[RC: Highlighted in yellow are suggestions.

Modifications proposed by this reviewer are highlighted in red.]

Links between annual surface temperature variation and land cover heterogeneity for a boreal forest as characterized by continuous, fiberoptic DTS monitoring

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Abstract. A fiberoptic DTS (distributed temperature sensing) system using Raman-scattering optical time domain reflectometry was deployed to monitor a boreal forest research site in the interior of Alaska. Surface temperatures range between -40º C in winter to 30º C in summer at this site. In parallel experiments, a fibre-optic cable sensor system (multimode, GI50/125, dual core; 3.4 mm) monitored at high-resolution (0.5-metre intervals at every 30 minutes) ground surface temperatures across the landscape. In addition, ~~at several points~~ a high resolution vertical temperature profile ~~from~~ was acquired one-meter height above the ground surface ~~the upper subsurface?~~ ~~to a meter above~~. The total cable ran 2.7 km with about 2.0 km monitoring a horizontal surface path. Sections of the cable sensor were deployed in vertical coil configurations (1.2 m high) to measure ~~vertical~~ temperature profiles from the ground up at 5-mm intervals. Measurements were ~~collected~~ made continuously over a two-year interval from October, 2012 to October, 2014. Vegetation cover at the ~~of the overall~~ site (Poker Flat Research Range) consists primarily of black spruce underlain by permafrost. Land cover types within the study area were classified into six descriptive categories: relict thermo-karst lake, open moss, shrub, deciduous forest, sparse conifer forest, and dense conifer forest. The horizontal temperature data exhibited spatial and temporal ~~patterns~~ changes within the observed diurnal and seasonal variations. Differences in snow pack evolution and insulation effects co-varied with the land cover types. The apparatus used to monitor vertical temperature profiles generated high-resolution (c. 5 mm) data for air column, snow cover, and ground surface. This research also identified several technical challenges ~~of~~ in deploying and maintaining a DTS system under sub-arctic environments.

1 Introduction

Under the current climate conditions, boreal forest regions function as major carbon sinks (IPCC, 2013; Euskirchen et al., 2006; Piao et al., 2008; Ohta et al., 2008). Taiga regions however ~~can show~~ reveal considerable variations (heterogeneity) in land cover, hosting both dense and sparse forests, shrubs, grasses, open mosses, and bare ground. Depending on their structural features and seasonal variations, each of these land cover types behaves differently in terms of energy, mass, and momentum exchange. These factors include presence of and variation in different forms of canopy, aerodynamic and radiative characteristics, phenology and snow pack, all of which can influence geothermal flux, subsurface physical conditions, and microbial activity (Euskirchen et al., 2006; Pomeroy et al., 2008; Essery et al., 2009; Rutter et al., 2009; Kasurinen et al., 2014; Ikawa et al., 2015; Purdy et al., 2016). For boreal forests, surface and subsurface conditions are critical causal variables, especially in terms of their spatio-temporal variations. Surface heterogeneity can also exert non-linear influence on energy, mass, and momentum exchange with the atmosphere (Vrese et al., 2016; Sellers, 1999). In-situ field measurements can help quantify spatio-temporal temperature patterns and help constrain numerical eco-climatic models for taiga regions. Data ~~like that~~ presented and interpreted below thus offer specific empirical information about taiga environments and contribute to larger-scale predictions concerning impacts of Earth's warming climate (e.g., Beer et al., 2007; Sato et al., 2016).

Distributed temperature sensing (DTS) systems perform multi-sensor monitoring of an area using a fibre-optic cable configuration. ~~and Raman scattering techniques~~. Developed in the 1980s and improved thereafter, DTS was initially used in built environments, providing fire detection for example in industrial complexes ~~or~~ and power plants (Dakin et al., 1985; Dyer et al., 2012; Soto et al., 2016). The technique was subsequently adapted for hydrological and geophysical research seeking to measure temperature variations in natural environments (Selker et al., 2006a, 2006b; Tyler et al., 2009; Thomas et al., 2012; Lutz et al., 2012). The research described here represents for the first time how the method has been used to study thermal environments of a boreal forest. DTS monitoring techniques, which can provide continuous, high resolution data, are ideal for studying ~~large~~ seasonal variations in ambient temperatures (from -40º C in winter to 30º C in summer) and other conditions (persistent snow cover with deep hoar or ice layers, freeze / thaw cycles) that characterize interior parts of continental boreal forests ~~recommend these environment to~~. The data described here include temperature variations and snow pack evolution ~~that reflect~~ ~~the~~ in heterogeneous land cover of the boreal forest, and also a high resolution vertical temperature profile of the interval from the ~~upper~~ ground surface to a meter above.

Section 2 describes the research site and methodology. Section 3 describes ~~results of~~ ~~for the horizontal (sections 3.1, 3.2) and vertical (section 3.3)~~ temperature data acquired during the two-year experiment for selected horizontal (items 3.1, 3.2) and vertical (item 3.3) targets. Section 4 considers technical challenges of using DTS systems in sub-arctic environments and section 5 summarizes the study.

2 Methodology

2.1 Site

The Poker Flat Research Range (65˚07'24" N, 147˚29'15" W, 210 m a.s.l.) is a ~~research~~ facility managed by the University of Alaska Fairbanks (UAF) and located in the Interior of Alaska, about 50 km northeast of Fairbanks (Fig. 1). The general area is part of a discontinuous permafrost zone but the site itself is underlain by permafrost with active layer thickness of about 50 to 150 cm (Nakai et al., 2013). The research site includes an observation tower built in 2010 as part of a collaboration (known as JICS) between the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and UAF's International Arctic Research Center (IARC) (Sugiura et al., 2011; Nakai et al., 2013; Ikawa et al., 2015 ; Nagano et al., 2018). This observation tower was used ~~to discretely~~ for making discrete measurements of air temperatures at 1.5-m height, ~~downward~~ short-wave radiation measurements at 16-m height (tower top), and snow depth using an ultra-sonic sensor. The data from these sources were integrated into 30-minute intervals prior to analysis. Measurements were conducted for a period of two years, from October 13, 2012 to October 13, 2014.

A ~2.7 km fibre-optic cable was installed at the site (indicated by black line in Fig. 2a). The line traversed an ~~arcuate~~ irregular 2 km long path and included five different stations (numbered 1-5) ~~consisting of~~ with vertical temperature sensing ~~apparatus~~ equipment (see Sect. 2.2). The site's dominant vegetation type is black spruce, but locally the site exhibits considerable variation in surface conditions and vegetation types (see Fig. 2a). We classified land cover into six descriptive categories by applying a supervised classification algorithm (Maximum Likelihood) to RGB aerial imagery, collected on September 4, 2012. Land cover designations include relict thermokarst, lake/bare ground, open moss, shrub, deciduous forest, sparse conifer forest, and dense conifer forest. The Majority Filter tool (ArcGIS 10.3) was applied to reduce effects of speckle noise prior to classification. Figure 2b shows the occurrence frequencies of the six land cover types along the length of the cable.

Figure 2c shows land cover type associations along with radiative and structural canopy characteristics for each measurement segment (~50-cm intervals) along the cable. The Normalized Difference Vegetation Index (NDVI) was derived from a GeoEye1 image taken on September 25,

2010. The canopy rate, the upper sight ratio covered by vegetation canopy when projected on a hemisphere, was calculated from a series of semi-spherical pictures taken at a height of 30 cm for every 70 cm along the cable by a THETA fish-eye camera (RICOH, Inc. Cylindrical projection). Ellipses are color-coded for each land cover type and drawn with radii representing the standard deviation in canopy rate (horizontal) and NDVI (vertical).

Figures 2d - 2i shows typical ambient conditions for each land cover type. Relict thermokarst lake areas (Fig. 2d) ~~for example~~ include grassy depressions or flats once occupied by lakes formed by subsidence due to melting of ground ice from permafrost. This category also includes easily discernible bare grounds cleared by human activity. Moss areas (Fig. 2e) consist of open spaces covered by moss (mainly sphagnum moss, Sphagnum fuscum, and feather moss, Hylocomium splendens) or lichens, ~~with~~ where trees are absent. Shrub areas (Fig. 2f) are covered by dwarf to tall ~~shrubs~~ species. Deciduous forest land cover (Fig. 2g) consists of mixed forests with deciduous (birch, aspen, willow, etc.), and conifer (black spruce, Picea mariana, and white spruce, Picea glauca) species. The sparse conifer (Fig. 2h) and dense conifer (Fig. 2i) forest land cover types are occupied by spruces of varying density. The forest floors are mainly covered by moss with occasional shrubs where trees are sparse.

2.2 Methods

The fibre-optic DTS (distributed temperature sensing) system deployed in this study ~~used~~ makes use of Raman-scattering, optical time domain reflectometry techniques in measuring temperatures along the cable (Dakin et al., 1985). ~~Scattering of incident photons from~~ A laser pulse within the optical fibre (SiO_2) ~~includes~~ generates back scatter radiation at different frequencies (Raman scattering). The system can record intensity ratios within the scatter spectrum (i.e., Stokes and Anti-Stokes peaks). The latter peak is ~~highly~~ sensitive to the temperature of the medium ~~while the former is not~~ (Fig. 3). The location of the temperature measurement ~~detected~~ is ~~determined by~~ derived from the travel time data (i.e., optical time domain reflectometry). Measurements were performed in dual (looped) mode wherein the laser pulse is emitted from alternate channels at each end of the cable. Calibration was performed at 0º C using a 10-m segment of the cable.

This study used a 2.7 km long fiberoptic cable (multi-mode, GI50/125, dual core; 3.4 mm, S2002A, manufactured by BRUGG, Switzerland) installed ~~horizontally~~ over a 2.0 km surface path (referred to as the horizontal section). Temperatures were measured at 50 cm intervals along horizontal (non-coiled) sections of the cable. Portions of the cable were also coiled around PVC tubes (effective outer diameter of 11.5 cm, and length of about 120 cm). The tubes were vertically embedded in the ground to half of their length (60 cm deep), at five stations numbered 1-5 (Fig. 2a) along the horizontal pathway. Figure 2i shows a tube ~~being installed~~ prior to its installation while Figure 2e shows a tube ~~in operation~~ after installation. One loop of the coil measured about 36 cm so that three loops (c. 1 m) corresponded to two measurement segments (~~a segment =~~ each with length of 50 cm). This gave an effective vertical resolution of about 5 mm. Temperature data from the embedded tubes are referred to as ~~the~~ vertical sections. ~~Measurements taken~~

Data acquired at every 10 seconds were integrated over 30-minute intervals to reduce undesirable effects of measurement error and noise. The experiment operated continuously over a two-year interval from October, 2012 to October, 2014, except for several short-period disruptions due to cable or power supply failure. Temporal monitoring was referenced to Alaskan Standard time (UTC - 9 hours).

3 Results

Figure 4 shows an example of temperature data ~~averaged~~ acquired over a 24-hour period, on December 1, 2013, along ~~the~~ a horizontal section. The daily average tower air temperature (measured at height of 1.5 m) was -32.5º C and daily mean snow depth was 23.5 cm. In this figure, downward spikes corresponds to temperatures of those parts of the cable exposed above the upper surface of the snow pack (minimum temperature was -32.6º C while the maximum temperature was +1.0º C). ~~For this season, this~~ The temperature difference of more than 30º C is likely due to combinations of the thermal effects of insulation by snow pack and of the saturation and unfrozen moisture content of the near-surface soils.

3.1 Diurnal and seasonal variation

Figure 5 shows results of DTS measurements for the six different land cover types, carried out over the two-year period. Diurnal and seasonal variations in surface temperatures indicate the influence of both microclimates and micro-environments. Land cover types co-vary with surface conditions, canopy structure, and temporal patterns at each location. ~~Figure 5 illustrates DTS data on diurnal and seasonal temperature variations for each land cover type over the two-year period.~~ In this figure, the curves in blue color indicate daily maximum and minimum temperatures ~~(both in blue),~~ while the curve in dark blue color indicate ~~and~~ daily average temperatures ~~(dark blue) from the DTS data~~. ~~are plotted with.~~ The curves in orange and red color refer to ~~data for~~ air temperatures acquired at JICS tower (1.5 m high) ~~(orange and red, respectively)~~. The daily climatology?? is overlaid in black. The blank periods (e.g., days 10-146, 165-191, and 261-295) ~~denote values~~ refer to intervals for which ~~missing from~~ either DTS or tower datasets are missing. At the beginning of the 2012-2013 winter, the cable was ~~unexpectedly~~ accidentally severed at a point close to the DTS equipment. This event interrupted data collection along most of the cable section until ~~the cable~~ it could be spliced back together, after the snow melt. ~~Section 4 discusses difficulties of using DTS equipment in taiga environments~~.

For the winter period (days 400-550), open moss (Fig. 5b; canopy rate=0.29, NDVI=0.592), shrub (Fig. 5c; canopy rate=0.34, NDVI=0.515), and both conifer forest~~s~~ types (sparse conifer in Fig. 5e; canopy rate=0.35, NDVI=0.531, and dense conifer (Fig. 5f; canopy rate=0.43, NDVI=0.495) show relatively minor variations in diurnal and daily temperatures. By contrast, thermokarst lake (Fig. 5a; canopy rate=0.46, NDVI=0.404) and deciduous forest (Fig. 5d; canopy rate=0.43, NDVI=0.239) land cover types show greater variability in daily temperatures and resume pronounced diurnal cycles relatively early on, after day 480. The ground cover for the latter two cases includes grass or limited floor vegetation, both of which are of lesser surface roughness (Figs. 2d and 2g). Differences between the two groups stem primarily from differences in snow pack characteristics. Snow pack tends to be thinner and effectively redistributed or blown by wind for the latter land cover types. Grasses are also prone to form void space between snow pack and the ground surface. Snow pack variation is further described in section 3.2 below.

In summer time (days 220 to 350, and 570 to 700), dense conifer forest exhibited daily surface temperature ranges (DTS data) less than those observed for the air column (tower observations). By contrast, open moss, shrub, and sparse forest types showed daily surface temperature ranges that were greater than those of the overlying air column. The grassy relict lake and deciduous forest land cover types showed an intermediate response. These tendencies likely reflect the openness of the canopy (or vegetation) cover above ~~at~~ the land surface (i.e., how much solar and longwave radiation reach the sensor cable), as well as local albedo of different surfaces (i.e., how much the ground surface of different land cover types reflects back). Figures 6a- 6c show daily values (i.e., maximum, minimum, and average) for the DTS ~~temperature~~ anomaly relative to the corresponding tower values for days without snow cover ~~or missing values~~. Results were aggregated into four groups based on daily cloudiness, as defined by the percentage of daily total downward solar radiation between the tower (at 16-m height) and the top of the atmosphere. A box-and-whisker plot shows maximum values (100%-ile) as the top of the upper error bar, 75%-ile as the upper edge of the box, 50%-ile as the colour-coded bar, 25%-ile as the lower edge of the box, and the minimum (0%- ile) as the bottom of the lower error bar. The plot shows uniform, gradual changes in anomaly distributions from sunny days to cloudy days (Figs. 6a-6c). The size of anomaly dispersions for each land cover type (represented by the total span of the whiskers) decreases with increasing cloud cover, due to clouds' diffusing effects. Daily average temperatures at the surface generally exceed those observed by the JICS tower (at 1.5 m height). Daily maximum values appear to contribute to this effect more than do daily minimum values. The latter (daily minimum) values are closer to the tower-observed values. Among different land cover types, open moss and deciduous forest tend to give higher daily maximum and lower daily minimum anomalies.

Figures 6d and 6e show phases of diurnal extremes (i.e., exact time of either the original daily maximum or daily minimum temperature) for the DTS (colour-coded bars) and JICS tower (black line) observations, respectively. The daily maximum for surface temperatures (Fig. 6d) ~~obtains~~ are reached two hours before that of the air temperature. Relict thermokarst lake areas (grassy or bare grounds) tend to reach ~~to~~ the daily maximum temperature earlier and deciduous forest areas later than other land cover types. For the daily minimum temperature (Fig. 6e), surface and air temperatures are more in-phase with each other. This temperature ~~obtains~~ is reached in the 3rd to 4th hour (3-4 am) slot for a normal daily cycle, or at the 23rd to 24th hour (11-12 pm).

3.2 Spatial snow cover characteristics

As shown in Figure 5, snow pack greatly affects winter-time thermal conditions at the interface between the ground and snow pack. Snow cover on the ground surface strongly influences the radiative and energy budget, the water cycle, and phenology (Sturm et al., 2005; Liston, 1999; Tan et al., 2011; Immerzeel et al., 2010; Jönsson et al., 2010). Seasonal snow pack data (e.g., timing of when / how snow pack accumulates and disappears) is important for interpreting observed temperature values and for constraining energy budgets within numerical models. Snow pack is affected by the land cover types, which can amplify contrasting conditions (Liston, 1999, 2004; Sturm et al., 2005). Here, we describe how DTS data indicate different trajectories of snow pack evolution (namely, appearance and disappearance) and produce apparent insulation effects for different land cover types.

Figure 7a shows dates of initial snow accumulation (the middle panel) and final disappearance (left and rightmost panels) for each land cover type, as counted from the date shown at the bottom of the respective panel. The presence of a continuous snow cover was defined ~~by whether~~ considering the periods during which the daily amplitude in DTS temperatures fell short of 40% of that of JICS tower (1.5 m high) observations. As shown in Figure 7b, this 40% threshold effectively differentiates between snow-free and snow-covered conditions. The overall contrast between accumulation and disappearance dates (Fig. 7a) indicates that accumulation of snow cover tends to begin as spatially coherent and widespread, whereas disappearance of snow pack varies according to local conditions (Liston, 2004; Nitta et al., 2014). Among different land cover types, the majority (denoted by the margin between the 25%-ile and 75%-ile) of grassy (relict thermokarst lakes; blue) and shrubby (shrub; orange) areas vary more widely than do the forest land cover types (greens). Open moss (red) of relatively flat areas shows equal or greater variation than forest land cover types.

Another important geophysical effect of snow cover is the insulation it provides between the atmosphere and land surface. Figure 7b demonstrates this effect by showing the reduction in daily temperature range for the ground surface relative to the air. Open moss land cover shows the most spatially coherent and pronounced reduction. This implies spatial homogeneity in snow pack depth and physical properties (e.g., density, shape and size of snow grain, snow class), which could contribute to similar timing of snow disappearance (Fig. 7a). The strong insulation effect likely results from development of the depth hoar layer by radiative cooling. Relict thermokarst lake areas show high spatial variability in temperature range reduction. Forested land cover showed small reductions regardless of the ~~forest~~ vegetation types, possibly due to cooler ambient conditions beneath canopy.

3.3 Vertical temperature profiles

The fibre-optic cable wrapped around a 120 cm long, PVC tube provided high-resolution vertical temperature profiles for air and snow columns (Fig. 8a-b) at five locations each situated within different land cover types (Fig. 2a).

Items *a* and *b* in figure 8 indicate photos of PVC tubes and not temperature profiles.

~~Location~~ Site #1 is located in dense forest, #2 in sparse forest, #3 in open moss, #4 in shrub, and #5 in a relict thermokarst lake area. Figures 8c-d show seasonal changes in daily mean temperature and temperature range respectively, for station #1. White areas represent missing values due to either cable disruption or other technical issues. Blue areas in Figure 8d show daily temperature values whose ranges are curtailed either by snowpack (above-ground for the part above the black line) or ground (below the black line). Together with Figure 8c, Figure 8d shows the structure and variation in temperature regimes? for the air and/or snow column above-ground and during frozen or thawed subsurface conditions. The original 30-minute data reveals? thermal properties of the soil or snow media (i.e., thermal conductivity or diffusivity?).

Not indicated in Figure 8

4 Technical challenges

As described above, DTS provides continuous ~~datasets~~ records suitable for analysis of spatial variability in temperature. Data ~~continuity~~ acquisition however depends on uninterrupted functioning fibre-optic cables, power and communication capabilities, which in turn depend on robust equipment performance under harsh and highly variable local climate conditions. This section describes specific technical and environmental challenges identified during our study.

A continuous electrical power supply is critical for remote DTS field data collection. This requirement limits locations where DTS apparatus can be deployed. Even when available, the power system used here was subject to harsh temperature and precipitation conditions. A durable, uninterrupted power supply (UPS) is recommended for future experiments. Fibre-optic cables also pose significant logistical challenges when deployed in remote taiga forest environments. Irregular surface areas with variable moisture and numerous obstacles (such as trees) prevent construction of a simple, protected route for the cable. Deploying a ~3 km long cable from a large wooden spool, which together with the cable weighed more than 50 kg, around barriers and across soggy ground posed significant challenges. We chose a cable with a stainless-steel shielding tube, to optimize sensing capabilities but also protect from disruption by animals. The shielding turned out to have suboptimal flexibility (compared to that of woven stainless mesh shielding), which led to kinking and even breaking during installation. The tube-shielded cable was also too inflexible for the irregular ground surface.

A better future approach ~~to~~ for cable routing would be to use a smaller, lighter spool and shorter cable, installing the sensor as a series of shorter cable segments. A fusion splicer, already necessary for cable repair, could be used to splice shorter segments of cable in the field instead of installation of a single, long cable. Cable splicing and repair requires some training and experience, especially for performing correct core alignment under field conditions. Splicing is also not possible under harsh winter conditions (e.g., -20º C or below), even though the cable and DTS still function at these temperatures.

The DTS system is also vulnerable to cable breaks. Once the cable breaks, it cannot measure temperature beyond that point. For example, if the cable breaks at 1 m of a 1 km cable system, ~~in other words,~~ the remaining 999 m will produce no data. Dual-mode measurement (a cable loop connected to two channels at both ends) can prevent total loss of measurements beyond the break, although the resulting single-mode measurements need additional calibration.

5 Summary

We deployed a fibre-optic DTS (distributed temperature sensing) system, which uses ~~Raman-scattering,~~ techniques of optical time domain reflectometry to measure spatial and temporal variations in surface temperatures of a northern forest (taiga) site situated in Interior Alaska. The DTS system consist~~ed~~ of a 2.7 km fibre-optic cable, sections of which are installed on, above ~~or~~ and below surface areas ~~represented by~~ with a range of different land cover types. The system provided continuous temperature ~~measurements~~ data at half-meter ~~resolution~~ distance intervals and 30-minute ~~intervals~~ time periods. The site, the Poker Flat Research Range (managed by the University of Alaska Fairbanks), is underlain by permafrost and primarily covered by black spruce. Land cover types of the ~~actual~~ study area ~~were classified into six categories:~~ include relict thermokarst lake, open moss, shrub, deciduous forest, sparse conifer forest, and dense conifer forest. The DTS system collected data over a two-year period, from October, 2012 to October, 2014.

Data from horizontal sections of the DTS system (about 2.0 km of the cable) recorded diurnal and seasonal temperature ~~patterns~~ variations occurring in ~~that varied according to~~ different land cover types and surface conditions. Snow and canopy effects for example were evident in spatio-temporal temperature patterns. Data from vertical sections (cable wrapped around PVC tubes embedded in the ground) recorded air, snow, and ground temperatures at high resolution (~5 mm).

The DTS system proved operable and useful for geophysical investigations in the harsh taiga environment, which experiences annual temperature ranges of -40º C to 30º C. However, the system also ~~demonstrated~~ faced technical challenges ~~of~~ in attempting continuous temperature measurements ~~in this~~ of the local environment. Future ~~research~~ activities will continue to optimize DTS systems for geoscientific research in taiga areas and other ~~harsh~~ similar environments.

Data accessibility

The DTS measurement data analyzed in this paper along with ~~attributional~~ supplementary information are archived and accessible at the International Arctic Research Center (IARC) Data

Archive of the University of Alaska Fairbanks (http://climate.iarc.uaf.edu/geonetwork/srv/en/main.home?uuid=60804e98-a0d5-4bcc-ab70-5d47af2b50ca).

Author contributions

KS designed and prepared the experiment. All authors took part in the tasks of deployment of the equipment and maintenance of the measurement system. KS prepared the manuscript with contributions from all co-authors.

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Figure 1: Location of the DTS system installed at the Poker Flat Research Range (PFRR; University of Alaska Fairbanks).

Figure 2: (a) Layout of the fibre-optic cable sensor (black line) installed at the PFRR with stations numbered from 1 to 5 (in white), together with the land cover types designated from satellite images (dark blue: relict thermokarst lake, red: open moss, orange: shrubs, light green: deciduous forest, green: sparse conifer forest, blue: dense conifer forest). (b) Frequency of land cover types along the cable. (c) Scatter plot of surface-measured canopy rate and satellite-derived normalized difference vegetation index (NDVI; GeoEye1 image taken on Sept. 25, 2010). Images show examples of (d) relict thermokarst lake, (e) open moss, (f) shrub, (g) deciduous forest, (h) sparse conifer forest, and (i) dense conifer forest.

Figure 3: Schematics of Raman scattering.

Figure 4: Examples of temperature distribution measured by a horizontal section of the DTS system (daily mean for December 1, 2013).

Figure 5: Typical seasonal variations in daily temperatures for the six land cover types: (a) relict thermokarst lake, (b) open moss, (c) shrub, (d) deciduous forest, (e) sparse conifer forest, and (f) dense conifer forest. Plot shows daily maximum and minimum temperatures from the DTS system (blue lines) and the JICS tower (air column at 1.5 m height; orange lines) along with daily mean values (dark blue for DTS and red for the JICS tower). The black line shows daily climatology. Data span time period after October 13, 2012.

Figure 6: Distributional differences between (a) daily maximum temperatures, (b) daily minimum temperatures, and (c) daily average temperature under different degrees of cloudiness (32 observations for 0-25%, 69 observations for 25-50%, 80 observations for 50-75%, and 5 observations for 75-100%). Lower plots show median maximum (d) and minimum (e) temperature values and frequency (total hours) as measured by DTS for land cover types (colour-coded) compared to corresponding values from the JICS tower (1.5 m height; black-line histogram).

Figure 7: (a) Differences in snow melt (or accumulation) dates for different land cover types for the spring of 2013 (after April 21, 2013), autumn of 2013 (after October 19, 2013), and spring of 2014 (after April 1, 2014). (b) Damping rate for daily temperature range averaged over snow-covered days having continuous measurements (i.e., without missing or interrupted cable data) for the 50-day period following the respective start date of the season.

Figure 8: Subsurface and above-surface temperatures measured by vertical sections. (a) Photo of PVC tube with sensor cable wrapping prior to installation. (b) Photo of PVC tube with sensor (vertical section) installed within a dense conifer forest. Depth-time ~~cross-section~~ profiles for (c) daily mean temperatures and (d) daily temperature range during 2013 snow melt period.

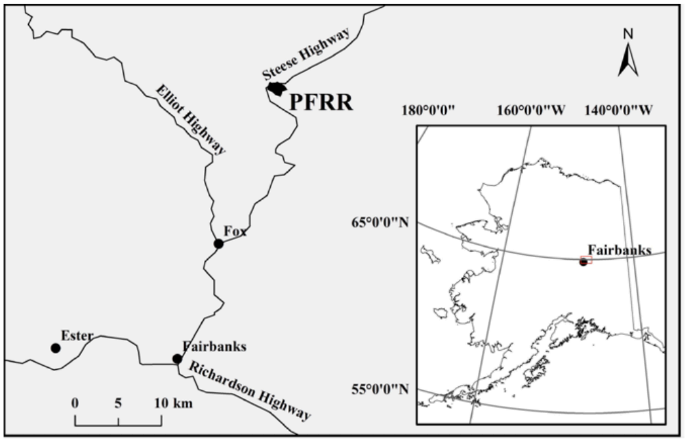


Figure 1

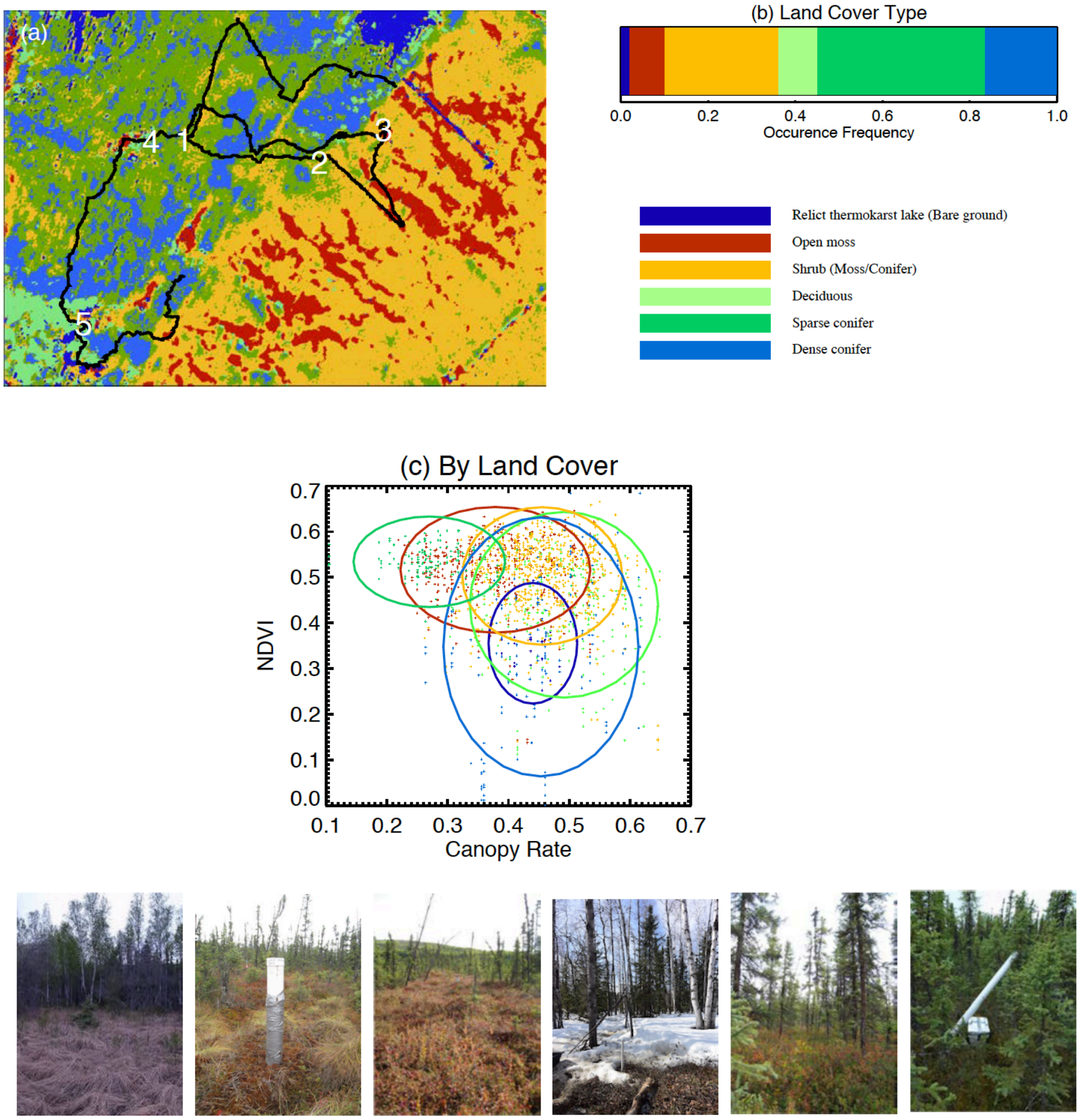


Figure 2

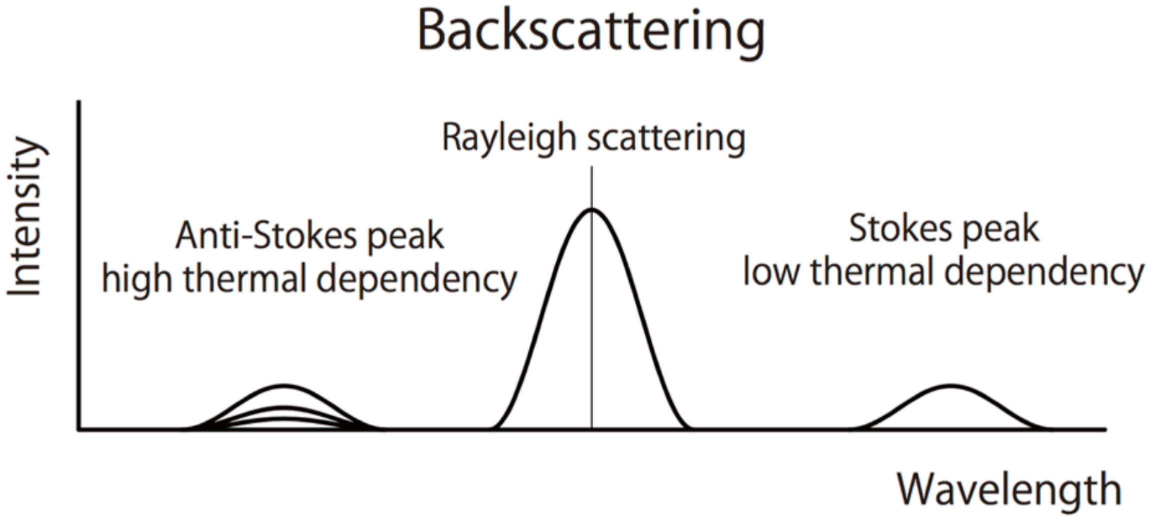


Figure 3

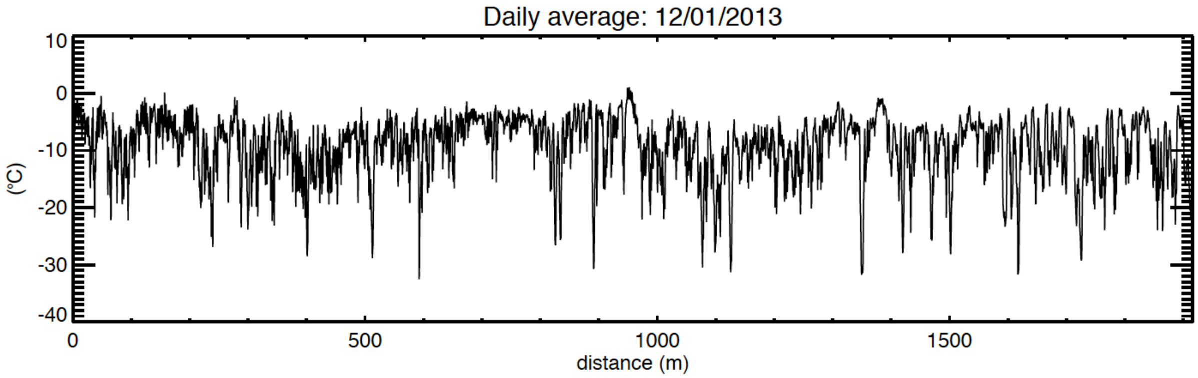
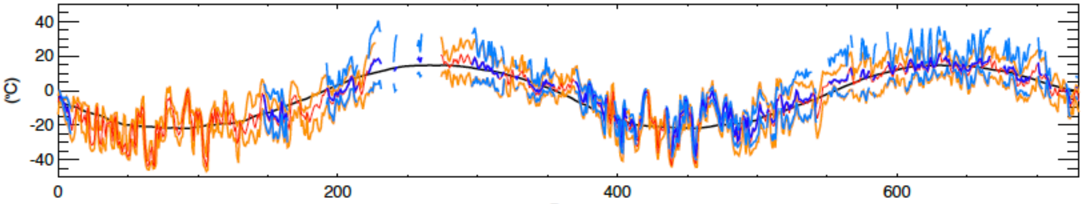
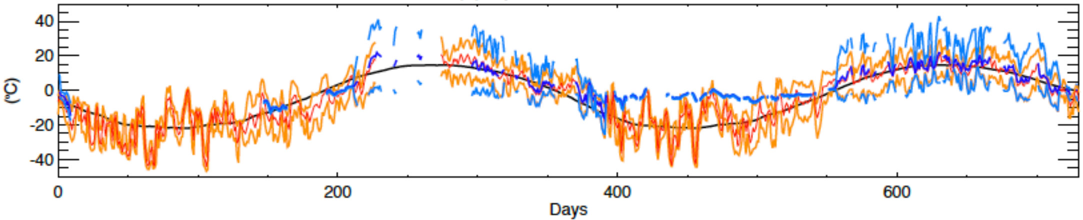


Figure 4

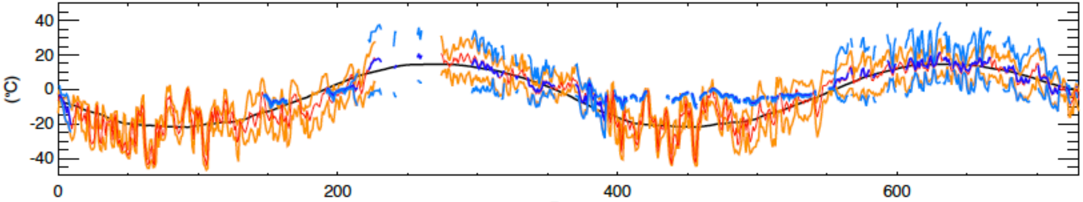
(a) Relict thermokarst lake



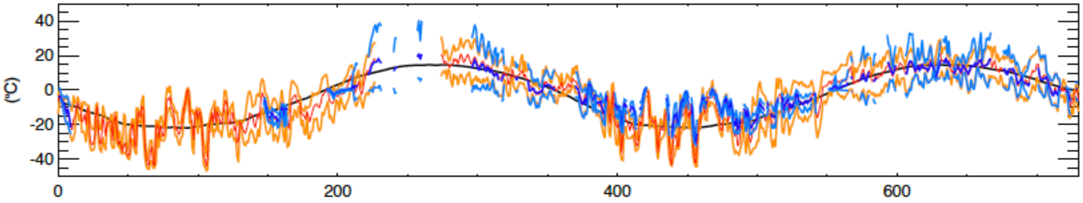
(b) Open moss



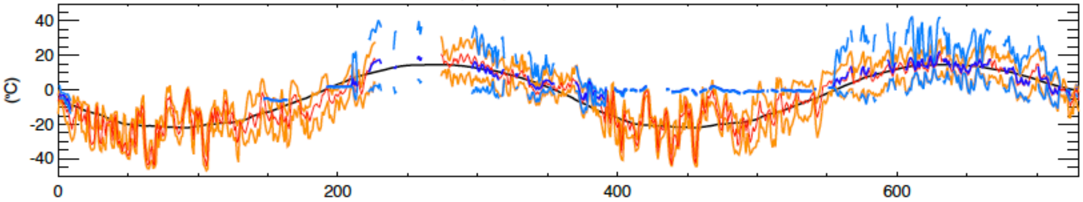
(c) Shrub



(d) Deciduous



(e) Sparse conifer



(f) Dense conifer

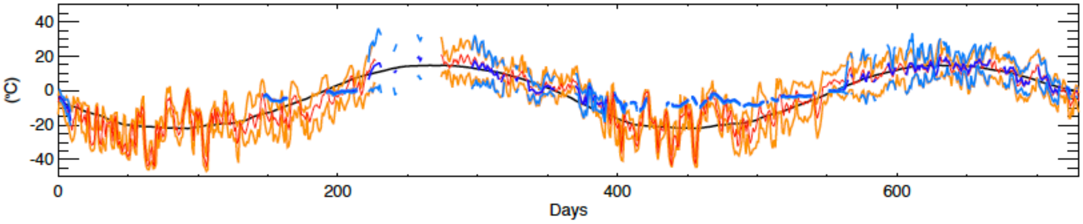


Figure 5

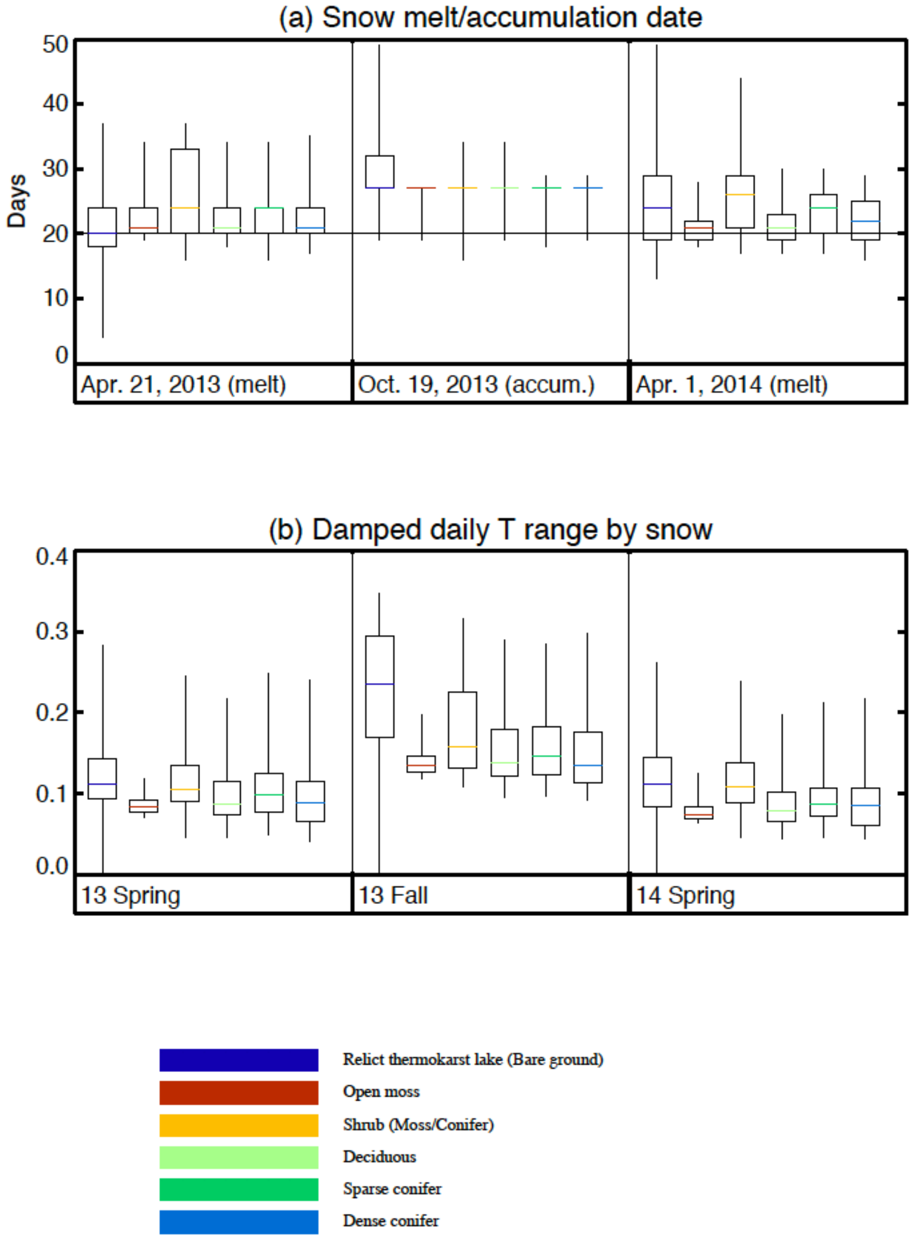
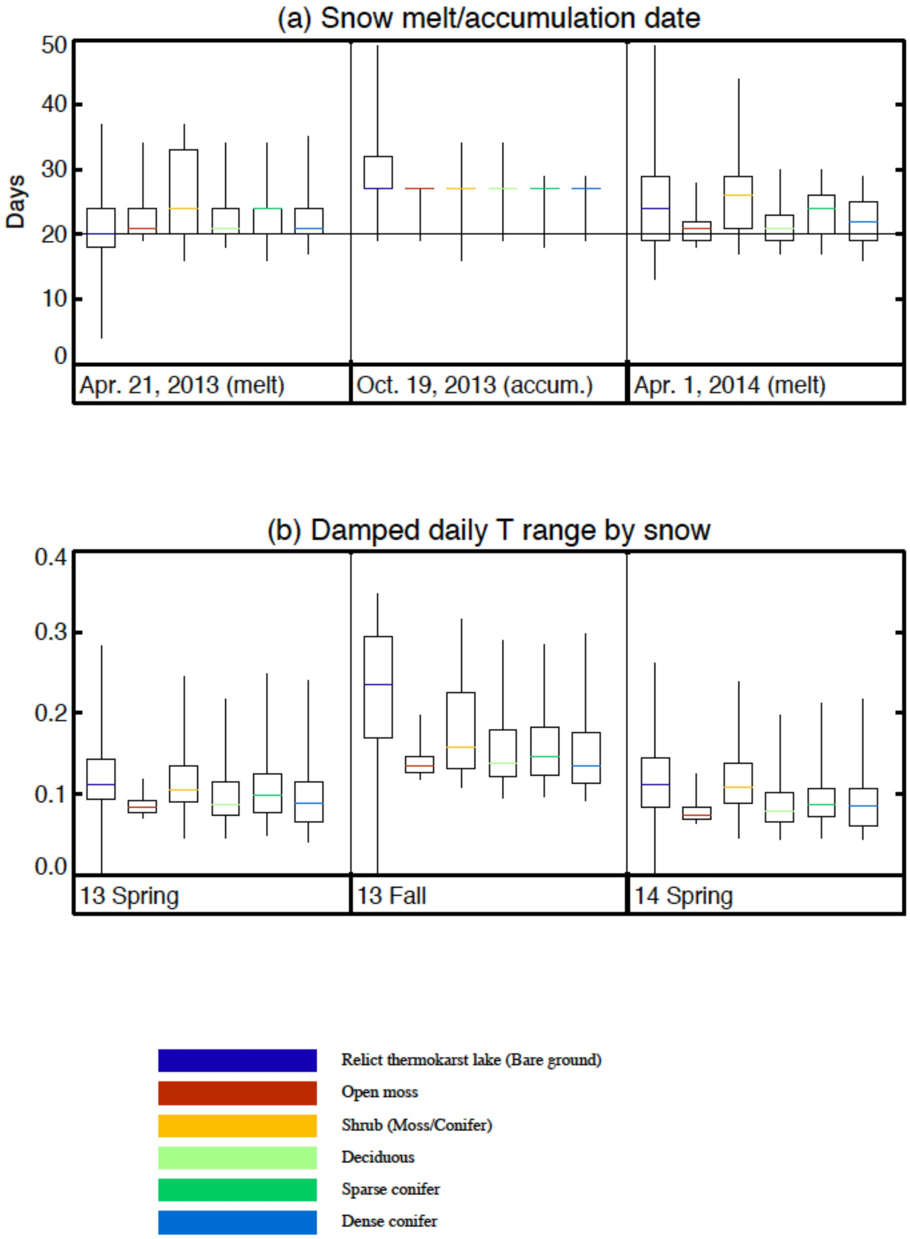

(a) Snow melt/accumulation date
Days
50
40
30
20
10
0
Apr. 21, 2013 (melt)
Oct. 19, 2013 (accum.)
Apr. 1, 2014 (melt)
(b) Damped daily T range by snow
0.4
0.3
0.2
0.1
0.0
13 Spring
13 Fall
14 Spring
Relict thermokarst lake (Bare ground)
Open moss
Shrub (Moss/Conifer)
Deciduous
Sparse conifer
Dense conifer

Figure 6


(a) Snow melt/accumulation date
Days
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40
30
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10
0
Apr. 21, 2013 (melt)
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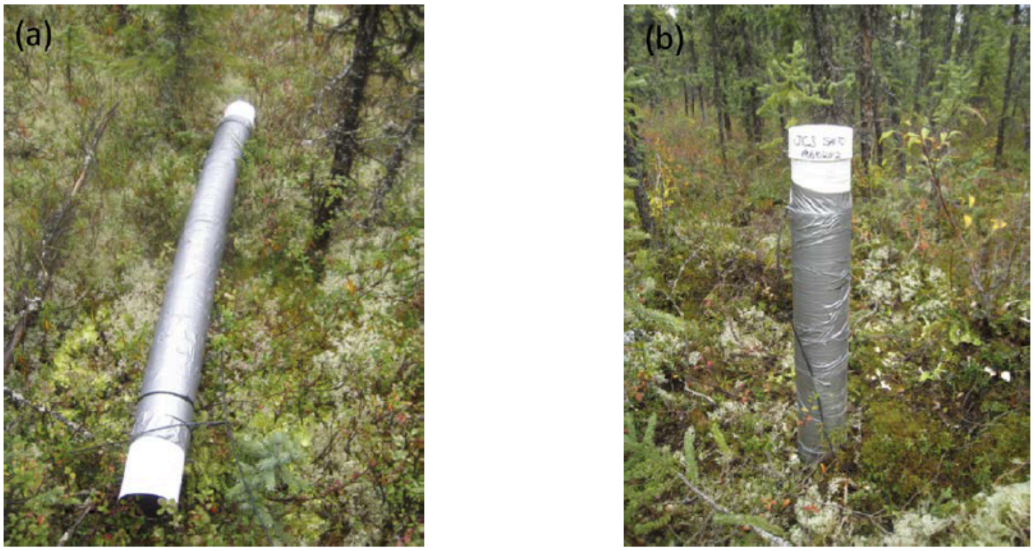
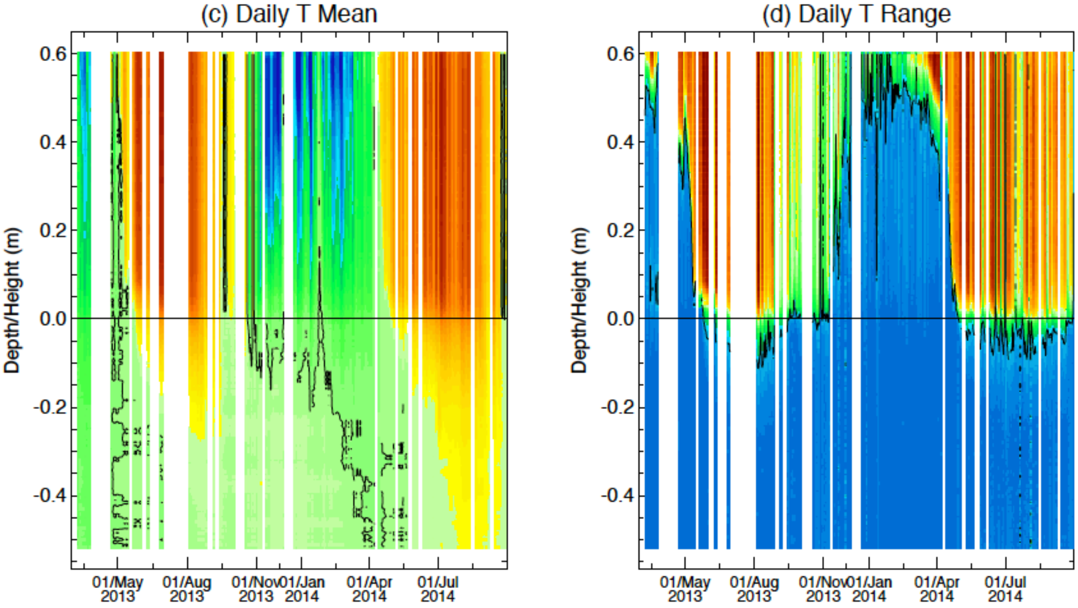
Relict thermokarst lake (Bare ground)
Open moss
Shrub (Moss/Conifer)
Deciduous
Sparse conifer
Dense conifer

Figure 7




(c) Daily T Mean

(d) Daily T Range

Figure 8