Measuring and modeling the impact of vegetation growth on tundra on snow physical properties. Impact on the permafrost thermal regime.

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**ABSTRACT**

The thawing of permafrost induced by Arctic warming is expected to become one of the strongest positive climate feedback, because of the associated release of greenhouse gases to the atmosphere. Predicting how fast permafrost will thaw is complex, as the relationship between permafrost thermal regime and air temperature depends on surface conditions, mainly the presence of a snow cover and the vegetation type. To investigate these effects, we have deployed snow, soil and meteorological monitoring stations near Umiujaq, Nunavik, Canada. The seasonal evolution of the snowpack was monitored, with a particular attention on its thermal properties (thickness and thermal conductivity) in relation to the vegetation cover. Results, in addition with field observations, demonstrate that the dense shrub twigs network shelters snow from wind erosion and compaction, favouring the formation of depth hoar layers of much lower thermal conductivity than the wind slabs that prevail in the absence of vegetation. Other impacts of the shrubs include the absorption of radiation, which by facilitating snow melting increases its thermal conductivity. As the prediction of these effects are currently not considered by snow models, we modified the Crocus snow scheme in order to simulate the impact of vegetation growth in tundra on the permafrost regime, and to obtain a preliminary quantification of a feedback between climate, vegetation, snow and permafrost.

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INTRODUCTION

Context

Permafrost is defined as ground that remains frozen for two or more consecutive years. About 25% of exposed land in the Northern Hemisphere are occupied by permafrost, mostly in high latitudes, representing several millions of km². Because of the cold temperatures, the microbial decomposition of vegetation debris is inhibited and organic matter accumulates. According to the latest estimates, the permafrost carbon stock is about 1300 ±200 Pg (1 Pg = 10¹⁵ g) (Hugelius et al. 2014). This estimate exceeds the atmospheric carbon pool (~830 PgC), as well as the fossil fuel reserves (IPCC report, 2013). Thus, permafrost represents a very large terrestrial carbon pool.

But under changing climate, the permafrost is warming and the microbial activity is thus enhanced. The thawing of permafrost is expected to be the source of large amounts of greenhouse gases (CO₂ and CH₄) released to the atmosphere, resulting in one of the strongest positive climate feedback. In order to predict the consequences on the global warming, it is then essential to estimate exactly the rate and amount of permafrost which is going to thaw.

However, it is not easy to calculate the permafrost thermal regime because of the numerous factors affecting the surface energy exchanges. The permafrost temperature depends not only on the direct influence of climate parameters such as air temperature, wind speed and solar radiations, but also on surface factors. The main surface characteristics that control heat exchanges are the snow cover, because of the insulating capacity of the snowpack, and the vegetation (Lachenbruch et al. 1965; French 1996; Sturm and McFadden 2001). But all these different factors also interact between them, which complicates the calculation of the ground thermal regime. For example vegetation affects snow physical properties, and therefore its insulating effect, in different ways according to the type of vegetation. But the vegetation type is also changing in response to the global warming, with shrubs expanding on tundra and the tree line moving north (Sturm et al. 2005; Myers-Smith et al. 2011; Ropars and Boudreau 2012).

Figure 1. Map of the Canadian Arctic and permafrost areas. Our study sites are indicated with red stars. Credit: Michaël Lemay.
Objectives

In order to better understand how permafrost will respond to the changing climate, our work consists in observing and measuring the interactions between snow, vegetation and permafrost, and to model them to simulate the accurate surface energy budget. Today, there is no snow physical model taking into account the vegetation effects. We aim to integrate the observed effects in the Crocus snow model (Brun et al., 1989) to better simulate the Arctic snowpack, and the resulting permafrost thermal regime.

Our study sites are located in the Arctic and Subarctic regions in the northern Canada (figure 1). On the eastern shore of Hudson Bay, Quebec, Canada, Umiujaq (56°33’N; 76°28’W) is an Inuit village just north of the tree line. Permafrost is discontinuous, and vegetation types there include herb tundra, shrub tundra (dwarf birch and willows from 20 cm to 1 m tall, figure 2) and forest tundra (spruces several meters high).

The diversity of vegetation types that we cover allows us to observe different effects of vegetation on snow physical properties, and on the resulting ground temperature. Here, we focus essentially on the interactions between shrubs, snow and ground temperature.

Figure 2. Photograph of Umiujaq shrub tundra.

Observations

Among the effects of shrubs on snow physical properties, we focus here on the following ones: a higher accumulation of snow of lower density and lower thermal conductivity.

The most obvious effect of vegetation on snow observed is a higher snow accumulation, due to the trapping of wind-blown snow and its sheltering from wind erosion. The result is a deeper snowpack, whose thickness increases with increasing vegetation height. Figure 3 shows statistics of snow depths measurements taken near Umiujaq in February 2015. The average snow depth was 89 cm in shrub tundra (in orange), and 128 cm in forest tundra (in blue).
The presence of shrubs also decreases the snow density, especially that of basal layers. By limiting wind compaction, and therefore the formation of high density wind slabs, and by reducing the snow compaction caused by the weight of upper layers, shrubs favor the development of thick depth hoar layers of low density (figure 4). Wind slabs can form above vegetation, but snow layers within the shrubs have lower density.

Another effect of shrubs on snow physical properties concerns its thermal conductivity. By favoring depth hoar formation and by preventing its compaction, shrubs also limits the increase of the snow thermal conductivity (figure 5, Domine et al., 2015). We could even observed the low density depth hoar collapse (14 cm curve, around 30 March), leaving a void that was not filled by snow. According to the heat equation derived from Fourier's law, a lower thermal conductivity
combined with a thicker snowpack will reduce the heat flux, producing a better insulating snowpack.

![Figure 5. Time series of effective snow thermal conductivities automatically measured in Umiujaq shrub tundra.](image)

**MODELING**

We use the Crocus detailed snowpack scheme, which models the energy budget and the metamorphism of the snow, in addition to the SURFEX-ISBA land surface water and energy budget model. Forcing data (air temperature and humidity, wind speed, precipitations, solar and atmospheric radiations) are from our automatic weather stations, complemented with ERA-Interim reanalysis data to fill the gaps. As output, we obtain the energy budget of the surface and the ground, the snow physical properties and the ground thermal regime. However, Crocus does not describe the effects of vegetation. This is why we are currently adding some of the observed effects of shrubs on snow physical properties in Crocus. As a first step, we limit snow compaction in shrubs and eliminate wind erosion of snow in shrubs.

Vegetation effects are implemented in the model depending on a vegetation height threshold. For the underlying snow layers, the erosion and compaction caused by the wind as well as the compaction induced by the weight of the snowpack are inhibited. The simulated snowpack is thus thicker and less dense, resulting in warmer ground temperatures in winter (figure 6). By adding 30 cm tall shrubs, simulated ground temperature increases by 0.9°C in early February, 10 cm below the surface. At the same period, the warming is 3.7°C under 80 cm high shrubs.
CONCLUSION

The snow physical properties strongly impact the ground temperature, but they are also affected by the presence of vegetation. In response to the global warming, shrubs are expanding on tundra which produces a better insulating snowpack. It is thus essential to consider the interactions between snow and vegetation in models to better predict permafrost thaw.

We made many interesting observations of vegetation effects on snow, according to the type of vegetation. Adding the sheltering effect of shrubs in the Crocus snow model, which reduces the wind drift and the snow compaction, produces a thicker and better insulating snowpack similar to our observations. The consequences on the ground are warmer temperatures in winter. Some effects still need to be modeled, like the trapping of wind-blown snow or the impact of the solar radiations absorption by the twigs, but our results already show a more accurate simulated ground thermal regime.

REFERENCES

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