Frost boils, soil ice content and apparent thermal diffusivity

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ABSTRACT: Cryoturbation in continuous permafrost regions often results in a visually striking mixing of soil horizons or materials. We are studying frost boils that formed in lacustrine sediments in the Galbraith Lake area, north of Alaska's Brooks Range, and the heat transfer and phase change dynamics that maintain these features through seasonal cycles. These frost boils are distinctly visible at the ground surface, and are silty-clay upwellings that penetrate the surrounding organic soil. Sensors were installed in a vertical plane from the frost boil's center outward to measure soil temperature, thermal diffusivity, liquid water content and thermal conductivity. The temperature field, water content and thermal properties during freezing and the concomitant changes in ice content are examined and discussed with respect to frost boil mechanics. Preliminary data suggest that ice content changes and differential snow cover dynamics are important in the maintenance of the frost boil structure over many freeze-thaw cycles.

1 INTRODUCTION

A frost boil is a roughly radially symmetric discontinuity in soil horizons and surface characteristics. Frost boils are often associated with sorting of soil materials based on grain size (Washburn 1956). They can be the result of convection cell like cryoturbation, diapir formation or upwellings of lower soil horizons under pressure. Given the dependence of their distribution on climate, repeated freeze and thaw events are a factor required for their formation (Yershov 1998). Frost boils are generally recognized at the surface by the lack or difference in vegetation. In the case of cryoturbation, material at the surface is subsumed by cryoturbation faster than pioneer species can establish themselves. In the case of plug formation or pressure upwellings, however, the unvegetated surface is the result of a change in surface characteristics that renders the environment inhospitable. Such boils can appear sorted if the upwelling soil horizon has a particle size distinct from that of the surface layers. The centers of frost boils are usually higher than their margins as a result of the upper movement of material beneath the center. The center may be higher or lower than the vegetated periphery.

Kessler et al. (2001) created a strictly mechanical model of the spontaneous formation of sorted circles from two layers distinct in particle size. In their model, and in conceptual models mentioned elsewhere (French 1996; Washburn, 1956), frost heave has both a vertical and horizontal component. In a frost boil, the horizontal component in the upper horizons is directed radially outward during freezing. During subsequent thawing, however, consolidation occurs vertically. The cumulative effect over a number of freeze-thaw cycles is an upwelling of material in the center of the boil and its subsumption at the edges. Thermal expansion and changes in total moisture content are factors in this type of cryoturbation. MacKay & MacKay (1976), however, concluded in their study of mud hummocks that most mass displacement occurred not during freezing but during the summer. Nonetheless, differences in water content will lead to the differences in heave observed between the center of the frost boil and its edge. This study seeks to quantify these differences and their influence on cryoturbation and thermal dynamics.

2 METHODS

A frost boil in the Galbraith Lake basin (68°28.890'N, 149°28.744'W) was excavated and instrumented in the fall of 2001, when the active layer was at a maximum thaw depth for that year. Many frost boils exist in the area of the excavation and they share a number of characteristics. They have developed in poorly to imperfectly drained soils on a flat lacustrine and perhaps fluvial deposit. The frost boils are visible at the surface as roughly circular patches of vegetation free soil, 0.2 to 1.5 m in diameter (most are 0.8 to 1.0 m), that are cracked vertically in a columnar fashion to a depth of up to 0.2 m. Their distribution is for the most part random,

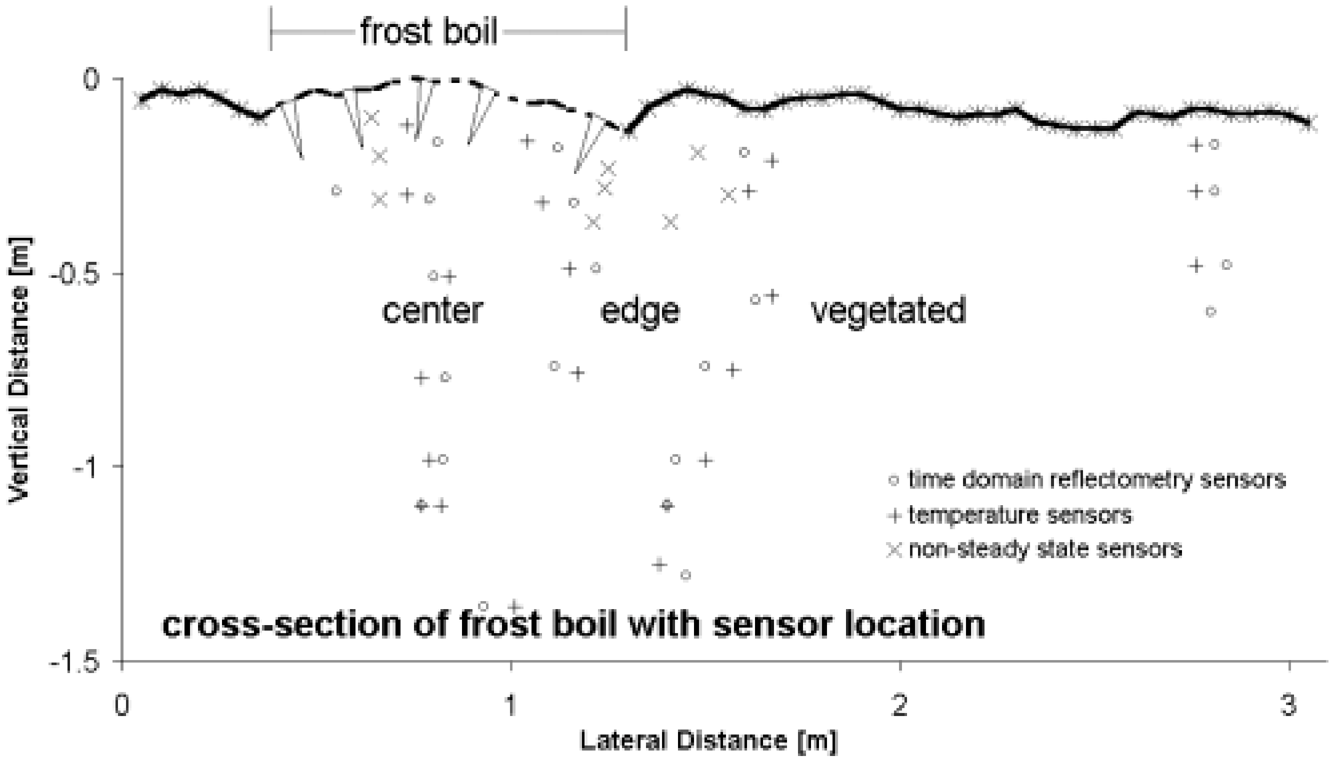

Figure 1. A cross-section of the instrumented frost boil with the positions of some the instruments. The frost boil itself is 1 m in diameter at the surface. Non-steady state sensors are for the measurement of effective soil thermal properties.

but some groups of boils lie along straight lines extending for up to 10 m. In a few cases, these boils are not circular but oblong.

Care was taken during excavation to organize soil removed from the pit and to minimize disturbance to the profile on restoring the excavated soil. The pit was 1.5 m deep and transected the boil from its center to a point 1 m distant. An additional pit was excavated 2 m from the center. The frost table was encountered at 0.84 m beneath the boil and at less than 0.7 m beneath the tundra adjacent to the boil. Samples were taken from the profile and soil characteristics are discussed in Ping et al (2003). Three sets of temperature, water content (time domain reflectometry) and non-steady state thermal probes were installed at about 0.25 m beneath the surface in a transect from the frost boil center to a point 2 m from the center and 1.5 m from its edge (Fig. 1). The data from September 2001 until February of 2002 are presented here. Thermistors were calibrated in an ice bath and measured relative to a high precision reference resistor. Time domain reflectometry probes were calibrated using a two-point method and have a precision of +/- 0.03 v/v. As an initial assessment of water content, Topp's equation for relating soil dielectric values to water content was used. The non-steady state heat diffusion sensors consist of a 0.001 x 0.06 m heat supply mounted between thermopiles in a thin film. By measuring the response of the thermal gradient to heating, the thermal conductivity and diffusivity of the medium in which the probe is inserted can be measured. The probes have been calibrated for the range 0.3 to 4.0 W/mK. Snow depth was measured daily at the site using a sonic distance sensor mounted on a meteorological tower. Snow depth and morphology was observed directly at three times during the winter.

3 RESULTS

3.1 *Temperature*

Surface temperatures at the site decreased from mean values of 5 °C in September to less than –15 °C by mid-February. Snowfall began in September and accumulated to a depth of 0.18 m over the regions surrounding the frost boils by February (Fig. 2).

Thaw depth was 0.14 m greater beneath the center of the boil than beneath the organic layer and vegetation surrounding the boil in September 2001. Freezing in the exposed mineral soil of the center was more complex than in the vegetated boundary, and characterized by frequent diurnal freeze-thaw cycles down to 0.2 m between September 12 and October 5. During this period, the temperature fluctuations at the same depth beneath the organic horizon were insufficient to cause phase change, but both profiles lost energy and became isothermal around September 19. The descent of the freezing front progressed more rapidly beneath the center of the boil.

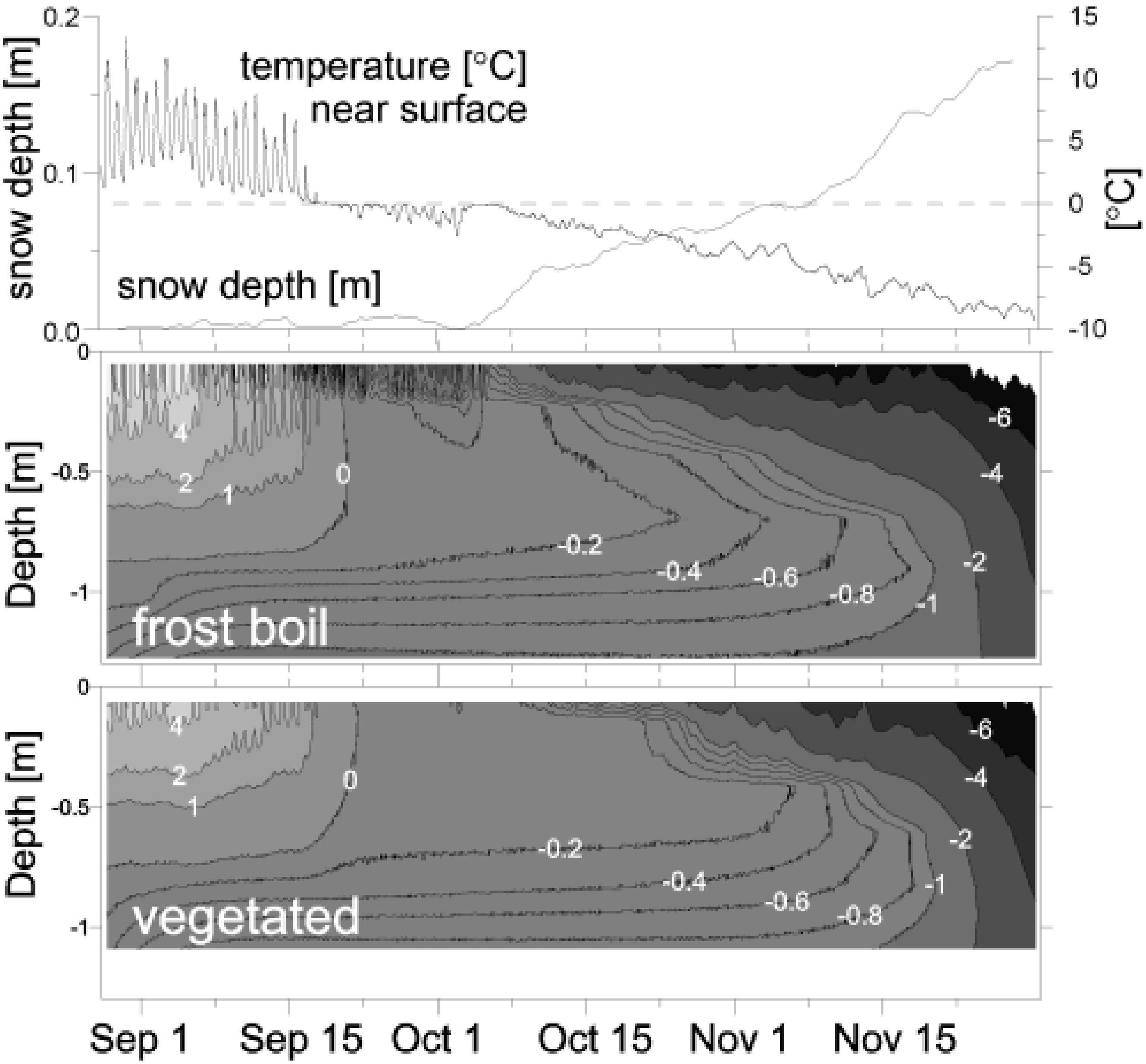

Figure 2. Surface temperature and snow depth in the vegetated region surrounding the frost boil are shown in the top graph. The temperature fields are for the frost boil center and the vegetated profile adjacent to the frost boil.

3.2 *Snow*

The exposed mineral soil of the frost boil remained snow free later in the fall than the vegetated area surrounding the boil. The slight elevation of the frost boil apex above the surrounding tundra and differences in vapour transport through the soil into the snow pack resulted in differences in snow morphology as well. The frost boil is not as susceptible to wind slab formation as the surrounding tundra and snow above the boil remains thinner and less dense. By February 2002, the vegetated surface snow profile contained a layer of wind slab underlain by hoar frost and overlain of recent snow. Over the frost boils, however, there was no identifiable wind slab, and less snow. Although no longer visible at the snow surface, the frost boils could be identified underfoot by these differences in snow character.

3.3 *Moisture Content*

Figures 3 and 4 show unfrozen moisture content as a function of time and temperature. The frost boil center, edge and vegetated surface layers (at depths of 0.30, 0.25, 0.25 m, respectively) had high moisture contents, indicative of near saturation, before freezing (Fig. 3). The soil began freezing in the mineral soil on September 17 and almost a week later in the organic horizon at 0.25 m depth. Two weeks after freezing began, the unfrozen water content in the vegetated soil dropped by 0.45 and in the center of the boil by less than 0.15 m. The freezing point lay between 0 and -0.05 °C for all three locations (Fig. 4).

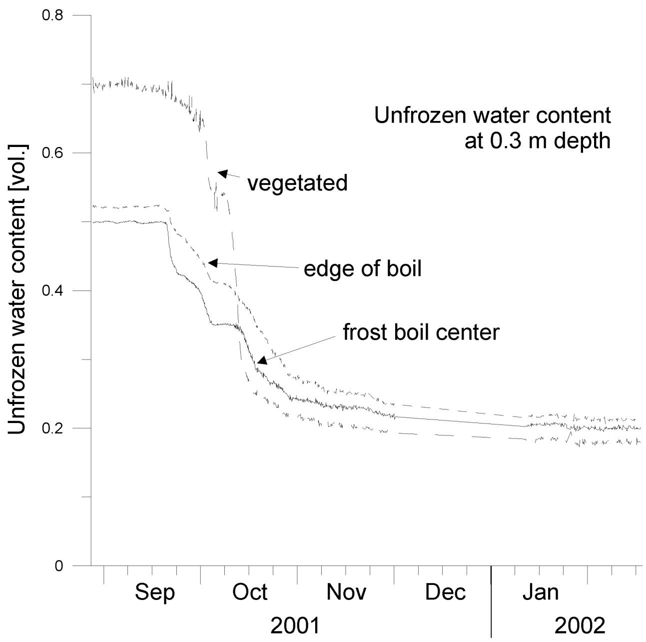

Figure 3. Decrease in unfrozen water content associated with fall freezing for three sensors at 0.25 m depth, at the frost boil center, edge and at 1.3 m from its center.

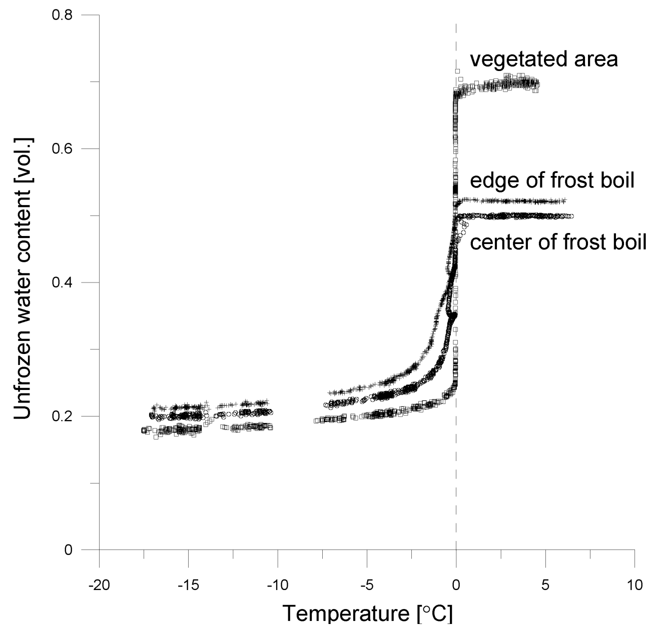

Figure 4. Freezing characteristic curves for the same locations as in Figure 3. The stable water contents above 0 °C reflect saturation moisture levels before freezing.

3.4 *Thermal Properties*

Effective thermal properties (conductivity and diffusivity) were measured using the non-steady state probes during freezing. Measurements were made every three days for two weeks in early September and from December through February. Effective volumetric heat capacity was calculated based on measured thermal conductivity and diffusivity values:

$$C_{eff} = \frac{K_{eff}}{\alpha_{eff}} \tag{1}$$

where K_{eff} = effective thermal conductivity and α_{eff} = effective thermal diffusivity. The effective volumetric heat capacity of the soil changed during freezing (from September to December.) by 1.2, -1.2 and -1.9 x 10^5 J/m^{3}K for the frost boil center, boundary and tundra sensors, respectively (Fig. 5), corresponding to unfrozen water content decreases of 0.30, 0.31 and 0.52 (Fig. 4).

4 DISCUSSION

The freezing front descent in the frost boil is faster than in the vegetated area around the boil. The shallower and later snow pack on the exposed mineral soil, and the lack of an organic horizon, expose it to steeper temperature gradients at the surface, and the heat flux out of the soil is greater. A thawed layer (temperatures > -0.2 °C) beneath the vegetation persists two weeks longer than beneath the frost boil. The drop in heat capacity with unfrozen water content (Fig. 6) in the organic layer results in higher rates of heat diffusion out of the soil, with the result that the vegetated temperature profile cools more rapidly after November 1 than the frost boil profile. By the end of November, the temperature distributions at both locations are very similar.

Hinzman et al. (1991) observed effective thermal conductivity values in the range of 0.2 to 1.6 W/mK for soils from the foot hills of the Brooks Range, in dry organic soils to saturated mineral soils. Decreased temperature resulted in increases in thermal conductivity proportional to total water content. Thermal conductivity values in the frost boil center increased from 0.3 to 1.3 W/mK (cf. Hinzman et al. 1991, who observed changes in thermal conductivity from 0.9 to 1.3 W/mK for a saturated mineral soil). In this study, the thermal conductivity in the boundary and inter-boil soil fell during freezing, indicating either drying or a drop in ice content during this period. Goodrich (1986) recorded seasonal variations in thermal conductivity of a variety of soils, but saw changes smaller than those recorded here (maximum of 0.8 W/mK for organic soils). He attributed differences between thermal conductivity of similar materials to differences in total moisture content. Nakano and Brown (1972) reported that effective thermal conductivities of organic and mineral soils behaved oppositely on freezing. Their frozen organic soils had higher conductivities than unfrozen by a factor of 2 to 3, whereas the mineral soils tended to decrease in conductivity on freezing.

The thermal conductivity of soil is dependent in a complicated fashion on soil composition and geometry (Farouki 1981), but heat capacity varies with

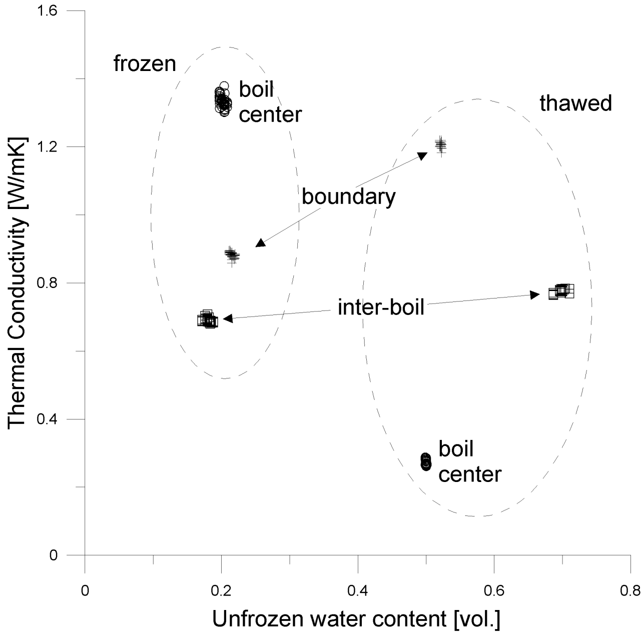

Figure 5. Thermal conductivity values before (September 2001) and after (December to February 2002) freezing. The frost boil center's mineral soil increases in conductivity during freezing.

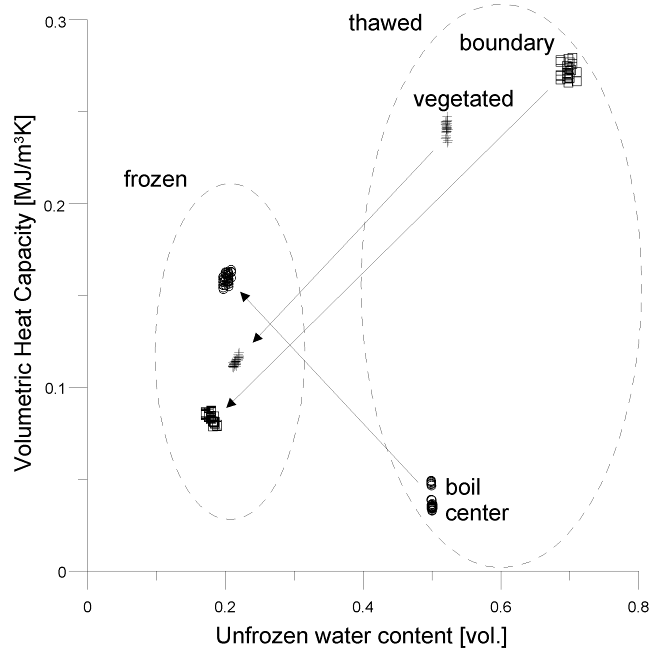

Figure 6. Volumetric heat capacity values calculated from measured thermal conductivity and diffusivity values.

composition only. In this study, heat capacity is calculated from measurements made of diffusivity and thermal conductivity. In general, the volumetric heat capacity depends on soil composition:

$$\Delta C = \sum_{n=a,w,i,s} C_n \Delta\theta_n \tag{2}$$

where C_i = volumetric heat capacity of phase i; and θ_i = volumetric content of the same phase in the soil and subscripts a, w, i and s refer to air, water, ice and solid, respectively. Since the soil is near saturation before freezing, changes in gas volume are assumed to be negligible. We also assume that ice replaces water during phase change, with negligible changes in soil volume. Changes in ice content can then be estimated based on changes in volumetric heat capacity. Ice lens formation during freezing produces inhomogeneities in phase density and increases the ice content beyond that predicted by saturated liquid water content. These effects are ignored, and changes in ice content are given by:

$$\Delta\theta_i = \frac{1}{C_i}\left(\Delta C_{eff} - C_w \Delta\theta_w\right) \tag{3}$$

yielding changes in volumetric ice content of 0.6, 0.7 and 1.0 v/v for the frost boil center, edge and vegetated region, respectively, all at 0.25 m depth. These are larger than the porosity determined as liquid water content at saturation via time domain reflectometry. Since water's heat capacity is more than double that of ice, phase change from liquid water to ice can be expected to decrease the effective heat capacity of the soil. The heat capacity of the frost boil center, however, increased during freezing, as the result of increases in thermal conductivity. The effects of snow cover, of vegetation absence or presence and of increases in thermal conductivity create differences in the temperature field and thermal properties between the frost boil and the surrounding soil during freezing.

5 CONCLUSIONS

On the basis of this preliminary physical data, the deformation of soil horizons by a frost boil results in localized changes in surface characteristics and material properties. The energy exchange at the surface is affected and the thermal dynamics of the soil change. The frost boil center freezes more quickly, thaws deeper and is subject to more diurnal freezing and thawing cycles than the surrounding vegetated soil. Differences in material properties lead to lower saturation water contents near the surface of the frost boil than adjacent to it. Changes in water content during freezing are smaller in the frost boil center than for the surrounding organic soil. Despite the saturation of the soil prior to freezing, changes in thermal conductivity for soils close to 0.25 m depth are not directly related to phase change of the soil constituents. Heat capacity at 0.25 m depth in the center of the frost boil increased during freezing, but fell at edge of the boil as a result of similar changes in thermal conductivity which suggest that ice content increased substantially within the frost boil but not at its edge.

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