to monitor the temperature of the needle as it is heated during 100 s at constant power. The rate of heating depends on snow thermal conductivity. The temperature rise is plotted as a function of $Ln\ t$, where t is time, and the slope of the curve is inversely proportional to k_{eff} (Morin et al., 2010). Snow specific surface area (SSA) is the ratio of the surface area of snow crystals accessible to gases over the snow sample mass (Domine et al., 2007). It was obtained by measuring the snow reflectance at 1310 nm using an integrating sphere, from which SSA was derived using a fairly simple algorithm (Gallet et al., 2009). SSA was measured with a vertical resolution of 1 to 2 cm. In shrubs, difficulties were encountered to sample snow. This was due to shrub stems preventing the insertion of the box cutter, or to the collapse of the depth hoar upon the slightest contact. SSA and density measurements could therefore sometimes not be done with the desired vertical resolution.

2.3 Numerical simulations

Snow physical properties were modelled using the Crocus multilayer physical snowpack model coupled to the ISBA land surface scheme within the SURFEX interface (Vionnet et al., 2012). We forced the model with observed meteorological data when available. Before August 2014, air temperature and wind speed measured by instruments located in Qarlikturvik valley at 73°09’07.9”N, 79°59’19.0”W were used. Since August 2014, Crocus was forced by data from a fairly complete nearby meteorological station at 73°09’01.4’’N, 80°00’16.6”W, very close to some of our study sites. It measures air temperature, wind speed, relative humidity, and upwelling and downwelling shortwave and longwave radiation with a CNR4 radiometer from Kipp & Zonen, ventilated and heated with a CNF4 instrument. Other instruments measure snow height and snow and ground temperature and thermal conductivity, but these are not used as forcing data, but rather as a model output check. Because of the summer active layer, the CNR4 radiometer shifted from its horizontal position in late August 2014, causing errors in the radiation measurements. Precipitation was not measured neither, so for this and possible data gaps, we used ERA-interim reanalysis data (Dee et al., 2011). When field data was available, ERA-interim data were corrected to better match local meteorological conditions using the method of (Vuichard and Papale, 2015). ERA-interim amounts of precipitation were not modified, but the phase was recalculated using local temperatures.

With forcing data, Crocus calculates the energy budget of the surface and of each snow layer. This is used to simulate processes occurring in the snow such as thermal diffusion, compaction, phase change (melt/freeze), liquid water percolation, and snow metamorphism, leading to a prediction of the time evolution of snow type (e.g. fresh snow, faceted crystals, depth hoar, small rounded grains, melt forms, etc.). Many snow physical properties can be calculated from these model outputs. The thermal conductivity of snow, which is used to solve the thermal diffusion equation in the snowpack, is calculated from snow density using the equation of Yen (1981). This equation implies that snow thermal conductivity increased monotonically with density.

The Crocus snow model does not account for the effect of vegetation. Shrubs trap wind-blown snow, limit snow erosion by wind, and stems act as absorbers, decreasing the albedo of the surface. The network of stems also prevents snow compaction. This latter effect was simulated by increasing the viscosity of dry snow in the presence of shrubs by a factor 100 up to a snow height of 10 cm and by a factor 10 to the top of the shrub. The 10 cm threshold was set to simulate the greater biomass and stem density at the shrub base. Wind effects on snow, i.e. fragmentation, compaction and sublimation of the surface snow layers were deactivated in shrubs. The decrease of surface albedo by shrubs was simply simulated by decreasing snow albedo by an adjusted factor.

Trapping of wind-blown snow by shrubs was not simulated.

Another effect not simulated by Crocus is the upward transport of water vapour due to the high temperature gradient in Arctic and subarctic snowpacks (Sturm and Benson, 1997). This process is useful to explain e.g. the transformation of melt-freeze layers or wind slabs into depth hoar or indurated depth hoar, and Crocus will therefore not predict such changes (Domine et al., 2013).

3 Results

A total of 14 snow pits were studied in 2014 and 21 pits in 2015. The 2014 campaign was exploratory and the 2015 campaign was more complete and targeted. The 2015 data are therefore reported and discussed in more detail.

3.1 Snow height

In 2014, four series of random snowpack height measurements were done at three sites, producing 1429 values (Table 1). In 2015, the same sites were measured again, as well as an additional three sites, totalling 901 values. One site consisted of low centered polygons (wetland) while the other five were on mesic areas. Of these, two featured scattered willow bushes covering about 10% of the ground, one was the exceptional site fully covered with willows mentioned above, one was in hummock terrain without shrubs in the flat bottom of the valley, and one was further up on the NW facing slopes, also with hummocks.

The polygons site was studied on 14 May 2014 and also two days later to investigate the impact of a snow fall on 15 May and of a wind storm on 16 May. In 2015, the last site, studied on 19 May, shows the lowest average value (21.3 cm) for this campaign. On that day, the temperature almost rose to 0°C, there was bright sunshine and it felt very warm. Thin snowpacks were observed to be melting and many areas became snow-free. We therefore believe that this low value is at least partly explained by the meteorology of that day. Out of the other five sites, only that fully covered with willows shows a significantly higher value than the other sites. The standard deviation of snowpack height appears to scale with the irregularity of topography. The largest standard deviation is for the low-centered polygon site, where the deep troughs separating the polygons could have 80 cm of snow, while the high polygon edges had very thin snow. Large standard deviations were also observed when hummocks were present.

We investigated the impact of isolated bushes on snow height. At those sites, shrubs covered about 10% of the surface. In 2015, a visual examination did not reveal any obvious impact. From the surface structure of the snowpack, prevailing winds appeared to have been across the valley, i.e. coming from the north or south in the valley oriented east–west. We therefore measured snow height at the center of bushes, and every 50 cm up to 3 m from the center uphill (south) and downhill (north) of the bush. Figure 2 illustrates that there was no systematic effect of an isolated bush on snow height. Snow height could either be at a local minimum (bush named Willow D1) or maximum (Willow D1b) in the bush. When the bush was not an extremum, the uphill side (Willow D2) or the downhill side (Willow D2b) could have thicker snow. We conclude that in 2015, an isolated bush appeared to have no clear impact on snow height. This is consistent with the data of Table 1. In fact the effect of topography was found to prevail over that of vegetation. As intuitively expected, thick snowpacks were in hollows and thin ones on bumps.

The situation was different in 2014. In the absence of shrubs, snow had often been eroded down to a more erosion-resistant melt-freeze crust. In willows, blowing snow had accumulated in the bush and downwind from it (Fig. 3). Even though measurements were less detailed in 2014, and no separate measurements were done in and outside the bushes, examination of photographs clearly indicates that in 2014 snow was thicker in bushes and in their wind shadow than far from them.

A crucial observation regarding snow height in shrubs is then the difference between 2014 and 2015: in 2014, shrubs had a direct effect on snow height (Fig. 3) while in 2015 they did not (Fig. 2). Our proposed interpretation is simply that in 2015, snow height was greater (27 cm) than in 2014 (16 cm) and shrubs impact snow height only up to their own height. In the "scattered willows" site, shrubs were 20 to 30 cm high. However, above 25 cm, the stem density was much lower than below, so that their effect on snow height above 25 cm was minimal. In 2014, which was a low snow year, average snow height was much lower that shrub height and the impact of shrubs could be felt. In 2015, when snow height reached or exceeded shrub height in the "scattered willows" areas, the impact of shrubs was not detectable. The data from the "large willow patch" site confirms this. Shrubs there were about 10 cm higher and therefore allowed more snow trapping and accumulation, explaining the 34.9 cm snow height.

3.2 Stratigraphy

Figure 4 shows typical snow stratigraphies on herb tundra in the polygons area, in the large shrub area and on slopes with hummocks in 2015. Grain type symbols are mostly those recommended by the classification of Fierz et al. (2009). Snow science was initially focused on avalanche prediction and that classification reflects this emphasis by being perfectly adapted to Alpine snow. However, it does not allow the precise description of several snow types encountered in Arctic snow. In particular, indurated depth hoar (Domine et al., 2012;Sturm et al., 1997) is not represented, despite its frequent occurrence in Arctic snowpacks. That snow type forms in dense wind slabs under very high temperature gradients not encountered in Alpine snow. Its density can exceed 400 kg m^{-3}. Large depth hoar crystals coexist with small grains that have not been subject to fast crystal growth, probably because water vapour vertical transfer has followed preferential paths in the dense snow. This often gives indurated depth hoar a milky aspect. Unlike typical depth hoar (e.g. taiga depth hoar, (Sturm and Benson, 1997;Taillandier et al., 2006)) which has a very low cohesion, indurated depth hoar is reasonably cohesive, although fairly brittle, and large blocks can easily be cut out of it and manipulated. A variation of indurated depth hoar forms in refrozen layers. Given very high temperature gradients, melt-freeze layers can indeed partially of fully transform into depth hoar (Domine et al., 2009), which then retains some cohesion. It is harder than soft depth hoar, but usually more brittle than indurated depth hoar formed in wind slabs. In willows, we encountered indurated depth hoar formed in refrozen layers and propose a new symbol for this frequent Arctic snow type in Fig. 4.

As typical in the Arctic (Derksen et al., 2014;Sturm and Benson, 2004;Domine et al., 2012;Domine et al., 2002), the snowpack at Bylot Island mainly consists of a basal depth hoar layer and a top wind slab. The depth hoar mostly forms in autumn when the large temperature difference between the cold air and the ground which is still warm generates a large temperature gradient in the thin snowpack (Domine et al., 2002). The resulting intense water vapour fluxes lead to the growth of large depth hoar crystals. Later in the season, the temperature gradient decreases because the ground has cooled and because the snowpack is thicker. Depth hoar does not form anymore and wind-deposited snow instead forms hard wind slabs. Layers of depth hoar or faceted crystals can nevertheless form between two wind slabs. If a layer is not strongly remobilized by wind, it can keep a low density and a low thermal conductivity. If it is subsequently overlaid by a wind slab, a temperature gradient can be established in the lower density snow, because it has a lower thermal conductivity than both wind slabs above and below it.

These features were observed at Bylot Island and are visible in Fig. 4. The depth hoar layer in the absence of shrubs was typically 5 to 10 cm thick. It could be thicker in the hollows in hummock areas. In shrubs, it typically rose to the shrub height, as wind-packing of snow usually does not take place in shrubs. Above the shrubs, a wind slab was found, but it was softer than on herb. Explaining why depth hoar always keeps forming in shrubs late in the season while it does not on herb tundra requires the consideration of snow physical properties, detailed in the next section. In 2015, most signs of melting were found in shrubs, and this is reported in Fig. 4 as indurated depth hoar in the Willows 3 stratigraphy. This may be explained by the absorption of solar radiation by the shrubs in autumn. Very slight melt signs were also detected outside the shrubs, as indicated in the Hummock 1G stratigraphy, with the presence of indurated depth hoar and of a very thin melt-freeze crust.

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

Another variable that has to be taken into account to understand melting is the concentration of light-absorbing impurities in the snow. Some snow layers had a noticeable brown colour, most likely due to the presence of mineral dust. A likely source was the black hills to the north and indeed the dirty snow layers had been deposited by a northerly wind. Signs of melting at the surface of dirty snow layers were frequent. This is what explains melting in the Hummock 1G stratigraphy. A further noteworthy observation is the exceptionally large size of the depth hoar crystals in the willows, which reached 30 mm near the base.

3.3 Snow physical properties

We first compare physical properties of snow in the large willow patch with those on herb tundra located in the polygons. We select sites having about the same snow height to facilitate comparison.

Figure 5 shows that in general snow on herb tundra has higher densities, thermal conductivities and SSAs than in willow shrubs, because shrub snow is dominated by depth hoar, which has lower values than wind slabs for all these variables. The dense network of stems prevents snow compaction in shrubs, and the resulting low densities facilitate depth hoar growth (Marbouty, 1980). Densities as low as 125 kg m^{-3} were measured. Furthermore, many gaps, i.e. spots without snow, were observed in dense stem networks. At the base of the snowpack, gaps were often found, most likely due to the collapse of depth hoar because of continued vertical water vapour fluxes from the base to the top of the snowpack, leading to significant mass loss. This has already been detected in low Arctic shrub tundra (Domine et al., 2015). These basal gaps cannot be mistaken for lemming burrows, which were also observed (Fig. 4). Gaps due to depth hoar collapse have an erratic shape while lemming holes have a regular shape. Depth hoar has a lower thermal conductivity than wind slabs (Domine et al., 2012;Sturm et al., 1997). This effect will combine to the lower densities, which lead to a thicker snowpack, to form a snowpack with better thermal insulation properties in shrubs. Ground cooling in shrubs is therefore slower, maintaining a higher temperature gradient that further facilitates depth hoar growth. Indeed, the temperature of the snow-ground interface in mid-May 2015 was around -12°C in shrubs and -18°C on herb tundra. There is therefore a positive feedback between depth hoar formation and ground temperature which qualitatively explains why depth hoar can keep forming up to the top of the shrubs. Above the shrubs, snow is not protected from wind packing and wind slabs can form. The SSA of depth hoar in shrubs is lower than on herb tundra because crystals in shrubs are larger and to a first approximation, SSA is inversely proportional to grain size. Snow albedo depends on its SSA (Domine et al., 2008) so that this effect will contribute to decreasing snow albedo in shrubs. This lower albedo will combine to the absorption of solar radiation (when present) by shrub stems to produce a warmer snowpack in shrubs, further reducing ground cooling. In summary, in a large dense shrub patch, snow properties are dramatically modified relative to herb tundra and all the changes combine to reduce ground cooling in winter.

The above data were for a willow patch several hundred meters large. Snow properties inside and in the vicinity of smaller patches, only a few meters in size, need to be investigated as this is the most frequent occurrence of shrubs observed on Bylot and northern Baffin Islands. Differences can be expected, because wind can propagate much more easily in an isolated bush than in an extensive patch.

Figure 6 shows the stratigraphies inside two bushes about 1 m in diameter and in snow about 1 m south (uphill) of the bushes. The bush named “Willows D2b” had stems protruding up to about 35 cm and bush “Willows D1b” to about 22 cm. Figure 7 shows the corresponding vertical profiles of physical properties.

An obvious observation in Fig. 7 is the peculiar property of the layer around 15 cm in the profile “Willows D2b center”. The high density and thermal conductivity values are probably due to melting of that layer in autumn, which produced a very hard melt-freeze crust. Why such intense melting took place is uncertain, but it could be due to a higher stem density and/or more mineral dust in the snow. Besides this observation, physical properties at the center of the bushes appear similar to those of the large

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

willow patch. The specific surface area of the "Willows D1b center" is slightly higher than those of the other bush sites, but this is probably not significant. Given that we only have 5 profiles inside bushes, it is difficult to make conclusive statistics in this case.

An interesting observation is that about 1 m south of the bushes, the snow physical properties are much closer to those in shrubs than those on herb. The influence of shrubs on snow properties therefore extends beyond the shrub area itself. We hypothesize that since shrubs reduce wind speed in their vicinity, snow compaction by wind is limited. Snow of lower density than in the absence of shrubs is then deposited during drifting snow events. Depth hoar formation is then facilitated, leading to a lower thermal conductivity and specific surface area.

In summary, our observations and measurements of snow properties on herb tundra and in shrubs and their vicinity indicate that:

- Shrubs increase snow height as long as it remains lower than their own height. Once snow height reached shrub height, shrubs have no detectable impact on snow height.
- Snow in shrubs has in general lower density, thermal conductivity and specific surface area than on herb tundra. This is because shrubs prevent snow compaction, facilitate depth hoar formation, and depth hoar has low values for these 3 variables. Depth hoar forms up to shrub height, here 20 to 30 cm, while on herb tundra it forms only to about 5 to 10 cm.
- Shrubs absorb light and facilitate snow melting. This on occasions led to the formation of dense melt-freeze layers of higher thermal conductivity and specific surface area than depth hoar. However, at our high Arctic site, this does not seem to be frequent.
- The influence of shrubs on snow physical properties extends beyond the bushes, presumably because of the impact of shrubs on wind velocity.

4 Discussion and modelling

A central question this work seeks to answer is: what is the effect of shrubs on the insulating properties of the snowpack? A convenient way to express the insulating property of a medium made of different layers is to calculate its thermal resistance R_T defined as:

$$R_T = \sum_i \frac{h_i}{k_{eff,i}} \qquad (1)$$

where h_i is the thickness of layer i. R_T thus has units of $\mathrm{m^2\,K\,W^{-1}}$. R_T conveniently relates the heat flux through the snowpack F to the temperature difference between its surface and its base, T_{top}-T_{base}, and is thus very simple to use, for example in single-layer snow models:

$$F = -\frac{T_{top} - T_{base}}{R_T} \qquad (2)$$

Table 2 sums up the 21 R_T values measured in May 2015. From R_T and snow depth values, the average thermal conductivity of the snowpack was calculated as:

$$\overline{k_{eff}} = \frac{h}{R_T} \tag{3}$$

R_T and $\overline{k_{eff}}$ values are shown in Table 2. The last column of Table 2 ranks the mean thermal conductivities, with 1 the lowest and 19 the highest. Two snow pits studied in a thick snow drift formed at the base of a steep talus were excluded from the ranking, as the mode of formation of these drifts is very different from those of snowpacks in more homogeneous areas, and including them in the comparison would not serve our purpose. They are nevertheless listed at the end of Table 2 for the sake of completeness.

A striking feature of Table 2 is that of the seven lowest $\overline{k_{eff}}$ values (in bold in Table 2), five are for pits in willows. The other two pits, ranked 3 and 5, are respectively for a very thin snowpack where the fraction of depth hoar was high (7 out of 12 cm) and for a snowpack sheltered by a small ridge next to a polygon edge, where soft wind-blown snow of low k_{eff} had recently accumulated. The 3 pits studied in the large willow patch (Willows 1 to Willows 3) all had very low $\overline{k_{eff}}$, and the highest three R_T values are in this willow patch. A tempting conclusion is therefore that the growth of *Salix richardsonii* shrubs decreased the snow thermal conductivity by facilitating depth hoar formation. Since these shrubs also favor snow accumulation, at least up to their own height, both effects add up to lead to an enhanced thermal resistance, thus limiting winter ground cooling.

However, Table 2 also shows that among the highest five $\overline{k_{eff}}$ values (in italics in Table 2), four are found in isolated willow bushes. Two of those pits have been detailed in Figs. 6 and 7. Their high $\overline{k_{eff}}$ was caused by snow melt, which resulted in hard dense conductive layers. From our observations, we hypothesize that melting was caused by light absorption by shrub stems, and this was further facilitated by mineral dust contained in the snow layers that melted. There is also the possibility that vegetation debris entrained slightly beyond the bushes facilitated melting in those pits dug about 1 m from the bushes.

In summary, our data and observations indicate that the impact of shrubs on snow thermal properties can go both ways. If the air temperature remains low enough, then willows limit snow compaction and favor depth hoar formation, therefore leading to the formation of a highly insulating snowpack. However, if the air temperature is high enough so that the increased radiation absorption by willows can lead to snow melting, then hard melt-freeze layers with high k_{eff} can form, leading to a snowpack with reduced thermal insulating properties.

We attempted to simulate these effects with the ISBA-Crocus model. Three scenarios were tested: (1) *herb*, where no vegetation is present, and this is intended to simulate snow on herb tundra; (2) *shrub*, where the effect of 40 cm-tall shrubs on snow density is simulated by limiting compaction and deactivating wind-induced processing of surface snow; (3) *shrubalb*, which is similar to shrub, but snow albedo has been decreased by 30 or 60%, for runs *shrubalb30* and *shrubalb60*, respectively.

Figure 8 shows the evolution of snow height and R_T under the *herb*, *shrub*, *shrubalb30* and *shrubalb60* scenarios, for the 2014-2015 winter. The effect of shrubs on snow compaction is obvious: snow height is increased by about 60% in the presence of shrubs. This increase in snow height leads to an increase in R_T, and this is further enhanced by the fact that depth hoar formation is facilitated in the presence of shrubs. Our field observations lead us to expect that decreasing snow albedo would lead to episodes of snow melt. This, by forming denser melt-freeze crusts with a higher k_{eff}, leads to a snowpack with a lower thermal resistance. A surprising result of our simulations is that decreasing the snow albedo did not produce the expected effect until late March. In the fall, decreasing the albedo by 60% reduced the thermal resistance by just 1 m² K W^{-1}, whereas in mid-winter the *shrubalb* runs predict a higher R_T. A detailed analysis of our model output data indicates that this is because at 73°N, according to our model, downwelling shortwave radiation is insufficient to strongly impact snow temperature through albedo effects. No melting takes place and thermal conductivity is therefore not increased.

Figure 9 shows the air temperature and wind speed, the incoming shortwave radiation and the snow depth in fall 2014. Simulated snowpacks began to accumulate on 12 September. A sharp drop in incident radiation took place on 10 October, implying that albedo effects become negligible after that date. Figure 10 shows the simulated density profiles on 10 October. The *shrubalb30* snow was slightly affected by the decrease in albedo, with a mean density of 153 kg m^{-3} on 10 October instead of 145 kg m^{-3} for the *shrub* run (Fig. 10). The snowpack was also thinner, resulting in a lower thermal resistance for the *shrubalb30* run (mean R_T = 2.9 m^2 K W^{-1}) than for the *shrub* run (mean R_T = 3.2 m^2 K W^{-1}) on 10 October. The *shrubalb60* snow accumulated slower because the first snow fall (12 September) melted, resulting in a thinner snowpack. As the downwelling shortwave radiation was low between 19 and 22 September (<70 W m^{-2}, Fig. 9), the snowpack was not affected by the albedo effect during the snow fall that took place at that time. Because of the thinner snowpack, the gradient metamorphism was stronger in the *shrubalb60* snowpack, leading to a lower density because, in Crocus, layers featuring faceted crystals or depth hoar are set to a higher apparent viscosity and thus undergo a lower rate of densification through compaction processes. A strong wind event occurred on 10 and 11 November, compacting and sublimating the *shrub* and *shrubalb30* snow layers which exceeded the shrub height, resulting in a decrease of R_T. As the *shrubalb60* snowpack was thin enough to remain protected by the shrubs, its thickness became equal to those of the *shrub* and *shrubalb30* snowpacks (Fig. 9) and its thermal resistance became higher (Fig. 8) since thermal conductivity increases with increasing density in Crocus. At the end of March 2015, incident radiation became large enough to induce snow melt, leading to an earlier snowpack disappearance for the *shrubalb* runs (Fig. 8).

A critical fallout of our work is an evaluation of the potential of shrub growth to affect ground temperature. Figure 11 presents a simulation of ground temperature at 5 cm depth on herb tundra and on shrub tundra using ISBA-Crocus. Since this work is focused on winter processes and all model modifications related to shrubs pertain to their interactions with the snowpack, we ran the model in summer with the conditions valid for herb tundra in all cases, with the consequences that summer results are much less variable than winter ones. Measurements on herb tundra are also shown. In summer 2014 we also placed ground temperature sensors in willows. Unfortunately they were dug out by foxes and the data loggers suffered water damage so we have no data in willows. Simulations indicate that in winter 2014-2015, the presence of shrubs raised ground temperature by up to 13°C. For the 2013-2014 winter the temperature difference was only up to 8°C because the snowpack was thinner that previous year, so its potential to influence ground temperature was lower. In the fall 2014, the ground temperature was colder for the *shrubalb60* run than for the *shrub* one because the lower snow R_T allows the cold air to affect the ground more. This cooling should be enhanced by a better simulation of the thermal conductivity of the melt-freeze snow, which is currently calculated from the snow density only. Melt-freeze layers usually have a higher thermal conductivity than other snow types for a given density (Sturm et al., 1997), because bonds between grains are stronger. Otherwise, the winter ground temperature is warmer under shrubs, and this warming is particularly significant in spring because of the earlier melting of the snowpack, which allows the warm spring air to heat up the ground. Except in early fall, the ground temperature data are fairly well simulated in winter in the absence of shrubs, with simulated temperatures within 4°C of data. The warmer ground temperatures in the simulations are explained by the thinner snowpack at our measurement site than in the simulations (Fig. 8). The general good agreement between data and simulations supports the reliability of our simulation. The early fall differences are due to an imperfect simulation of the soil thermal properties, and in particular to a higher thermal conductivity of the surface layer in the simulations. This effect rapidly becomes negligible as the insulating effect of snow increases.

The effect simulated here is greater in magnitude than that measured by (Myers-Smith and Hik, 2013), who measured a 4 to 5°C (up to 8°C) winter warming under shrubs at a different location and in a different ecosystem. Their shrubs were 50 cm high willows and dwarf birch and it is likely that thermal effects are site and ecosystem-dependant. Since our simulations did not describe differences in summer effects between herb and shrubs, the 13°C warming effect of shrubs that we simulated in 2014-2015 (and 8°C warming the previous year) can be assigned here to the sole effect of shrubs on snow. It is clear that our model is imperfect and this must be considered as a preliminary attempt to simulate snow properties in the presence of shrubs. In fact, we simulate thicker snowpacks and higher thermal resistances than measured, so actual effects are probably somewhat lower than simulated ones. In particular, the interactions between snow, shrubs and radiation are not satisfactory, as we were not able to adequately reproduce the observed snow melt in the presence of shrubs, even as we decreased albedo by 60%. A shrub stem broadband albedo is very low, <0.1 (Juszak et al., 2014), and probably produces a hot spot where melting would be induced locally, possibly with water percolating to wet the whole snowpack. This of course cannot be modelled adequately with a 1-D model by homogeneously reducing snow albedo, as we did. Furthermore, summer effects may mitigate the shrub-induced winter warming. We made point temperature measurements in early July 2014 and found that the ground had thawed less under the shrubs. We also observed that thermally-insulating moss had grown under the shrubs, and this may partly explain the slower thawing. Besides soil and litter thermal properties, other summer effects of shrubs include modification of surface albedo, soil shading and greater evapotranspiration (Myers-Smith and Hik, 2013;Pearson et al., 2013;Loranty and Goetz, 2012). All these factors should be modelled in detail for a full quantification of the impact of shrubs on the permafrost thermal regime.

5 Conclusion

These observations and simulations show that shrub-snow interactions are very complex. Our study confirms that shrubs often increase snow height and thermal resistance and decrease albedo but we also make many additional observations, some of which are novel:

- Shrubs increase snow height only up to their own height. If snow fall is sufficient, their effect on snow height becomes undetectable.
- Snow physical properties are dramatically affected by shrubs. In the absence of enhanced melting, shrubs decrease snow density, favour depth hoar formation with concomitant decrease in snow thermal conductivity and SSA. A consequence is the increase in snowpack thermal resistance.
- Shrubs increase radiation absorption by snow and this can lead to melting, which results in increased density and thermal conductivity. There is therefore a threshold effect, where sufficiently high temperature and radiation combine to reverse the effect of shrubs on the insulating properties of snow.
- Increased snowpack thermal resistance in the presence of shrubs and in the absence of melting is expected to contribute to ground warming. Simulations indicate that the magnitude of this warming reaches 13°C at Bylot Island for the 2014-2015 winter and 8°C the previous winter.

However, we stress again that our modelling effort is preliminary and many developments are still required for the proper simulation of shrubs on snow properties and on permafrost thermal regime. Not only must snow-shrubs interactions be described in more detail, but summer effects of shrubs on the surface energy budget must also be included for a reliable prediction of the thermal regime of permafrost in the presence of shrubs.

Author contributions

F. Domine designed research. M. Barrere and F. Domine performed the field measurements. F. Domine analyzed the field data. M. Barrere performed the model simulations with suggestions and advice from S. Morin. F. Domine prepared the manuscript with input from M. Barrere and comments from S. Morin.

Supplement

A spreadsheet has been produced to supply all data used in the graphs.

Acknowledgements

This work was supported by the French Polar Institute (IPEV) through grant 1042 to FD and by NSERC through the discovery grant program. The Polar Continental Shelf Program (PCSP) efficiently provided logistical support for the research at Bylot Island. We are grateful to Gilles Gauthier and Marie-Christine Cadieux for their decades-long efforts to build and maintain the research base of the Centre d'Etudes Nordiques at Bylot Island. Field trips were shared with the group of Dominique Berteaux, who helped make this research much more efficient and fun. Bylot Island is located within Sirmilik National Park, and we thank Parks Canada and the Pond Inlet community (Mittimatalik) for permission to work there. Help in running the model from Matthieu Lafaysse and Vincent Vionnet (CNRM-GAME/CEN) is acknowledged. LGGE and CNRM-GAME/ CEN are part of LabEx OSUG@2020 (ANR10 LABX56).

References

Bilodeau, F., Gauthier, G., and Berteaux, D.: The effect of snow cover on lemming population cycles in the Canadian High Arctic, Oecologia, 172, 1007-1016, 10.1007/s00442-012-2549-8, 2013.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Holm, E. V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137, 553-597, 10.1002/qj.828, 2011.

Derksen, C., Lemmetyinen, J., Toose, P., Silis, A., Pulliainen, J., and Sturm, M.: Physical properties of Arctic versus subarctic snow: Implications for high latitude passive microwave snow water equivalent retrievals, J. Geophys. Res., 119, 7254-7270, 10.1002/2013jd021264, 2014.

Domine, F., Cabanes, A., and Legagneux, L.: Structure, microphysics, and surface area of the Arctic snowpack near Alert during the ALERT 2000 campaign, Atmos. Environ., 36, 2753-2765, 2002.

Domine, F., Taillandier, A. S., and Simpson, W. R.: A parameterization of the specific surface area of seasonal snow for field use and for models of snowpack evolution, J. Geophys. Res., 112, F02031, 10.1029/2006jf000512, 2007.

Domine, F., Albert, M., Huthwelker, T., Jacobi, H. W., Kokhanovsky, A. A., Lehning, M., Picard, G., and Simpson, W. R.: Snow physics as relevant to snow photochemistry, Atmos. Chem. Phys., 8, 171-208, 2008.

Domine, F., Taillandier, A.-S., Cabanes, A., Douglas, T. A., and Sturm, M.: Three examples where the specific surface area of snow increased over time, The Cryosphere, 3, 31-39, 2009.

Domine, F., Gallet, J.-C., Bock, J., and Morin, S.: Structure, specific surface area and thermal conductivity of the snowpack around Barrow, Alaska, J. Geophys. Res., 117, D00R14, 10.1029/2011jd016647, 2012.

Domine, F., Morin, S., Brun, E., Lafaysse, M., and Carmagnola, C. M.: Seasonal evolution of snow permeability under equi-temperature and temperature-gradient conditions, Cryosphere, 7, 1915-1929, 10.5194/tc-7-1915-2013, 2013.

Domine, F., Barrere, M., Sarrazin, D., Morin, S., and Arnaud, L.: Automatic monitoring of the effective thermal conductivity of snow in a low-Arctic shrub tundra, The Cryosphere, 9, 1265-1276, 10.5194/tc-9-1265-2015, 2015.

Essery, R., Li, L., and Pomeroy, J.: A distributed model of blowing snow over complex terrain, Hydrol. Processes, 13, 2423-2438, 10.1002/(sici)1099-1085(199910)13:14/15<2423::aid-hyp853>3.0.co;2-u, 1999.

Euskirchen, E. S., McGuire, A. D., Chapin, F. S., Yi, S., and Thompson, C. C.: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks, Ecological Applications, 19, 1022-1043, 10.1890/08-0806.1, 2009.

Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K., and Sokratov, S. A.: The International classification for seasonal snow on the ground UNESCO-IHP, ParisIACS Contribution N°1, 80, 2009.

Fortier, D., and Allard, M.: Late Holocene syngenetic ice-wedge polygons development, Bylot Island, Canadian Arctic Archipelago, Can. J. Earth Sci., 41, 997-1012, 10.1139/e04-031, 2004.

Frost, G. V., and Epstein, H. E.: Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s, Global Change Biology, 20, 1264-1277, 10.1111/gcb.12406, 2014.

Gallet, J.-C., Domine, F., Zender, C. S., and Picard, G.: Measurement of the specific surface area of snow using infrared reflectance in an integrating sphere at 1310 and 1550 nm, The Cryosphere, 3, 167-182, 2009.

Gauthier, G., Bety, J., Cadieux, M. C., Legagneux, P., Doiron, M., Chevallier, C., Lai, S., Tarroux, A., and Berteaux, D.: Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra,

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

Philosophical Transactions of the Royal Society B-Biological Sciences, 368, 10.1098/rstb.2012.0482, 2013.

Gouttevin, I., Menegoz, M., Dominé, F., Krinner, G., Koven, C., Ciais, P., Tarnocai, C., and Boike, J.: How the insulating properties of snow affect soil carbon distribution in the continental pan-Arctic area, J. Geophys. Res., 117, G02020, 10.1029/2011jg001916, 2012.

Juszak, I., Erb, A. M., Maximov, T. C., and Schaepman-Strub, G.: Arctic shrub effects on NDVI, summer albedo and soil shading, Remote Sens. Environ., 153, 79-89, http://dx.doi.org/10.1016/j.rse.2014.07.021, 2014.

Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, Proc. Nat. Acad. Sci. U.S.A., 108, 14769-14774, 10.1073/pnas.1103910108, 2011.

Lawrence, D. M., and Swenson, S. C.: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming, Environ. Res. Lett., 6, 045504, 2011.

Liston, G. E., McFadden, J. P., Sturm, M., and Pielke, R. A.: Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs, Global Change Biology, 8, 17-32, 2002.

Loranty, M. M., and Goetz, S. J.: Shrub expansion and climate feedbacks in Arctic tundra, Environ. Res. Lett., 7, 1-3, 10.1088/1748-9326/7/1/011005, 2012.

Marbouty, D.: An experimental study of temperature-gradient metamorphism, J. Glaciol., 26, 303-312, 1980.

Ménard, C. B., Essery, R., Pomeroy, J., Marsh, P., and Clark, D. B.: A shrub bending model to calculate the albedo of shrub-tundra, Hydrol. Processes, 28, 341-351, 10.1002/hyp.9582, 2014.

Morin, S., Domine, F., Arnaud, L., and Picard, G.: In-situ measurement of the effective thermal conductivity of snow, Cold Regions Sci. Tech., 64, 73-80, 10.1016/j.coldregions.2010.02.008, 2010.

Myers-Smith, I. H., and Hik, D. S.: Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow-shrub interactions, Ecology and Evolution, 3, 3683-3700, 10.1002/ece3.710, 2013.

Pearson, R. G., Phillips, S. J., Loranty, M. M., Beck, P. S. A., Damoulas, T., Knight, S. J., and Goetz, S. J.: Shifts in Arctic vegetation and associated feedbacks under climate change, Nature Clim. Change, 3, 673-677, 10.1038/nclimate1858

http://www.nature.com/nclimate/journal/v3/n7/abs/nclimate1858.html#supplementary-information, 2013.

Ropars, P., and Boudreau, S.: Shrub expansion at the forest-tundra ecotone: spatial heterogeneity linked to local topography, Environ. Res. Lett., 7, 10.1088/1748-9326/7/1/015501, 2012.

Sturm, M., and Benson, C. S.: Vapor transport, grain growth and depth-hoar development in the subarctic snow, J. Glaciol., 43, 42-59, 1997.

Sturm, M., Holmgren, J., Konig, M., and Morris, K.: The thermal conductivity of seasonal snow, J. Glaciol., 43, 26-41, 1997.

Sturm, M., and Benson, C.: Scales of spatial heterogeneity for perennial and seasonal snow layers, Annals of Glaciology, Vol 38, 2004, 38, 253-260, 2004.

Sturm, M., Douglas, T., Racine, C., and Liston, G. E.: Changing snow and shrub conditions affect albedo with global implications, Journal of Geophysical Research-Biogeosciences, 110, G01004, 10.1029/2005jg000013, 2005.

Taillandier, A. S., Domine, F., Simpson, W. R., Sturm, M., Douglas, T. A., and Severin, K.: Evolution of the snow area index of the subarctic snowpack in central Alaska over a whole season. Consequences for the air to snow transfer of pollutants, Environ. Sci. Technol., 40, 7521-7527, 10.1021/es060842j, 2006.

Tape, K., Sturm, M., and Racine, C.: The evidence for shrub expansion in Northern Alaska and the Pan-Arctic, Global Change Biology, 12, 686-702, 10.1111/j.1365-2486.2006.01128.x, 2006.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J. M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geosci. Model Dev., 5, 773-791, 10.5194/gmd-5-773-2012, 2012.

Vuichard, N., and Papale, D.: Filling the gaps in meteorological continuous data measured at FLUXNET sites with ERA-Interim reanalysis, Earth Syst. Sci. Data, 7, 157-171, 10.5194/essd-7-157-2015, 2015.

Yen, Y.-C.: Review of thermal properties of snow, ice, and sea ice, United States Army Corps of Engineers, Hanover, N.H., USACRREL Report 81-10, 1-27, 1981.

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

515 Table 1. Average and standard deviation of snowpack height (cm) in Qarlikturvik valley. Three sites were measured in May 2014 and 6 sites in May 2015.

Date	Location	Lat. N	Long. W	n	Height ± σ
14 May 14	Polygons	73°09’	80°00’	314	16.2±13.7
16 May 14	Polygons	73°09’	80°00’	360	16.9±12.8
17 May 14	Scattered willows 1	73°10’	79°54’	356	16.3± 7.5
18 May 14	Plain, hummocks	73°10’	79°55’	399	25.1±11.2
12 May 15	Polygons	73°09’	80°00’	236	25.3±13.1
15 May 15	Scattered willows 2	73°09’	79°56’	123	27.0± 9.3
16 May 15	Scattered willows 1	73°10’	79°54’	149	26.8± 9.0
17 May 15	Large willow patch	73°10’	79°49’	130	34.9± 7.9
18 May 15	Slope, hummocks	73°09’	79°56’	140	29.3±11.5
19 May 15	Plain, hummocks	73°10’	79°55’	123	21.3± 9.8

Table 2. Some thermal characteristics of the snow pits studied in May 2015. R_T and $\overline{k_{eff}}$ have SI units. Values of $\overline{k_{eff}}$ are ranked from lowest to highest. The lowest seven values are in bold and the highest 5 values are in italics. Pits dug in a thick drift are excluded from the ranking.

Pit name	Terrain type	Depth, cm	R_T	$\overline{k_{eff}}$	Rank
Herb 1	Polygon, low center	28	4.1	0.068	13
Herb 2	Polygon, low center	41	7.1	0.058	9
Herb 3	Polygon, low center	30	5.9	0.051	5
Herb 4	Polygon, high center	25	3.4	0.074	14
Herb 5	Polygon, high center	20	2.5	0.081	16
Willows D2b North	Near shrub	42	2.7	0.155	19
Willows D2b Center	In shrub	30	3.4	0.088	17
Willows D2b South	Near shrub	32	3.5	0.090	18
Willows D1b North	Near shrub	19	2.5	0.076	15
Willows D1b Center	In shrub	20.5	3.7	0.056	7
Willows D1b South	Near shrub	20.5	3.7	0.055	6
Willows 1	In shrub	38	9.2	0.041	1
Willows 2	In shrub	43	10.1	0.042	2
Willows 3	In shrub	40.5	8.6	0.047	4
Hummock 1G	Hill, hummock	30	5.0	0.061	11
Hummock 1D	Hill, hummock	12	2.8	0.043	3
Hummock 2	Hill, hummock	42	7.3	0.057	8
Hummock 3	Plain, Hummock	19	2.9	0.065	12
Hummock 4	Plain, Hummock	35	5.7	0.061	10
	Averages	**30.1**	**6.2**	**0.067**	
Drift 1	Drift	41	7.6	0.054	
Drift 2	Drift	88	8.6	0.102	

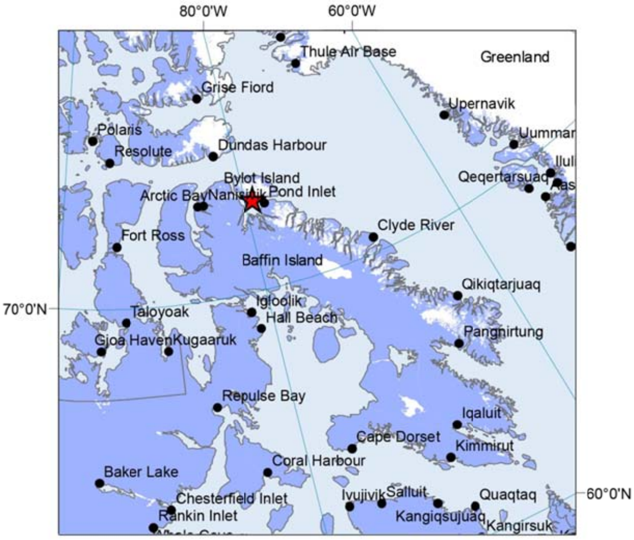
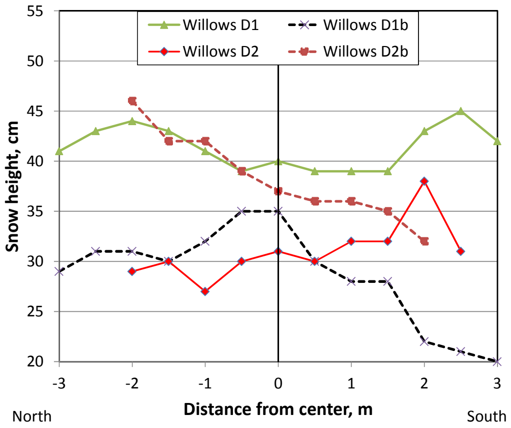


Figure 1. Map of parts of the Canadian Arctic Archipelago showing the position of Bylot Island, just North of Baffin Island. Our study site is on the south-west plain of the mostly mountainous Island.



535

Figure 2. Effect of the presence of isolated bushes on snow height in May 2015. The origin is at the center of the bush. Snow height was then measured uphill (south, positive values) and downhill of the bush. The four bushes studied were given arbitrary names.

Figure 3. Photographs of snow trapping by willows in May 2014. Increased snow height caused by the presence of shrubs is obvious. On both pictures the contrast has been enhanced with a photograph modification software.

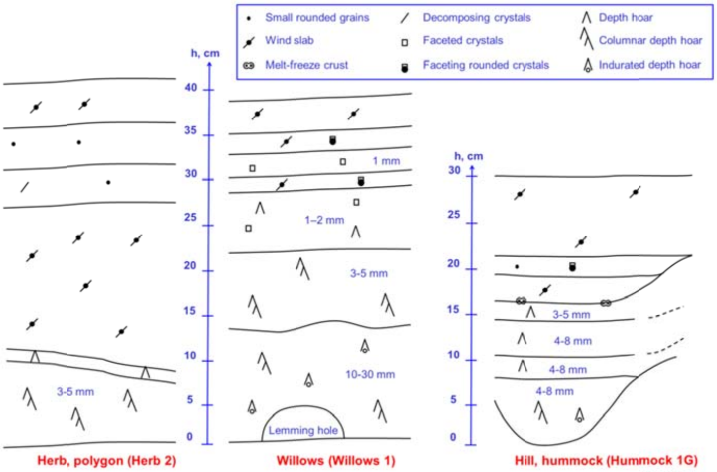


Figure 4. Simplified snow stratigraphy on herb tundra (polygons area), in the large shrub area, where shrubs reached 30 to 35 cm in height, and on the NW facing slopes with hummocks, in May 2015. Pit names are mentioned in parentheses (Herb 2, etc.) to allow correspondence with data in Table 2. The size (largest dimension) of depth hoar and faceted crystals is indicated. Grains in wind slabs and small rounded grains were in the range 0.2 to 0.3 mm. A new symbol is proposed for indurated depth hoar formed from refrozen layers

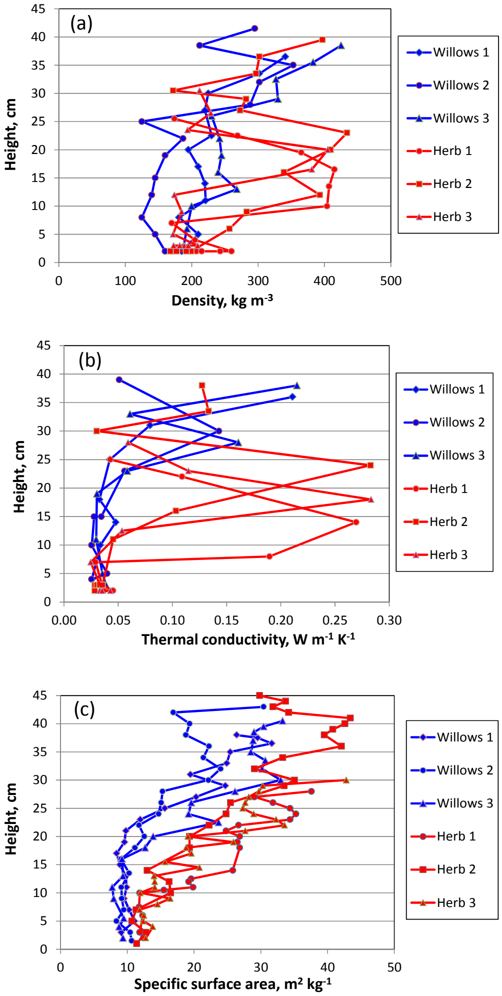


Figure 5. Comparison of physical properties of snow in three pits each in the large willow patch and on herb tundra. (a) Density; (b) thermal conductivity; (c) specific surface area. In the basal depth hoar, several measurements were sometimes made at the same height because of visible lateral variations.

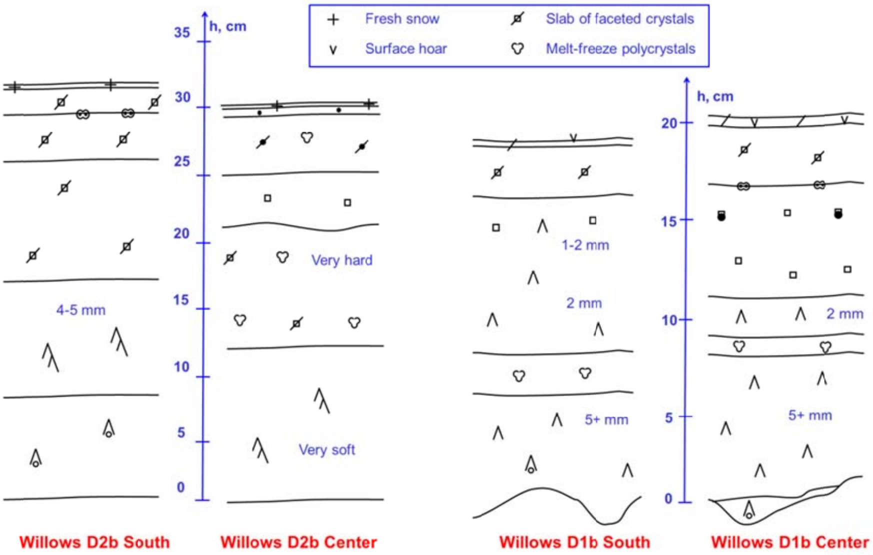


Figure 6. Simplified snow stratigraphy in isolated willow bushes. Two stratigraphies in the center of the bush and to the south (uphill) of bushes, about 1 m from the nearest shrub, are shown. Note the different vertical scales for both sites. The size (largest dimension) of depth hoar crystals is indicated. Only symbols not shown in Fig. 4 are explained.

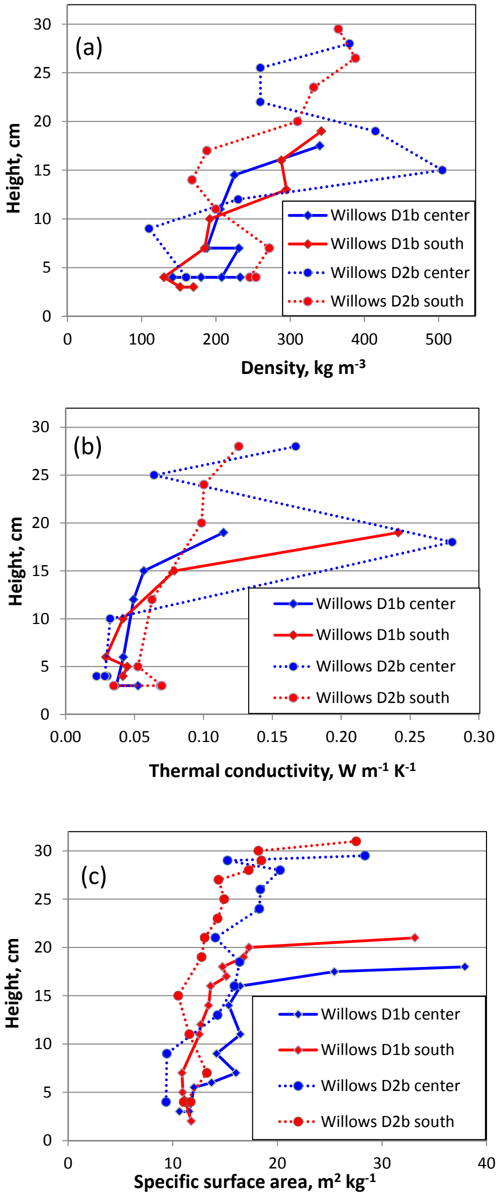
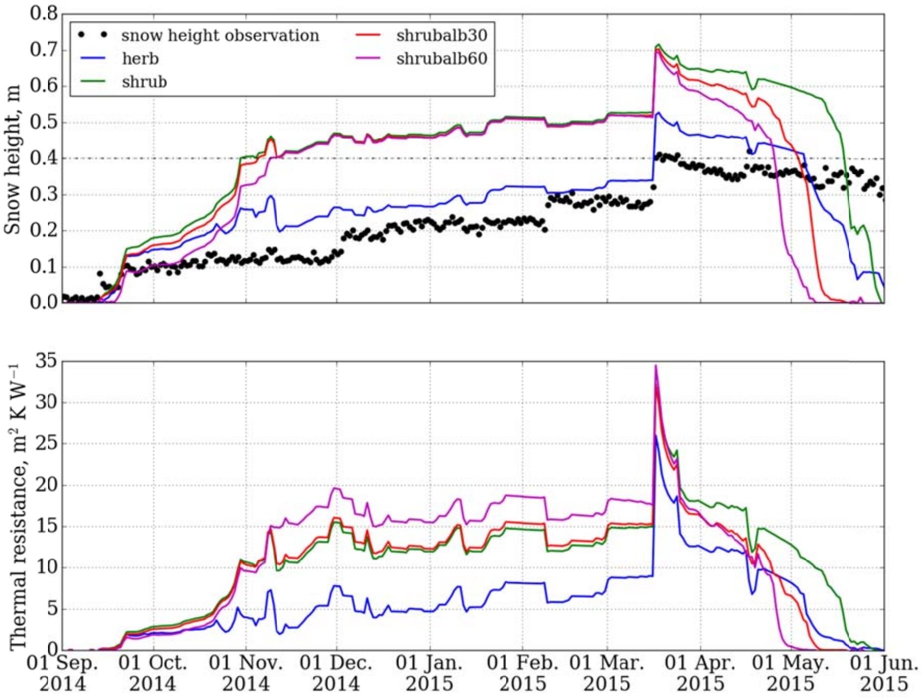


Figure 7. Physical properties of snow in isolated willow bushes (curves named “center”) and about 1 m uphill (“south”) of the bush. (a) Density; (b) thermal conductivity; (c) specific surface area. In the basal depth hoar, several measurements were sometimes made at the same height.



585 Figure 8. Simulation of the evolution of snow height (a) and snowpack thermal resistance (b) with the *herb*, *shrub*, *shrubalb30* and *shrubalb60* scenarios, for the 2014-2015 winter. Snow height monitored with an ultrasound snow gauge is also shown.

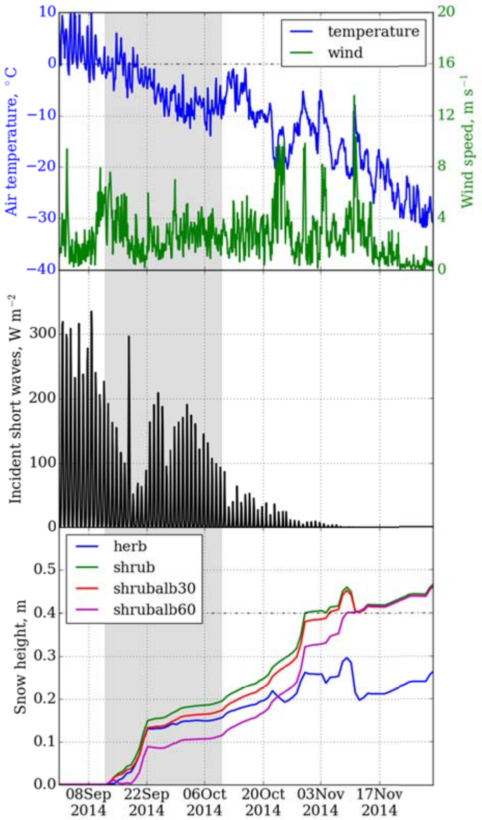


Figure 9. Air temperature, wind speed, incoming shortwave radiation and snow height in fall 2014. The shaded area indicates the period when snow is affected by albedo decrease.

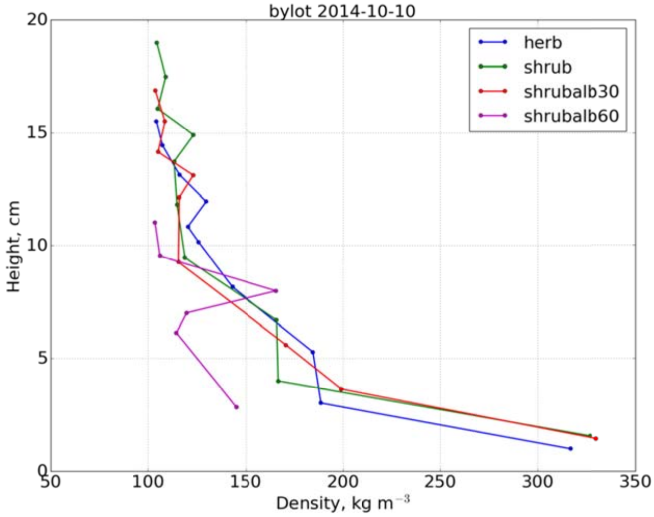


Figure 10: vertical density profiles simulated by Crocus on 10 October 2014, for the different scenarios. Densities shown are for the middle of the layers used by Crocus.

Biogeosciences Discuss., doi:10.5194/bg-2016-3, 2016
Manuscript under review for journal Biogeosciences
Published: 4 February 2016

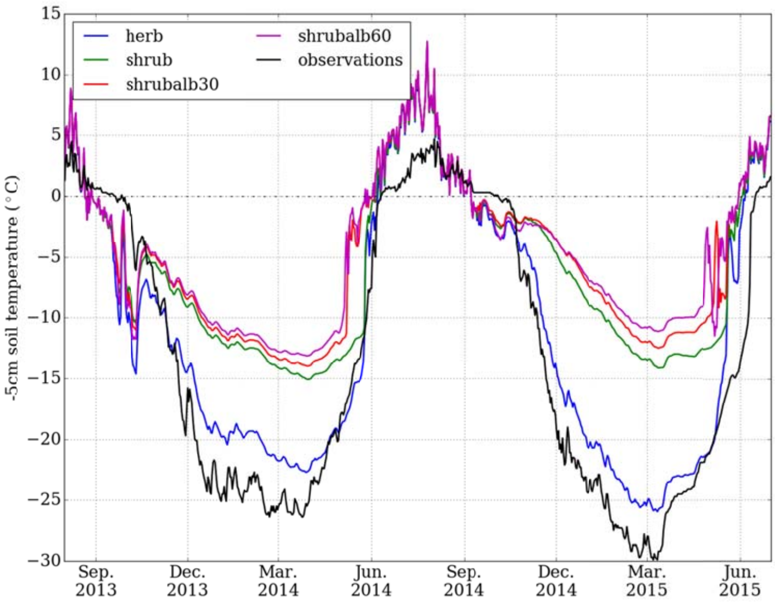


Figure 11. Simulation of ground temperature at 5 cm depth with the *herb*, *shrub*, and *shrubalb* scenarios, for the 2014-2015 winter. Measurement at our meteorological station, on herb tundra in a low center polygon area, is also shown for comparison.