Establishing a Distributed Permafrost Observation Network in Western Alaska.

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Report submitted: Monday, November 03, 2014

Western Alaska Landscape Conservation Cooperative Project WA2011-01

Agreement number: *Cooperative Ecosystem Studies Unit (CESU) Agreement* F11AC00613

With support from: U.S. Fish and Wildlife Service, Selawik National Wildlife Refuge

Key words: permafrost temperature, active layer thickness and temperature, ecotype, Selawik National Wildlife Refuge

Citation:

Romanovsky, V. and Cable, W. 2014. Establishing a Distributed Permafrost Observation Network in Western Alaska. Western Alaska Landscape Conservation Cooperative Project 2014 Final Performance Report, 34pp

ABSTRACT

The area of Western Alaska including the Selawik National Wildlife Refuge (SNWR) is generally underrepresented in terms of permafrost thermal monitoring. Thus, the main objective of this study was to establish a permafrost monitoring network in Western Alaska in order to understand the variability in permafrost thermal regime in the area and to have a baseline in order to detect future change. Over the summers of 2011 and 2012 a total of 26 automated monitoring stations were established to collect temperature data from the active layer and permafrost. While most of these stations were basic and only measured the temperature down to 150 cm at 4 depths, three of the stations had higher vertical temperature resolution down to 3 m. The sites were selected based upon an ecotype map that had been created for the area in 2009 with the idea that ecotypes (basic vegetation groups) might be good indicators of the permafrost thermal state within an area experiencing similar climatic drivers. We found the Upland Dwarf Birch-Tussock Shrub ecotype to be the coldest with an average mean annual ground temperature at 1 meter (MAGT1.0) of -3.9 °C during the August 1st, 2012 to July 31st, 2013 measurement period. This ecotype is also the most abundant in the SNWR, covering approximately 28.4% by area. The next most abundant ecotype in the SNWR is the Lowland and Upland Birch-Ericaceous Low Shrub with an area coverage of approximately 10.5%. This ecotype had warmer permafrost than the Upland Dwarf Birch-Tussock Shrub ecotype with an average MAGT1.0 of -2.4 °C during the same measurement period. We also found that within some ecotypes (White Spruce and Alder-Willow Shrub) the presence or absence of moss on the surface had a strong association with the permafrost thermal regime. In fact the absence of moss in both these ecotypes seems to indicate the absence of near surface permafrost. In general, we found good agreement between ecotype classes and permafrost characteristics such as mean annual temperature, active layer thickness, and freeze back duration. Thus, we believe it might be possible to translate the ecotype map into a permafrost map using our measurements. Such a map would be useful in decision making with respect to land use and understanding how the landscape might change under future climate scenarios.

INTRODUCTION

Western Alaska in general, and the broad area centered on the Selawik National Wildlife Refuge (SNWR) and adjacent BLM and NPS lands in particular, are poorly represented in the network of permafrost temperature measurements developed in Alaska during the last 30 to 40 years by several scientific organizations (see http://permafrost.gi.alaska.edu/sites_map for UAF maintained sites). The permafrost temperature in this region has only been monitored in two relatively deep boreholes located near Nome and Kotzebue (60 and 29 m deep respectively). During the last several years, a network of shallow (2 to 6 m) boreholes has been established in the villages in this region as a part of the University of Alaska Fairbanks K-12 outreach program (PI Dr. Kenji Yoshikawa). However, this network is very limited and does not represent the wide local variation in permafrost conditions in the region. Based on existing data, permafrost mean annual temperatures in Western Alaska vary generally between 0 and -4°C (most of existing data

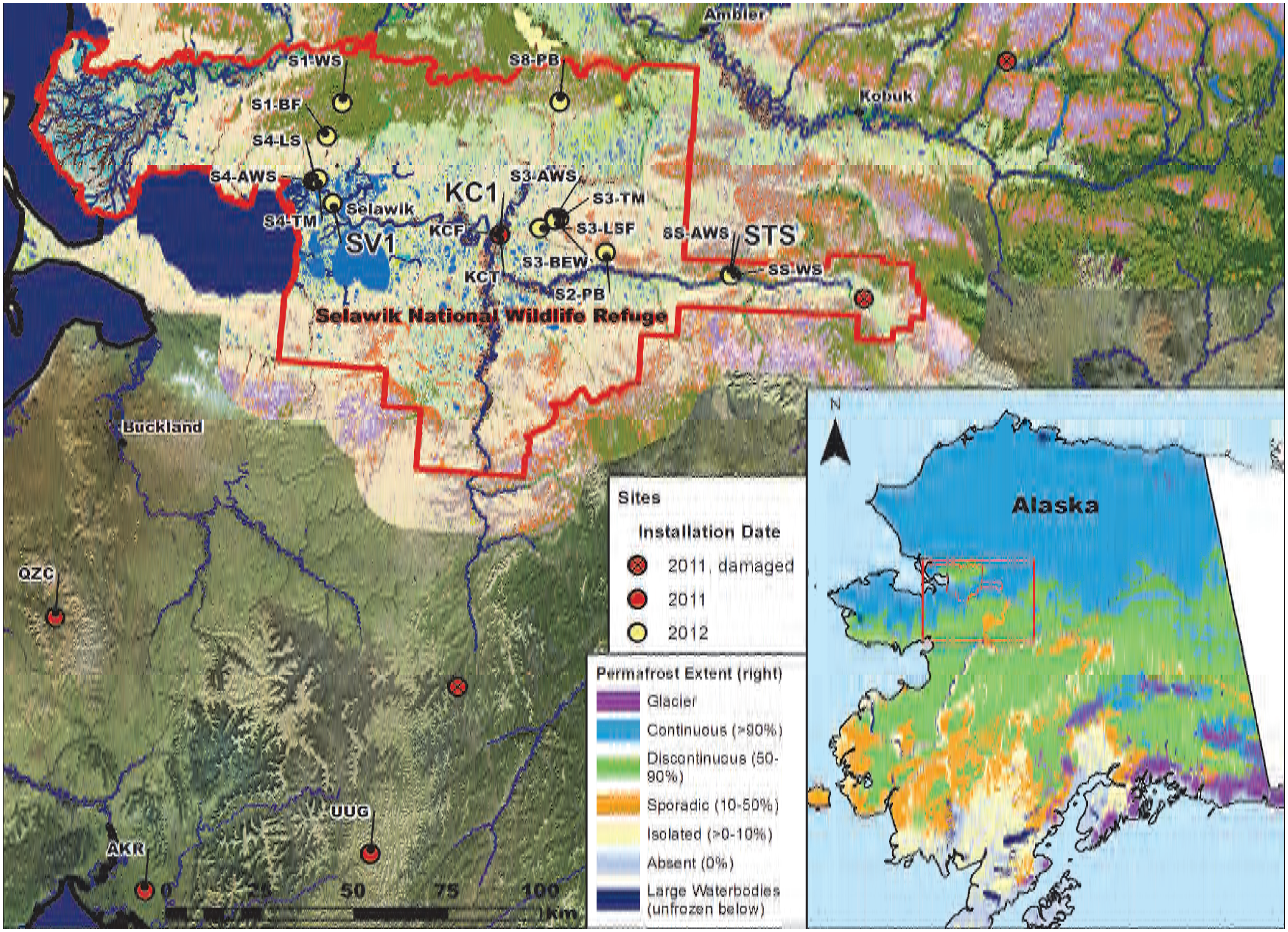

Figure 1. This figure shows the locations of the sites installed in 2011 and 2012. The ecotype class map (Jorgenson et al, 2009) is also shown, where available. The reference map of Alaska shows the permafrost distribution (Jorgenson et al, 2008).

fall in the range between 0 and -2°C) and the permafrost spatial distribution changes from continuous in the north to no permafrost in the south (Figure 1). In 2011, we proposed to start building a permafrost observation network in Western Alaska LCC region from the region located on the boundary between continuous and discontinuous permafrost, within and near the SNWR. Existing observations show that as a result of recent warming local permafrost degradation has already started near this boundary, not only in Alaska but also in Siberia (Romanovsky et al, 2010). Present and future thawing of permafrost in these regions will have a dramatic effect on these ecosystems because the permafrost generally has a high ice content, as a result of preservation of old ground ice in these relatively cold regions even during the warmer time intervals of the Holocene. The high vulnerability of the ecosystems to permafrost degradation in these transitional regions largely dictated our decision to begin establishment of a distributed permafrost observatory on the SNWR and adjacent BLM lands.

METHODS

Site Selection

The study area for this project is the Selawik NWR as depicted in the map in Figure 1. In the fall of 2011, in collaboration with Torre Jorgenson, sites for installation in summer, 2012 were selected based on integrative analysis of the existing data on generalized ecotype classes (Figure 1), soil landscapes, and vegetation type distribution as documented in Jorgenson et al. (2009). All maps from this publication are available in GIS format by contacting ABR, Environmental Research and Services (Fairbanks, AK; www.abrinc.com). This publication and an additional database compiled as a result of that project include a detailed description of many investigation sites visited during 2007-2008. A wealth of information about these sites is also available from the organizations that conducted this research. This information as well as the logistics approach used in that project guided us in determining locations for the distributed permafrost observation sites.

Measurement Design

Our measurement design consists of a two-tiered site layout. The first tier, core sites, (Figure 2) are collecting high temporal and vertical resolution temperature data. These sites consist of a CR1000 data logger (Campbell Scientific, Logan, UT) that collects and saves data from the attached logger sensors measuring air temperature, snow depth, a high vertical resolution thermistor probe with 16 thermistors spaced exponentially to 1.5 m depth[1], and three deeper soil temperature sensors (2.0, 2.5 and 3.0 m in most cases). The temperatures are measured every 5 minutes and hourly averages are stored on the data logger. The core sites are also equipped for remote communications using

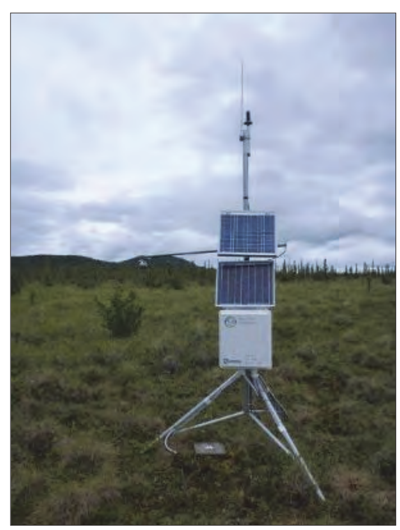

Figure 2. Typical Core Site.

[1] Thermistor probe spacing: 2, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 100, 125, and 150cm.

Iridium satellite transceivers or cellular modems (Selawik Village). We are currently collecting the data from the sites remotely on a weekly or daily basis.

Figure 3. Typical Distributed Site

The second tier of spatially distributed sites (Figure 3) are deployed to capture the spatial variability in active layer and permafrost temperatures in the region. These sites consist of a U-12 data logger (Onset, Cape Cod, Massachusetts) and four soil temperature sensors located within the active layer and upper permafrost (3, 50, 100, and 150 cm depth in most cases). These data loggers record an instantaneous temperature every 4 hours. Data from these sites has been collected manually once per year.

Fieldwork Activities & Data Management

At the end of July, 2011, 10 spatially distributed sites were installed in locations where Selawik NWR was installing snow depth sensors (Figure 1, red dots; Orlando 2013). These sites have a wider distribution and many are located outside of the Selawik NWR; however, they are still valuable for this study as the ecotypes are the same and the climate is similar.

At the end of July, 2012, an additional 13 spatially distributed sites and 3 core measurements sites with more intensive measurements were installed (Figure 1, yellow dots). Data from the core measurement sites is collected remotely with cellular modems or Iridium transceivers and can be accessed through each site's webpage[2]. In addition, during the summer of 2012 data was collected from some of the sites that were installed in 2011; however, many of these sites had been damaged by wildlife likely due to their proximity to aerial snow markers.

In early August, 2013, all established sites were visited and data were collected from the data loggers. Several of 2011 sites were decommissioned because of the damage to these sites by wildlife.

In late July, 2014 all sites were again visited for data collection. During these site visits a small soil pit was dug at each site in order to characterize the general soil layers and for comparison with the soil information collected by Jorgenson et al. (2009). Unfortunately a few sites were damaged by wildlife but all sites were repaired.

Data from these sites, the sites with near real-time data, and photos and information for all sites can be accessed from each site's webpage accessible via the interactive map on this project's webpage (permafrost.gi.alaska.edu/project/Selawik_NWR). Data from this project are also being archived at ACADIS (www.aoncadis.org).

[2] Selawik Village: http://permafrost.gi.alaska.edu/site/sv1, Kugurak Cabin: http://permafrost.gi.alaska.edu/site/kc1, Selawik Thaw Slump: http://permafrost.gi.alaska.edu/site/sts.

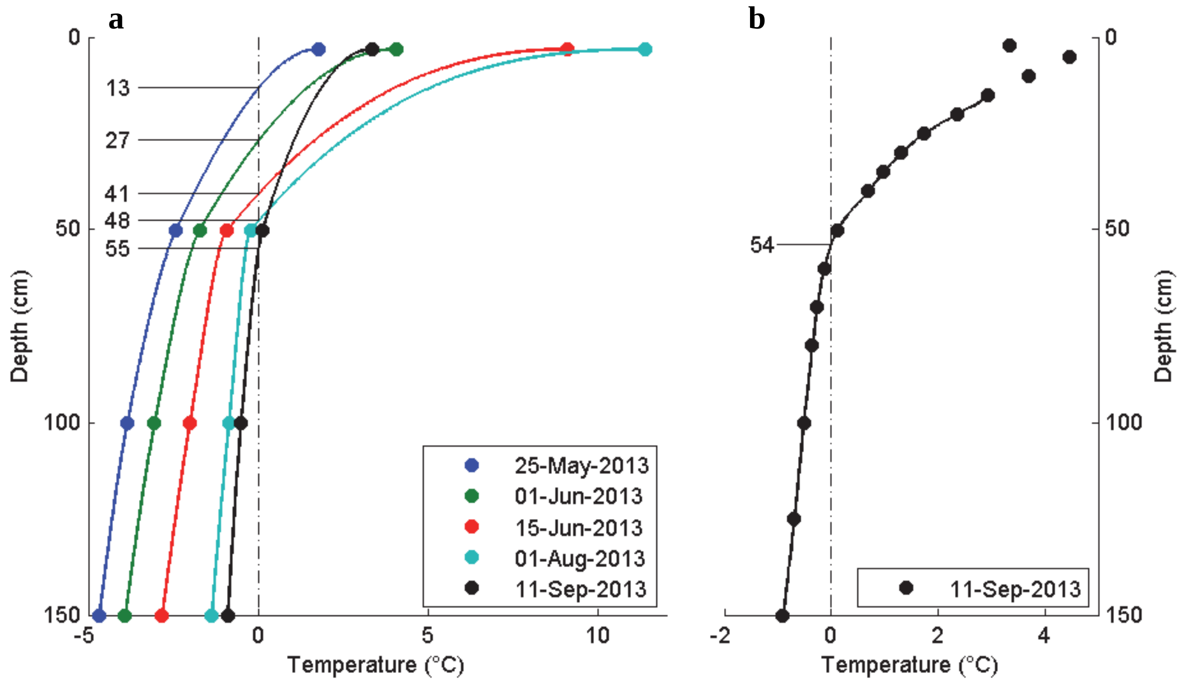

Figure 4. Temperature depth profiles from site KC1. (a) Shows temperature depth profiles using only 4 depths for selected days with the estimated thaw depth to the left. (b) Shows the temperature depth profile with all 16 temperature measurements for the date near maximum thaw depth.

Data Preparation & Analysis

All data analyses were conducted using custom scripts written in MATLAB (R2013a, MathWorks Inc.). All raw data were first adjusted using a zero-offset that had been determined for each temperature sensor using an ice bath calibration in the lab before sensor installation. Erroneous values in the raw (hourly and 4 hour) data, due to sensor malfunctions, were detected visually and removed. Gaps in the raw data of up to 4 hours were filled using an average of the point's preceding and following the gap. Daily averages, minimums, and maximums were calculated from the raw data for days with at least 75% data coverage; gaps of two days or less in the time series of daily averages were filled using linear interpolation of the previous and following points. Gap filling of both raw and daily data was performed in only a few cases as most data was continuous and without erroneous values. Yearly averages, minimums, and maximums were calculated from the daily data only when 99% of the data was available to insure the data weren't biased. A summary period from August 1st to July 31st of the following year was selected because this gave us a full year of data for analysis since the sites were installed in late July (summary periods 2011-2012 and 2012-2013). However, because the sites were visited in late July, 2014, July 10th, 2013 to July 9th, 2014 was used as the 2013-2014 summary period in order to have a full year of data for this year.

Thaw depth was calculated from the daily mean subsurface temperatures at each site by first applying a 29 day moving average to smooth the data. The moving average acted to stabilize the near surface temperature (3 cm) but had little effect on the deeper depths as they were already filtered due to the natural damping that occurs with depth in the soil. Then thaw depth was estimated for each day at each site by fitting a piecewise cubic hermite interpolating polynomial to that day's temperatures with depth and evaluated at 0°C. This approach forces the thermal profile interpolation to pass through each measurement point while preserving the shape of the profile (Figure 4a). It is important that the function fit to the data pass through each measurement point because at these points we know the temperature with certainty. The active layer thickness was then defined as the maximum thaw depth for the measurement period. As a way of testing the sensitivity of this technique, the active layer thickness was computed at the three core sites using only 4 of the 16 temperature measurement depths. The resulting active layer thickness corresponded very well to what can be estimated from the higher vertical resolution temperature measurements at these sites (Figure 4b). The difference between two estimates in 2013 was 1 cm at the Kugurak Cabin (KC1) site and 3 cm at the Selawik Village (SV1). In 2012 the difference between the estimates was 1 cm at all three core sites. Furthermore, this validation shows that our choice of measurement depths, particularly with a measurement at 50 cm, is optimal for this area because the active layer thickness is often near 50 cm.

The timing of the active layer freeze-up was also estimated, to within a few days. The initiation of the freeze-back period was defined as the date when the daily mean temperature at the near surface (3 cm) dropped and remained below a threshold of -0.3°C for the rest of the season. This threshold was chosen because it has been shown in our previous investigations the temperature interval between 0 and -0.3°C represents the temperatures of major changes in the physical state of water during the freezing process in silty soils (Romanovsky and Osterkamp, 2000). The end of the freeze-back period (time when the active layer was considered to be completely frozen) was defined as the date when all the temperature measurements had gone below this same threshold (e.g., 3 cm, 50 cm, 100 cm etc.). Combining the active layer thickness with the freeze-back duration tells us something about the relative active layer moisture content at each site. For example, a site with a deep active layer and a short freeze-back duration is likely dryer than a site with a shallow active layer and longer freeze-back duration.

MEASUREMENT RESULTS:

Air Temperature

The measurements of the air temperature at three core sites Selawik Village (SV1), Kugurak Cabin (KC1), and Selawik Thaw Slump (STS) allow for comparison of how this parameter changes from the west to the east within the research area. This comparison shows that the seasonal changes in the air temperature are very similar for the SV1 and KC1 sites. The difference in mean monthly temperatures between these two sites does not exceed 2°C and is

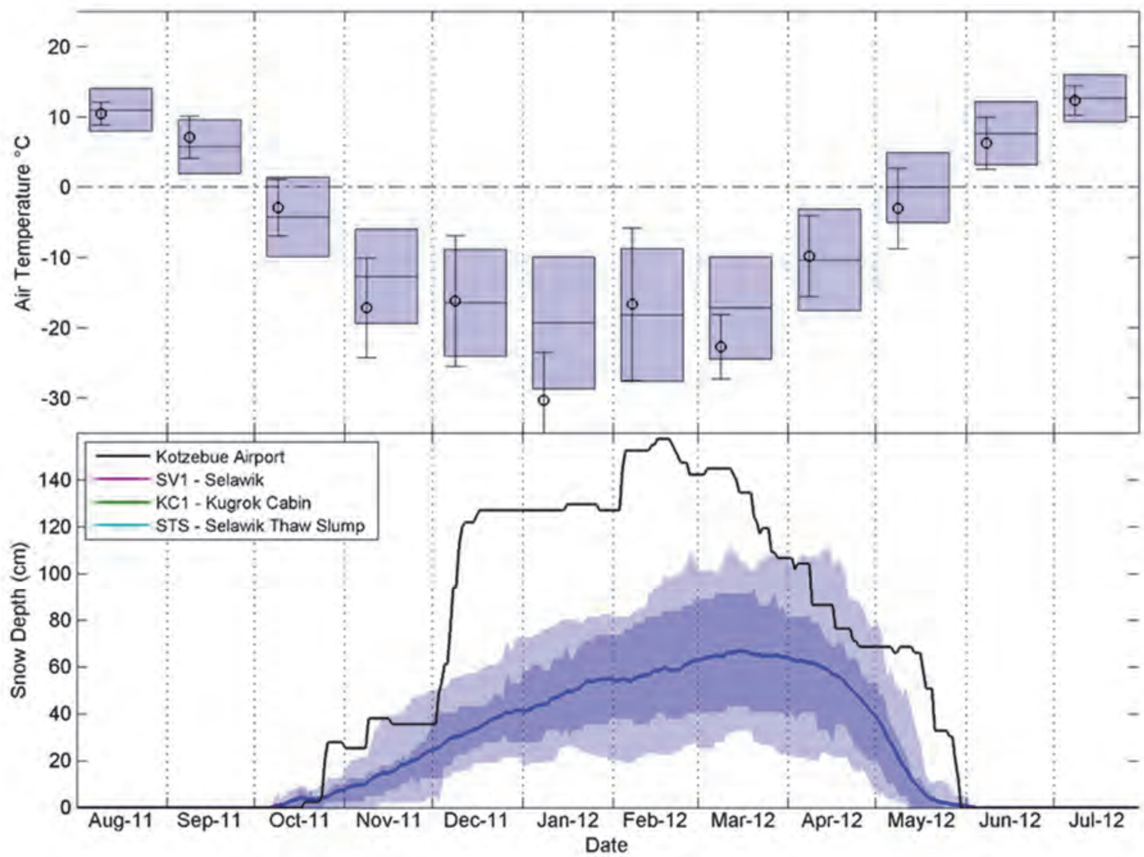

Figure 5. For the summary period August 2011 to July 2012. The top panel shows the mean monthly air temperature and standard deviation for our core sites and the Kotzebue airport overlain on top of the long-term (1981-2010) monthly mean and standard deviation (blue boxes) from the Kotzebue airport. The bottom panel shows the snow depth on the ground for our core sites and Kotzebue airport underlain by the long-term (1981-2010) average snow depth from the Kotzebue airport (dark blue line), 75^{th} to 25^{th} percentile (dark blue shading) and 90^{th} to 10^{th} percentile (light blue shading).

typically less than 1°C (Figures 5-7, top). Comparison of the monthly means for our three sites to the monthly means for the Kotzebue airport (OTZ) show mostly good agreement during this measurement period (August 1, 2012 to July 31, 2014). Unfortunately our STS site stopped functioning in August 2013 due to wildlife damage so we do not have data for the 2013-2014 summary period (this site was repaired in July of 2014). Mean annual air temperatures calculated from OTZ and our three core sites show that on an annual basis temperatures are similar between sites (Table 1). The temperature at STS however is a little warmer, which may be explained by slightly higher elevation of this site and presence

Year	OTZ	SV1	KC1	STS
2011 - 2012	-6.90			
2012 - 2013	-5.30	-5.74	-6.05	-4.69
2013 - 2014	-2.41	-3.14	-3.14	

Table 1. A summary of the mean annual air temperature for our three study years from the Kotzebue Airport (OTZ), our Selawik Village site (SV1), our Kugurak Cabin site (KC1), and our Selawik Thaw Slump site (STS).

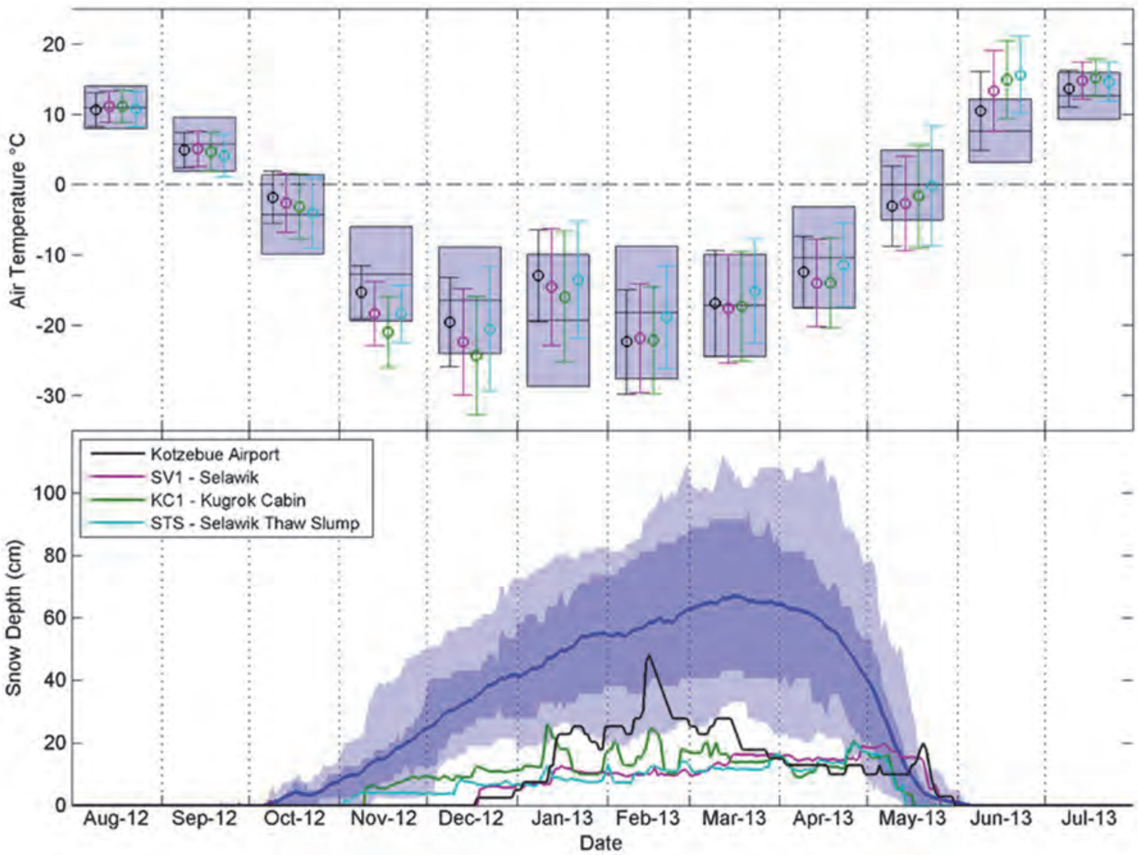

Figure 6. For the summary period August 2012 to July 2013. The top panel shows the mean monthly air temperature and standard deviation for our core sites and the Kotzebue airport overlain on top of the long-term (1981-2010) monthly mean and standard deviation (blue boxes) from the Kotzebue airport. The bottom panel shows the snow depth on the ground for our core sites and Kotzebue airport underlain by the long-term (1981-2010) average snow depth from the Kotzebue airport (dark blue line), 75th to 25th percentile (dark blue shading) and 90th to 10th percentile (light blue shading).

of temperature inversions compared to the other sites. The air temperature varies substantially from year to year however. The 2011-2012 measurement period was the coldest on average with temperatures close to the long-term (1981-2010) mean for OTZ with the exception of January 2012 that was considerably colder (Figure 5). Air temperature during the 2012-2013 summary period shows that most months could be considered normal with the exception of a slightly cooler December, 2012 and slightly warmer June, 2013 (Figure 6). During the 2013-2014 summary period the mean annual air temperature was the warmest (Table 1) with a considerably warmer October, 2013 and slightly warmer January, 2014 (Figure 7).

Snow Depth

In contrast to the air temperature, our snow depth records from all three core sites show that the snow depth was anomalously low during the winter seasons of 2012-2013 and 2013-2014 (Figures 6 and 7). These measurements agree well with the snow depth reported at the Kotzebue airport (OTZ) and are far below the long-term (1981-2010) average. In 2012 the first substantial

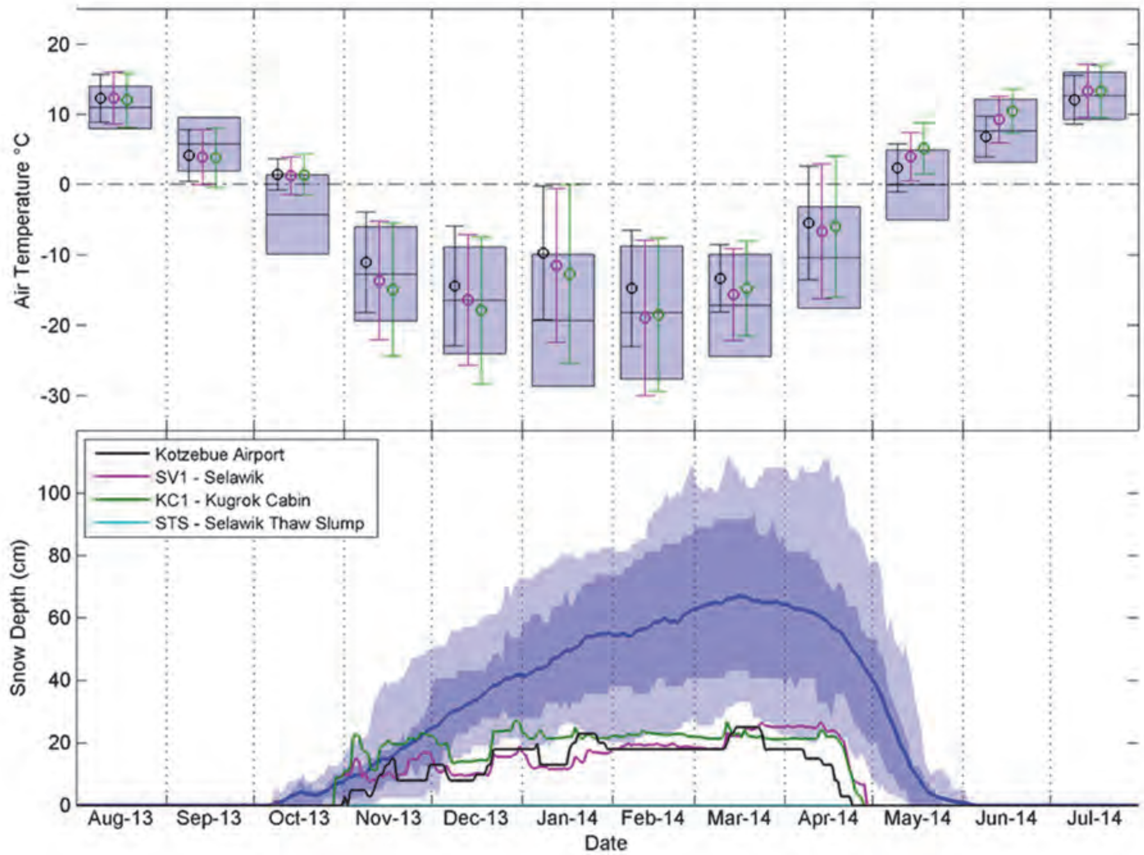

Figure 7. For the summary period August 2013 to July 2014. The top panel shows the mean monthly air temperature and standard deviation for our core sites and the Kotzebue airport overlain on top of the long-term (1981-2010) monthly mean and standard deviation (blue boxes) from the Kotzebue airport. The bottom panel shows the snow depth on the ground for our core sites and Kotzebue airport underlain by the long-term (1981-2010) average snow depth from the Kotzebue airport (dark blue line), 75th to 25th percentile (dark blue shading) and 90th to 10th percentile (light blue shading).

snowfall came very late in the season (mid-December) and by this time the active layer was already completely frozen at most sites. In 2013 the first substantial snowfall also came later (early-November) but due to the warmer than average October the active layer at most sites had just began to freeze. In contrast, during the 2011-1012 summary period the snow depth reported at OTZ was much higher than the long-term average (Figure 5).

Ground Temperatures

Based on our calculations freeze-back typically begins at approximately the same time across all sites, however, the duration is typically different between sites. During the 2012-2013 period the active layer began to freeze-back in early October, 2012 and was complete at most sites by the end of November, 2012 (Figure 8). The very late and

	MAGT1.0		
Site	**2011-2012**	**2012-2013**	**2013-2014**
QZC	-2.9	-3.6	-1.9
KCT	-2.0	-3.7	-1.4
KCF	-0.8	-2.6	-0.7

Table 2. The MAGT1.0 for the three sites from which we have three years of data.

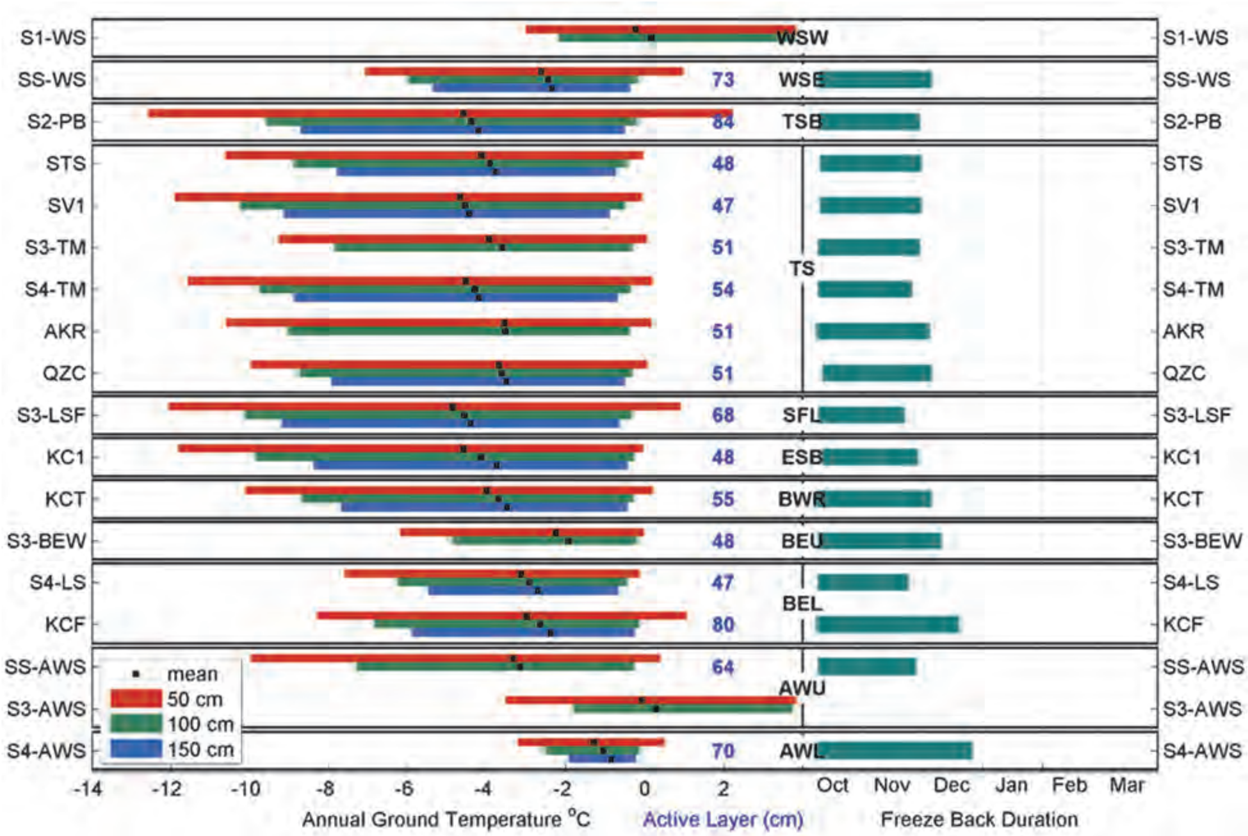

Figure 8. This figure displays annual summarized data for the August 1, 2012 to July 31, 2013 measurement period. Shown on the left is the annual mean and range from daily averages (colored bars) for 3 depths from each site; in the center is the calculated active layer depth; and on the right the duration of freeze back.

shallow snow-cover and related early freeze-up of the active layer resulted in unusually low winter, and thus annual, mean ground temperatures. During the 2013-2014 period freeze-back began much later (early-December, 2013) and at some sites lasted until late-February or early-March, 2014 (Figure 9). This late start to the freeze-back of the active layer is probably a result of the much warmer than average November, 2013. The analysis of the mean annual ground temperatures at 1 m depth obtained from the measurement sites that were established in 2011 shows that the mean annual temperatures at this depth were lower in the 2012-2013 measurement period than in 2011-2012 by 1.5 to 1.8°C (Table 2). During the 2013-2014 measurement period MAGT1.0 was the warmest of the three years (Table 2) which corresponds to the warmest mean annual air temperature. In general, the variation in MAGT1.0 seen between years is as large as the variation between ecotypes.

Occurrence of taliks

Mean annual ground temperatures at 3, 50, 100, and 150 cm depths calculated from data during the 2012-2013 period are shown in Figure 8 and Table 4 and a summary from the 2013-2014 period is shown in Figure 9 and Table 4. Out of 21 observational sites, two sites (S3-AWS and S1-WS) have mean annual temperatures at 1 m depth above 0°C, which may indicate the absence of permafrost in the upper 2 to 3 meters below the ground surface at these sites. Analysis of the

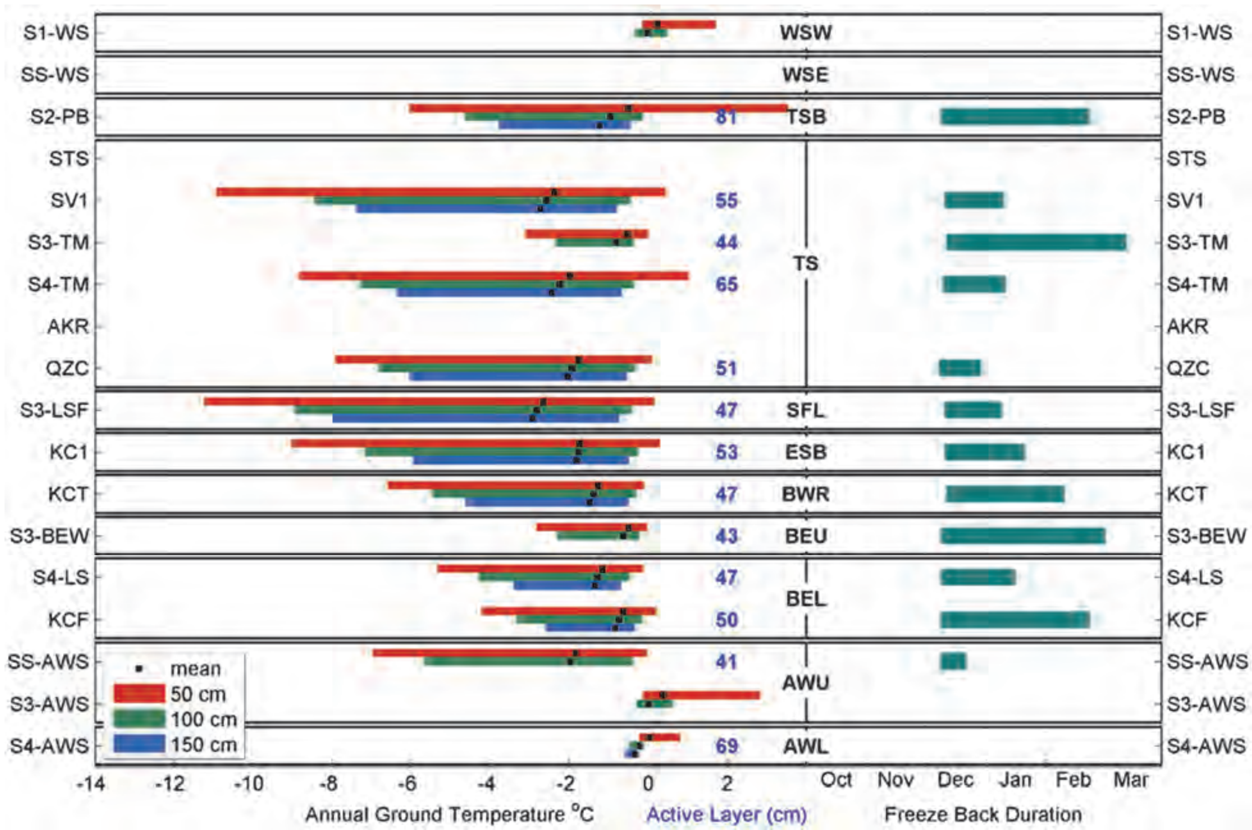

Figure 9. This figure displays annual summarized data for the August 1, 2013 to July 31, 2014 measurement period. Shown on the left is the annual mean and range from daily averages (colored bars) for 3 depths from each site; in the center is the calculated active layer depth; and on the right the duration of freeze back.

time series of the ground temperature dynamics (Figure 10 and 11) at these sites supports this conclusion. Thus, we suggest that a talik (perennially unfrozen layer) of unknown thickness exists at these locations. Additionally, one more site, a severely burned Upland White Spruce Forest (S8-BP), may also have a talik near the ground surface. Unfortunately this site had failures during both measurement periods and does not have a full year of ground temperature records because of equipment failures. Thus, in this case the mean annual temperature cannot be calculated with confidence. However, the ground temperature dynamics reflected in the available data for this site indicate that permafrost may be absent near the ground surface (Figure 12).

Permafrost Characteristics, by ecotype

In the following paragraphs we will present the permafrost results from each site (Table 3) by ecotype in order of decreasing areal coverage within the Selawik NWR (Table 5). When relevant, sites that deviate from the other sites within the same ecotype in terms of mean annual ground temperature, active layer thickness, and freeze-back characterizes will be highlighted.

The Upland Dwarf Birch-Tussock Shrub (TS) ecotype dominates over one-quarter of the area within the Selawik NWR (Table 5) and our measurements indicate it has the coldest soils. The MAGT1.0 was consistently low for this ecotype and varied between -3.5 and -4.6°C in 2012-

Site Code	Ecotype	Ecotype Code	Latitude	Longitude
S4-AWS	Lowland Alder-Willow Tall Shrub	AWL	66.653454	-160.148182
S3-AWS	Upland Alder-Willow Tall Shrub	AWU	66.611343	-158.683565
SS-AWS	Upland Alder-Willow Tall Shrub	AWU	66.501420	-157.609424
KCF	Lowland Birch-Ericaceous Low Shrub	BEL	66.561726	-159.000179
S4-LS	Lowland Birch-Ericaceous Low Shrub	BEL	66.655085	-160.136155
S3-BEW	Upland Birch-Ericaceous Low Shrub	BEU	66.607057	-158.679527
S1-BF	Upland Birch Forest	BFU	66.763641	-160.092071
KCT	Riverine Birch-Willow Low Shrub	BWR	66.562135	-159.003357
KC1	Lowland Ericaceous Shrub Bog	ESB	66.562380	-159.004640
S3-LSF	Lowland Sedge Fen	SFL	66.584576	-158.768248
QZC	Upland Dwarf Birch-Tussock Shrub	TS	65.547459	-161.403238
AKR	Upland Dwarf Birch-Tussock Shrub	TS	64.917500	-160.728144
UUG	Upland Dwarf Birch-Tussock Shrub	TS	65.055433	-159.473368
S4-TM	Upland Dwarf Birch-Tussock Shrub	TS	66.659274	-160.121866
S3-TM	Upland Dwarf Birch-Tussock Shrub	TS	66.612523	-158.655397
SV1	Upland Dwarf Birch-Tussock Shrub	TS	66.605569	-160.019213
STS	Upland Dwarf Birch-Tussock Shrub	TS	66.501157	-157.607440
S2-PB	Upland Burned Tussock Shrub	TSB	66.538220	-158.362833
S8-PB	Upland Burned White Spruce	WSB	66.891180	-158.700893
SS-WS	Upland White Spruce-Ericaceous Forest	WSE	66.499779	-157.604170
S1-WS	Upland White Spruce-Willow Forest	WSW	66.845685	-160.017046

Table 3. The location and ecotype of each site in this study is given here. Latitude and longitude were collected using a handheld GPS (WGS84).

2013 and between -2.6 and -0.8°C in 2013-2014 (Table 5). In general freeze back duration and timing at these sites is consistent, except for the AKR and QZC sites that are located further south and outside of Selawik NWR, and lasted on average 53 days in 2012-2013 and 44 days in 2013-2014. Active layer thickness is also very consistent at all these sites, approximately 50 cm. The TS sites also have consistent soil profiles consisting of a thick moss layer (3-6cm) underlain by fibric and humic organic layers often extending to the permafrost table (Figure 13).

It is interesting to compare the Tussock Post Burn site (S2-PB), a tussock shrub area where a tundra fire occurred in 2010, to the undisturbed TS sites. The MAGT1.0 at the S2-PB (Table 4) was as low as the other undisturbed sites of this ecotype; however, the active layer was significantly deeper and the freeze-back duration was longer, probably due to the deeper active layer. The explanation for the difference between the TS sites and the burned site can be seen in the soil profiles (Figure 13), while the TS sites have thick moss and organic layers, the moss and organic layers at the burned site are thin.

The Lowland Birch-Ericaceous Shrub ecotype (BEL) is the second most abundant ecotype within the Selawik NWR (Table 5). The BEL sites tend to be warmer than the TS sites (MAGT1.0 -2.9 to -0.7°C during our study, Table 5). While MAGT1.0 between the two sites measured within this ecotype are consistent, active layer thickness and freeze back duration vary. The S4-LS site had an active layer thickness and freeze back duration similar to that of the TS ecotype sites while the KCF site tended to have a deeper active layer and longer freeze back duration (Table 4) likely due to the lack of a moss layer and thinner organic layers at this site allowing deeper thawing during the summer (Figure 13).

The Upland White Spruce-Ericaceous Forest (WSE, 4.8% areal coverage) was sampled with one site (SS-WS). This site was found to have relatively cold permafrost (MAGT1.0 -2.4°C in 2012-2013) and a deeper active layer (73 cm in 2012-2013) but a freeze back duration not much longer than that of the TS ecotype sites (Table 4). An important factor distinguishing this from the other White Spruce sites is that is has a thick layer of moss on the ground surface which would impede warming of the ground during the summer (Figure 13). This site was disturbed by wildlife shortly after our visit in 2013 so we do not have data for the 2013-2014 period.

		2012-2013 Measurement Period				2013-2014 Measurement Period			
Site Code	Ecotype Code	Temp. at 3cm (°C)	Temp. at 100cm (°C)	Active Layer (cm)	Freeze Back Duration (days)	Temp. at 3cm (°C)	Temp. at 100cm (°C)	Active Layer (cm)	Freeze Back Duration (days)
S4-AWS	AWL	-0.15	-1.05	70	80	3.00	-0.20	69	
S3-AWS	AWU		0.30				0.02		
SS-AWS	AWU	-2.82	-3.15	64	50	-0.38	-1.96	41	13
KCF	BEL	-2.92	-2.64	80	73	1.62	-0.74	50	76
S4-LS	BEL	-2.53	-2.92	47	46	0.97	-1.27	47	38
S3-BEW	BEU	-1.66	-1.92	48	63	1.66	-0.63	43	84
S1-BF	BFU	1.02				3.14			
KCT	BWR	-3.27	-3.70	55	59	0.57	-1.37	47	60
KC1	ESB	-3.06	-4.13	48	49	0.60	-1.76	53	41
S3-LSF	SFL	-3.00	-4.56	68	44	-0.03	-2.80	47	29
QZC	TS	-2.49	-3.61	51	56	0.62	-1.92	51	21
AKR	TS	-2.46	-3.52	51	58				
UUG	TS								
S4-TM	TS	-3.03	-4.29	54	48	0.45	-2.23	65	32
S3-TM	TS	-3.38	-3.60	51	52	1.29	-0.81	44	92
SV1	TS	-2.83	-4.55	47	52	0.20	-2.57	55	30
STS	TS	-2.74	-3.92	48	52				
S2-PB	TSB	-3.05	-4.38	84	52	1.68	-0.95	81	76
S8-PB	WSB								
SS-WS	WSE	-3.02	-2.44	73	58				
S1-WS	WSW	-0.92	0.17			2.29	-0.01		

Table 4. A summary of the MAGT at 3 and 100 cm, the active layer depth, and the freeze back duration, for all study sites and for our two main measurement periods.

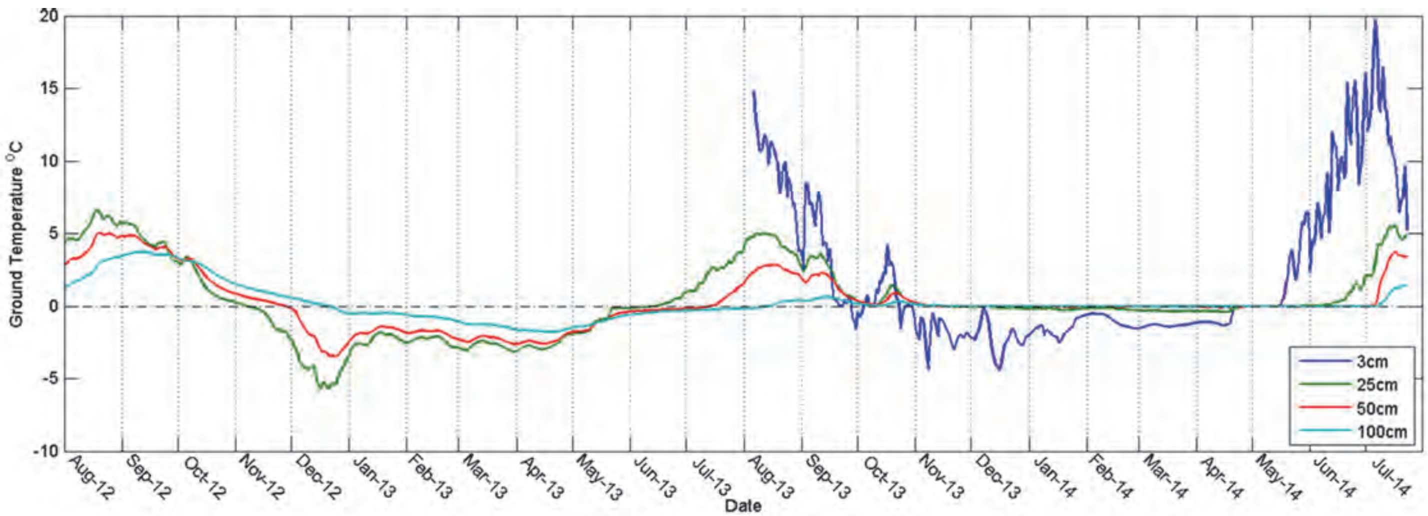

Figure 10. Time-series of ground temperatures at S3-AWS during August 1, 2012 to July 22, 2014. The 3cm sensor malfunctioned during the 2012-2013 measurement period and is therefore missing.

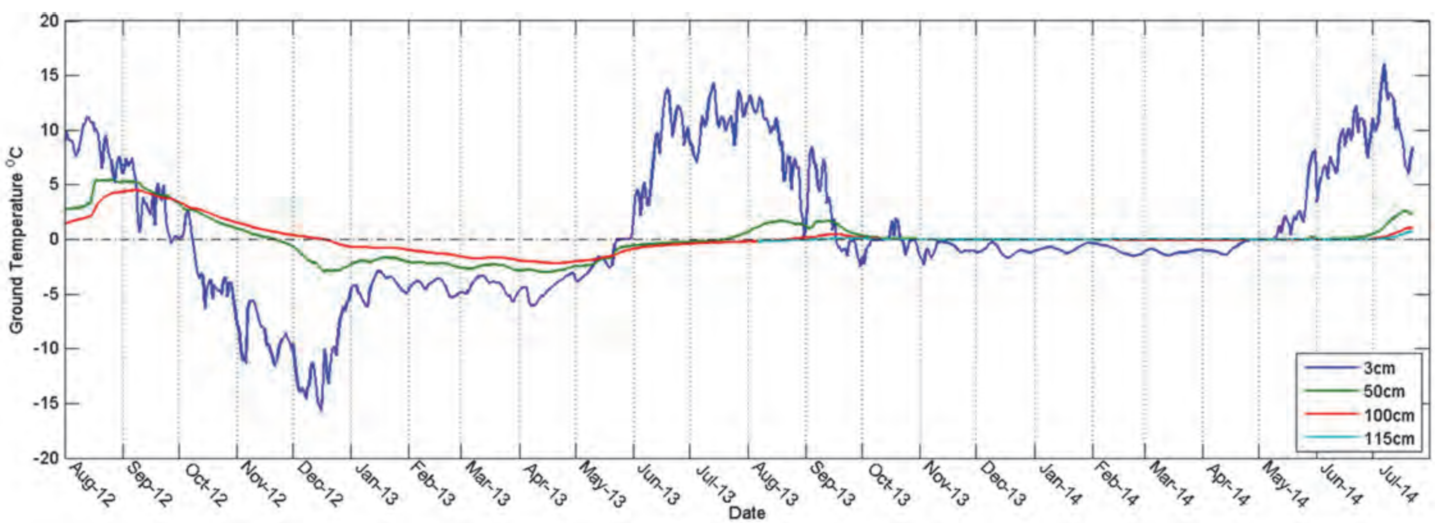

Figure 11. Time-series of ground temperatures at S1-WS from August 1, 2012 to July 22, 2014. The sensor at 115cm malfunctioned during the 2012-2013 measurement period and is not shown.

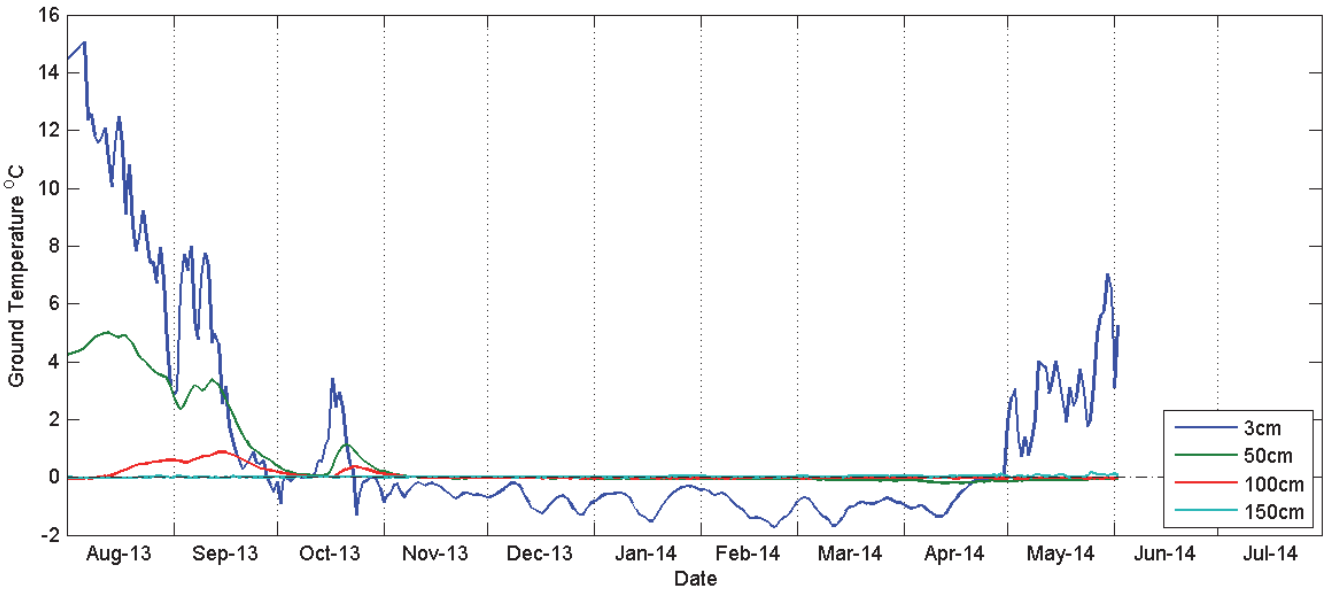

Figure 12. Time-series of ground temperatures from the Upland Burned White Spruce Forest site (S8-PB). The data logger malfunctioned at the end of May 2014 and was replaced during our site visit in July.

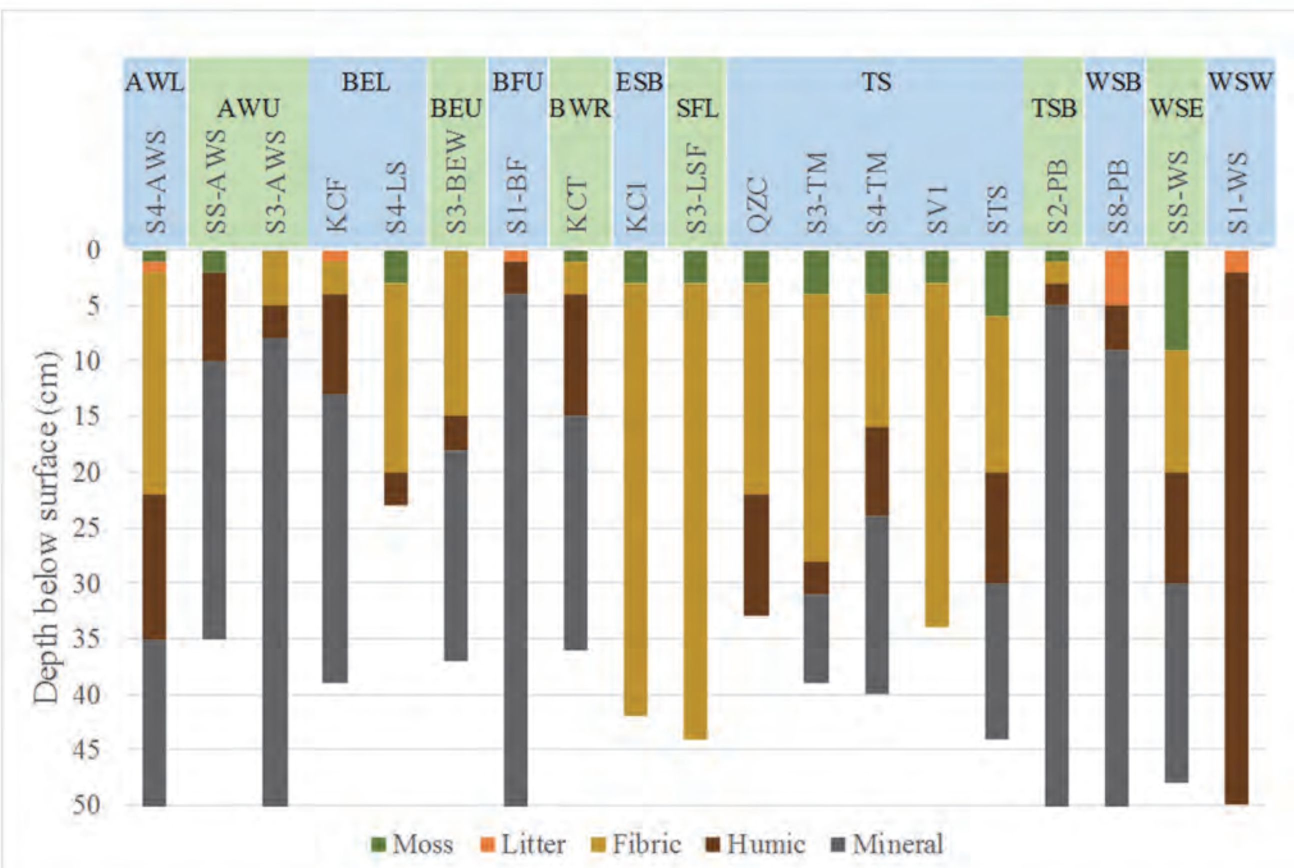

Figure 13. This figure shows the thickness and depth of each of the major soil layers from each site.

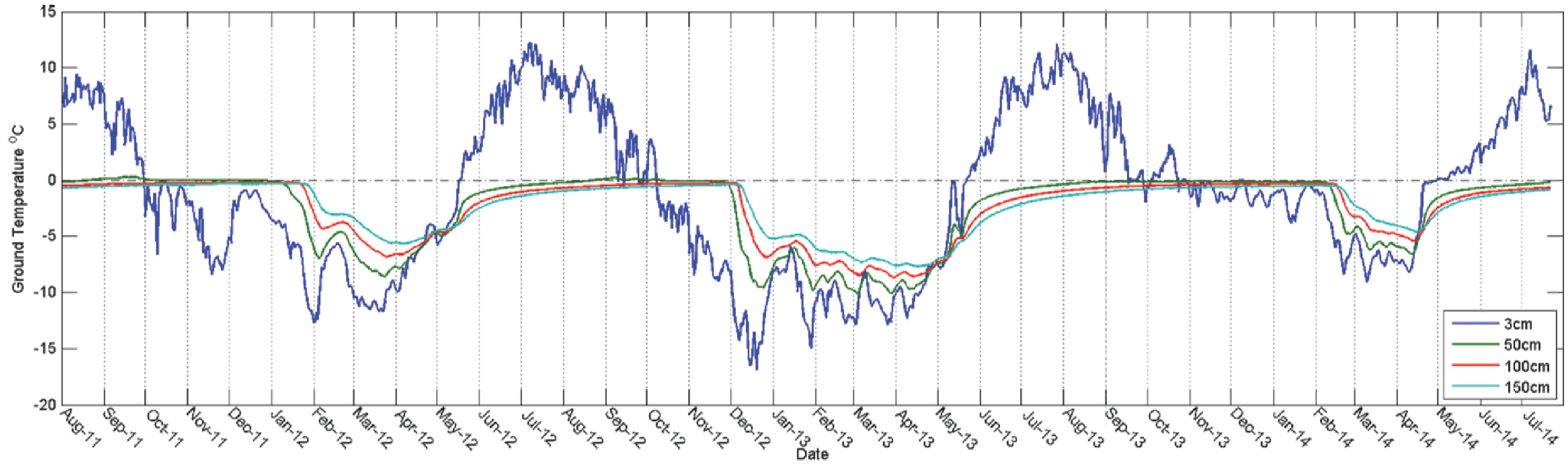

Figure 14. Time-series of ground temperatures from the KCT site covering the years 2011 to 2014.

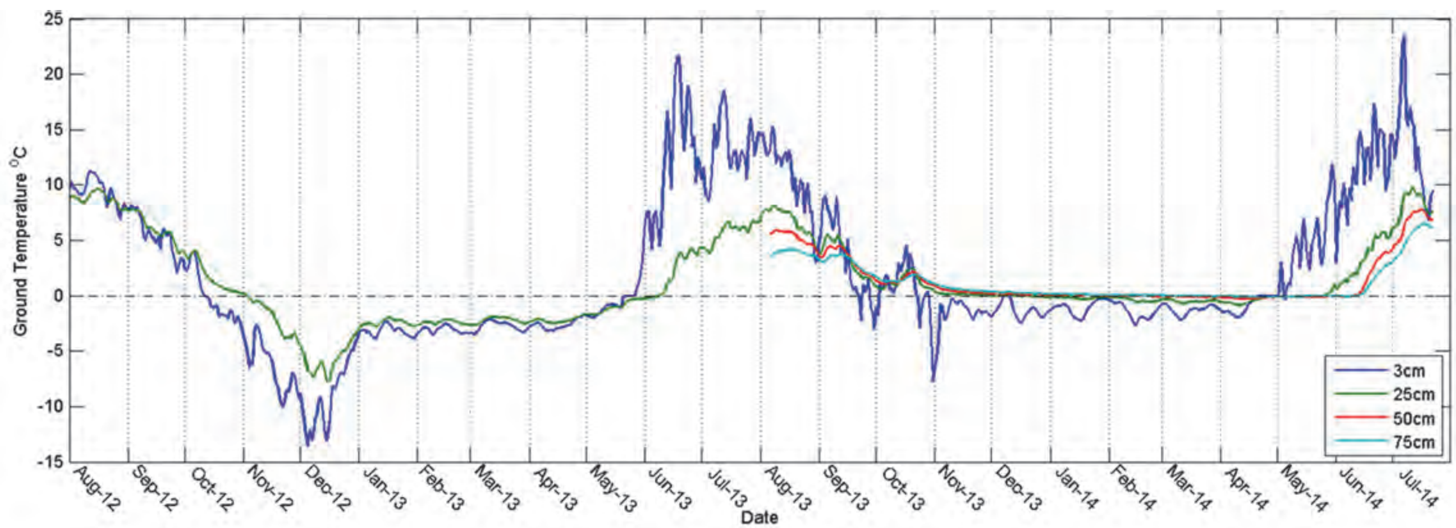

Figure 15. Time-series from the Upland Birch Forest site (S1-BF) from the period beginning August 1, 2012 to July 22, 2014. During the 2012-2013 measurement period the 50 and 75 cm, sensors were not functioning and are not shown.

Ecotype	Ecotype Code	%	MAGT1.0 range 2012-2013	MAGT1.0 range 2013-2014
Upland Dwarf Birch-Tussock Shrub	TS	28.4	-4.5 to -3.5	-2.6 to -0.8
Lowland Birch-Ericaceous Low Shrub	BEL	7.3	-2.9 to -2.6	-1.3 to -0.7
Lowland Birch-Willow Low Shrub		7.1		
Lowland Lake		5.7		
Upland Birch-Willow Low Shrub		5.1		
Upland White Spruce-Ericaceous Forest	WSE	4.8	-2.4 to -2.4	
Upland Alder-Willow Tall Shrub	AWU	4.4	-3.2 to 0.3	-2.0 to 0.0
Lowland Alder-Willow Tall Shrub	AWL	4.0	-1.0 to -1.0	-0.2 to -0.2
Riverine Wet Sedge Meadow		4.0		
Lowland Sedge Fen	SFL	3.6	-4.6 to -4.6	-2.8 to -2.8
Riverine Birch-Willow Low Shrub	BWR	3.3	-3.7 to -3.7	-1.4 to -1.4
Upland Birch-Ericaceous Low Shrub	BEU	3.2	-1.9 to -1.9	-0.6 to -0.6
Riverine Water		2.8		
Upland Willow Low Shrub		1.9		
Upland White Spruce-Willow Forest	**WSW**	1.8	0.2 to 0.2	0.0 to 0.0
Riverine Moist Willow Tall Shrub		1.7		
Riverine White Spruce-Willow Forest		1.6		
Lowland Willow Low Shrub		1.3		
Riverine Alder Tall Shrub		1.1		
Lowland Black Spruce Forest		1.0		
Lowland Ericaceous Shrub Bog	ESB	1.0	-4.1 to -4.1	-1.8 to -1.8
Upland Spruce-Birch Forest		0.8		
Coastal Brackish Sedge–Grass Meadow		0.7		
Riverine Willow Low Shrub		0.6		
Upland Birch Forest	**BFU**	0.6		
Upland Sedge-Dryas Meadow		0.5		
Riverine Poplar Forest		0.4		
Alpine Acidic Dryas Dwarf Shrub		0.2		
Coastal Water		0.2		
Upland White Spruce-Lichen Woodland		0.2		
Alpine Acidic Barrens		0.1		
Alpine Alkaline Barrens		0.1		
Riverine Barrens		0.1		
Riverine White Spruce-Poplar Forest		0.1		

Table 5. The range of MAGT1.0 for measured ecotypes is shown for the 2012-2013 and 2013-2014 periods. Also shown are the percent areal coverage, modified from Jorgenson et al. (2009).

Upland and Lowland Alder-Willow Tall Shrub (AWU and AWL) occupy a combine area of approximately 8.4% within the Selawik NWR (Table 5). The ground thermal data from sites within these ecotypes are somewhat variable with MAGT1.0 ranging from +0.3°C to -3.2°C in 2012-2014 (Table 4 and 5). The two most extreme sites are the two upland sites (S3-AWS and SS-AWS) with the lowland site (S4-AWS) falling in-between. The warmer of the two upland sites (S3-AWS) differs from the colder site (SS-AWS) in that it lacks a moss covered surface for protection from summer-time warming, similar to site S1-WS (Figure 13). Thus, again the understory vegetation and ground cover is important in determining the ground thermal regime. The Lowland Alder-Willow Shrub site (S4-AWS) also does not have a thick moss layer and may be a transitional site with a short-lived talik that may develop during several warmer years with consequent re-freezing during relatively colder years. This site is also has a very wet active layer as can be seen from the small annual temperature range and the long freeze back duration (Figures 8 and 9).

A small area of Lowland Sedge Fen (SFL, 3.6% areal coverage) is represented by one site (S3-LSF) and has a MAGT1.0 that is on the colder end of the range for the TS sites (Table 4 and 5). However, this site had a deeper active layer in 2012-2013 and a shorter freeze back duration in both years than the tussock shrub sites suggesting that it probably has a wetter active layer with much higher frozen thermal conductivity. This site also has a similar soil profile to the TS sites, composed a thick moss layer with a fibric layer extending down to the permafrost table (Figure 13).

The Riverine Birch-Willow Low Shrub ecotype (BWR, 3.3% areal coverage) has relatively cold permafrost (Table 2 and 4). Figure 14 shows the time-series of temperatures from this site (KCT) for the period from August 1, 2011 to July 21, 2013. This figure shows that the ground temperatures were much lower during the winter of 2012-2013 in comparison to the previous and following winter. The most striking difference is in the timing of the active layer freeze-up. In the winter of 2011-2012 the complete freeze-up of the active layer occurred near the January 17, 2012,in 2012-2013, the active layer was completely frozen by November 25, 2012, and in 2013-2014, the active layer was completely frozen by February 10, 2014. In terms of permafrost characteristics this site is quite similar to TS ecotype sites.

The Upland Birch-Ericaceous Shrub ecotypes (BEU) represent 3.2% areal coverage within the Selawik NWR (Table 5). This ecotype is represented by only one site (S3-BEW) but it is very similar to the same ecotype that is found in the lowlands (BEL) in terms of permafrost temperature, active layer thickness, and freeze back duration (Table 4 and 5).

The Upland White Spruce-Willow Forest (WSW) occupies a small area with only 1.8% areal coverage (Table 5). The site used to characterize this ecotype (S1-WS) has a much warmer and above zero MAGT1.0 than the other White Spruce site indicating the absence of near-surface permafrost (Table 4). We believe the key difference between these sites is the ground cover.

While the White Spruce site associated with Ericaceous species (SS-WS) has a thick moss cover on the ground surface, this site, associated with Willow species, has only a thin layer of organic material (decomposing willow leaf litter) offering little insulation from the summer's warm temperatures (Figure 13). Thus, other factors such as the understory vegetation and ground cover seem to be an important in determining the presence or absence of near-surface permafrost in these ecotypes.

One of our sites (KC1) represents the Lowland Ericaceous Shrub Bog (ESB) ecotype that covers approximately 1.0% of the area within Selawik NWR (Table 5). This site was on the colder end of the range in terms of MAGT (Table 4) and has an active layer thickness and freeze back duration similar to that of the TS ecotype sites (Table 5). This can probably be explained by the similar soil profile to the TS ecotype sites, a moss layer underlain by a fibric layer extending to the permafrost table, also similar to the S3-LSF site (Figure 13).

Site S1-BF, in an Upland Birch Forest (BFU, Table 5) had an equipment malfunction in 2012-2013 and while it work properly during 2013-2014 we do not have enough data to reliably calculate MAGT. The time-series of the data we have is presented in Figure 15 and shows that this site does not have any permafrost near the surface as it does not refreeze during the winter. This site also has a very thin organic layer (<5cm) covering the mineral soil (Figure 13).

Our results indicate that in the region of investigation near-surface permafrost may be absent in four ecotypes: Upland Burned White Spruce Forest (Figure 12), Upland White Spruce-Willow Forest (Figure 11), Upland Alder-Willow Shrub (Figure 10), and Upland Birch Forest (BFU, Figure 15). However, this conclusion should be applied carefully because at different locations

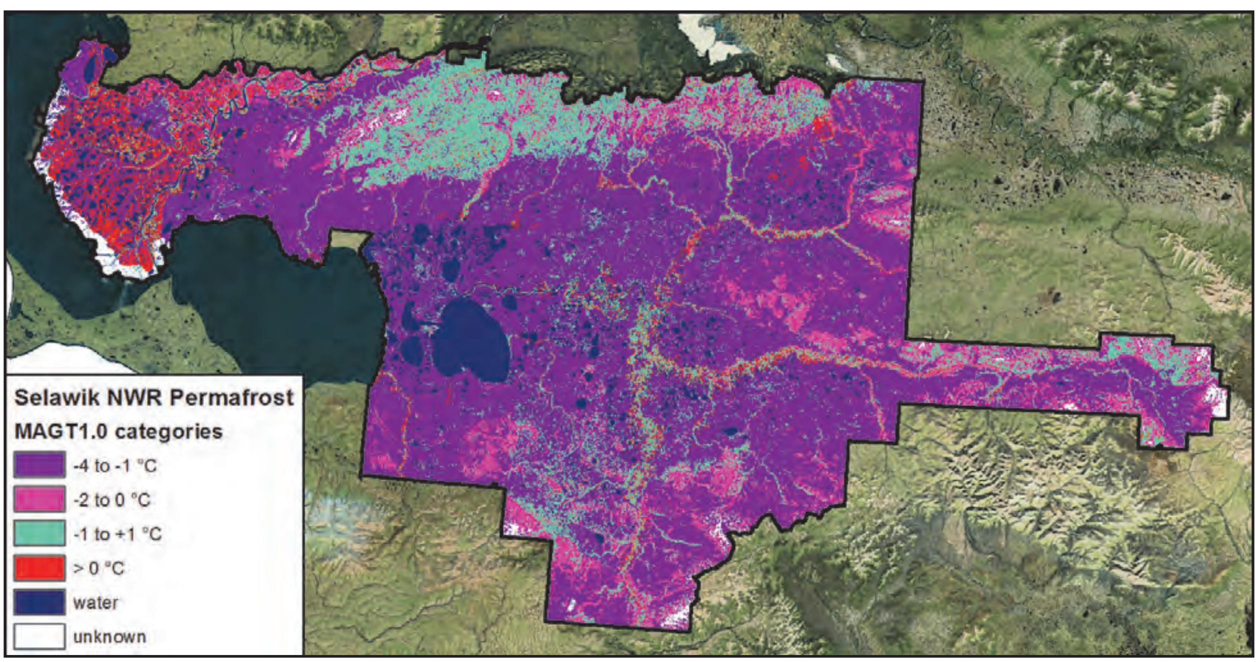

Figure 16. Map of MAGT1.0 for the Selawik NWR reclassified from the map by Jorgenson et al. (2009).

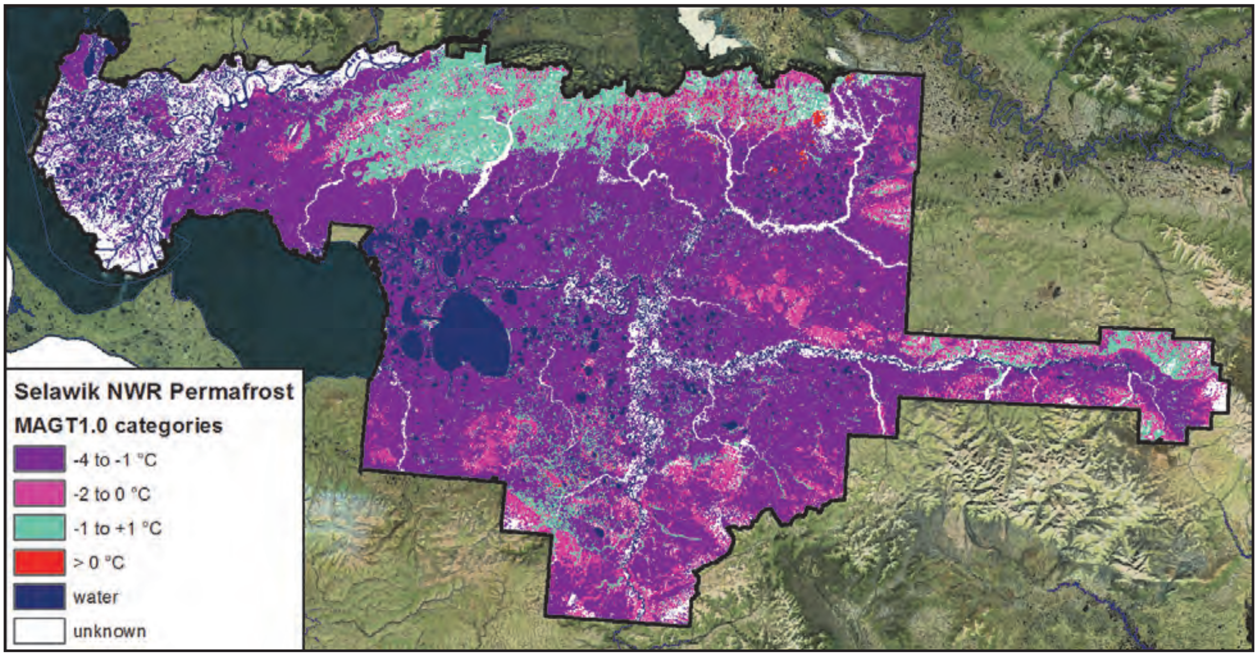

Figure 17. The same as the map in Figure 16 but only the ecotypes for which we made measurements shown.

with the same or similar ecotypes where moss and a thick fibric organic layer were present permafrost was observed immediately below the seasonally thawed layer (no talik was present) and the mean annual temperatures at 1 m depth were much lower than 0°C.

<u>Permafrost Map</u>

As a proof of concept we used the range of MAGT1.0 measured across these different ecotypes (Table 5) to reclassify the ecotype map from Jorgenson et al. (2009) into classes of permafrost temperature. First, for ecotypes from which we had measurements, we classified the range of MAGT1.0 into one of 4 categories: -4 to -1 °C, -2 to 0 °C, -1 to +1 °C, and greater than 0 °C. These ranges were chosen to accommodate the majority of mean annual temperature ranges for each ecotype observed during our measuring period. Then, for ecotypes where we didn't have any measurements we used the vegetation and soil descriptions in Jorgenson et al. (2009) and consulted with Torre Jorgenson to decide how they should be classified. Additionally, we added an unknown category for ecotypes where we were not comfortable placing them into a category due to lack of information. Finally, we created two versions of the MAGT1.0 map for Selawik NWR, one with all the ecotypes (Figure 16) and one where the ecotypes we did not make any measurements in are masked out (Figure 17).

THERMAL MODELING RESULTS:

<u>Reconstruction of the past changes in permafrost temperature and projection of the future changes</u>

To estimate the past changes in permafrost temperature and to make projections of these changes in the future we used a "permafrost temperature reanalysis" approach (Romanovsky et al., 2002). Using this approach, a sophisticated numerical model (Tipenko and Romanovsky, 2001;

Sergueev et al., 2003), which takes into account the temperature-dependent latent heat effects, was used to reproduce active layer and permafrost temperature field dynamics at the chosen sites in the Selawik area and in the Seward Peninsula where the active layer and near-surface permafrost temperatures have been measured for some period of time. The input data for these modeling efforts are prescribed specifically for each site and include detailed description of soil thermal properties and moisture for each distinct layer, surface vegetation, snow cover depth and density, and air temperature. With this modeling approach, which has been successfully used by Romanovsky et al. (1997), Osterkamp and Romanovsky (1999), and Romanovsky and Osterkamp (2001), variations in air temperature, and snow cover thickness and properties are the driving forces of permafrost temperature dynamics. The model was calibrated for each specific site using measured permafrost and active layer temperatures, for several years, and data from the closest meteorological station for the same time interval. After validation using measured data that were not involved in the calibration process, the calibrated model can then be applied to the entire period of meteorological records at this station, producing a time series of permafrost temperature changes at various depths. The same calibrated model can be applied for projections of future permafrost dynamics when a future climate change scenario is used as input data. For this project five sites were chosen to apply this reanalysis technique: Kugurak Cabin (KC1), Alder-Willow Shrub (S4-AWS) site, Council Tundra, Council Shrub, and Council Forest.

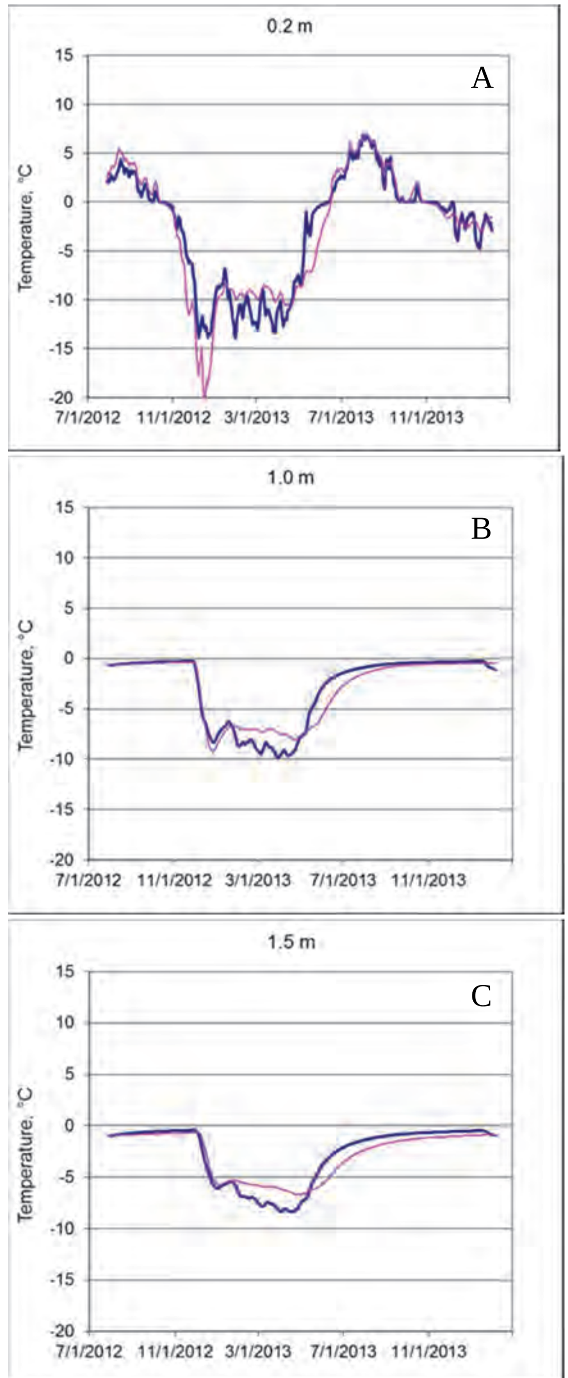

Figure 18. Comparison between measured data (blue) and calculated temperatures (red) near the ground surface (A), at 1 m depth (B), and at 1.5 m depth (C) at the Kugurak Cabin site.

<u>Kugurak Cabin site</u>

The Kugurak Cabin site (KC1) is located near the confluence of the Selawik and Kugarak Rivers. The surface vegetation at the site is represented by shrub birch, grasses, sedges, green moss, Labrador tea, and other low shrub. The organic soil layer at this location is deeper than 42 cm thick (Figure 13) and is composed of living moss (3 cm thick) and peat in the early stages of decomposition (fibric layer). Deeper under the organic layer a layer of gray silt is found.

This site is located relatively close to the Kotzebue meteorological station. Long-term air temperature and snow depth data are available since 1933 for this station. Comparison between air temperatures measured at the Kugurak Cabin site and at the meteorological stations in Nome and Kotzebue during 2012-2014 show that the air temperature from Kotzebue matches the Kugurak Cabin site much better than the records from Nome (Figures 6 and 7). Based on this comparison we decided to use the Kotzebue meteorological data as input data for our modeling.

Using Kotzebue air temperature and snow depth adjusted to match Kugurak Cabin we calibrated our site -specific numerical model to match the measured subsurface temperature collected form this site in 2012-2014 (Figure 18). The calibrated model produced subsurface temperatures that are in a good agreement with the measured ones.

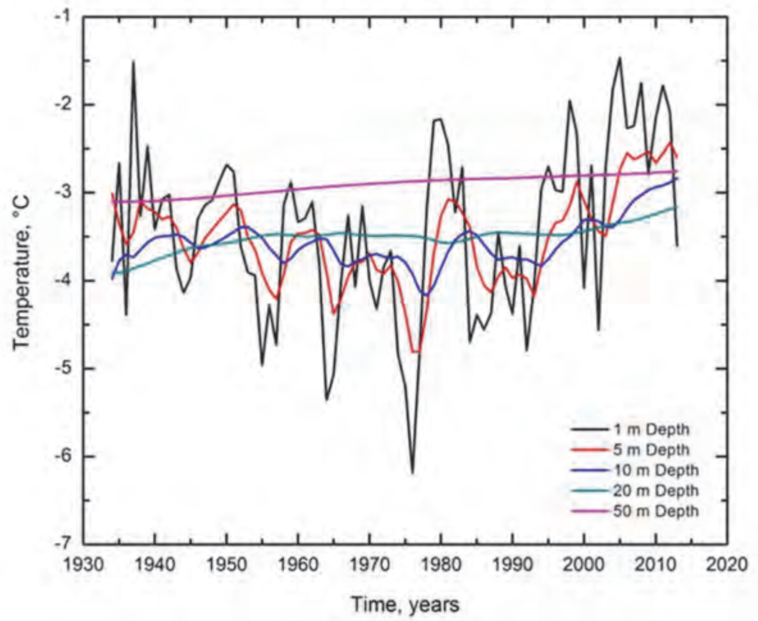

Figure 19. Reconstructed history of changes in mean annual ground temperature at different depths at the Kugurak Cabin site.

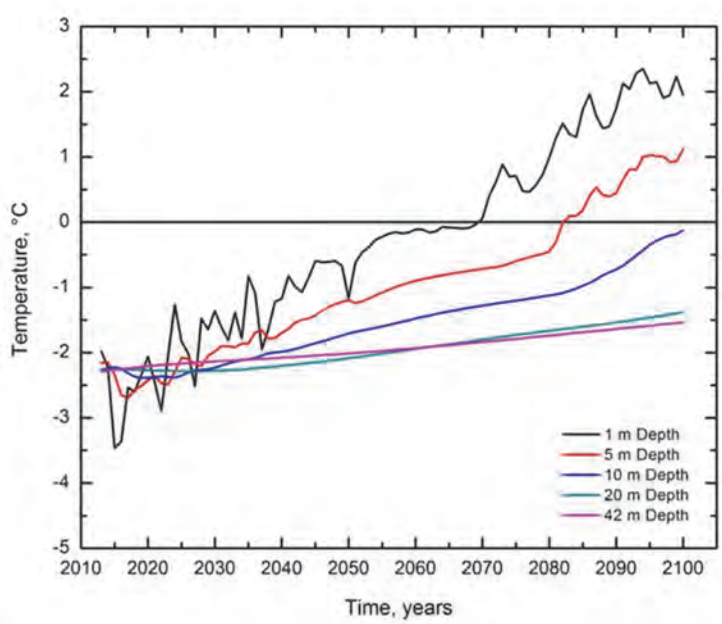

Figure 20. Projected changes in mean annual ground temperature at different depths in the 21st century at the Kugurak Cabin site.

The calibrated model was then used to reconstruct ground temperature dynamics at the Kugurak Cabin site for the period 1933-2013 (Figure 19). This reconstruction shows that there has been a general warming trend at all depths since the early 1940s with a total increase of more than 1°C. However, this increase has been much larger since the mid-1970s (up to 2°C), partly as a recovery from the colder 1960s and 1970s. The temperatures were generally higher in the late 1930s and 1940s than in the 1950s and 1960s. The ground temperatures reached their minimum by the mid-1970s. A drastic change in permafrost temperatures occurred in the late 1970s, where, in a very short period of time, the temperature in the near-surface permafrost increased by 4°C reaching its local maximum in the beginning of 1980s. Temperature decreased again by the late 1980s to early 1990s and again in the late 1990s and early 2000s. Since the early 2000s ground temperature has been more or less steadily increasing up to the present with a sharp minimum in 2012-2013.

To project changes in the ground temperatures into the future we used a composite of the future air temperature and precipitation scenarios produced by five AR4 GCMs that were found to produce the best results for Alaska (Walsh et al., 2008). This monthly forcing was used to run our calibrated for Kugurak Cabin site model for the 2015-2100 time period. The results indicate that a small cooling in permafrost temperatures observed in 2012-2013 and in 2015-2016 will be replaced by more or less steady warming in the late 2010s and onward. However, until the beginning of 2070s there will be no substantial thawing of permafrost at this site. From the beginning of 2070s a more substantial increase in permafrost temperatures is predicted. This steady increase will result in the thawing of near-surface permafrost and in a 5m deep talik formation by 2080. This talik will be progressively deepening and will reach the depth of 10m by 2100.

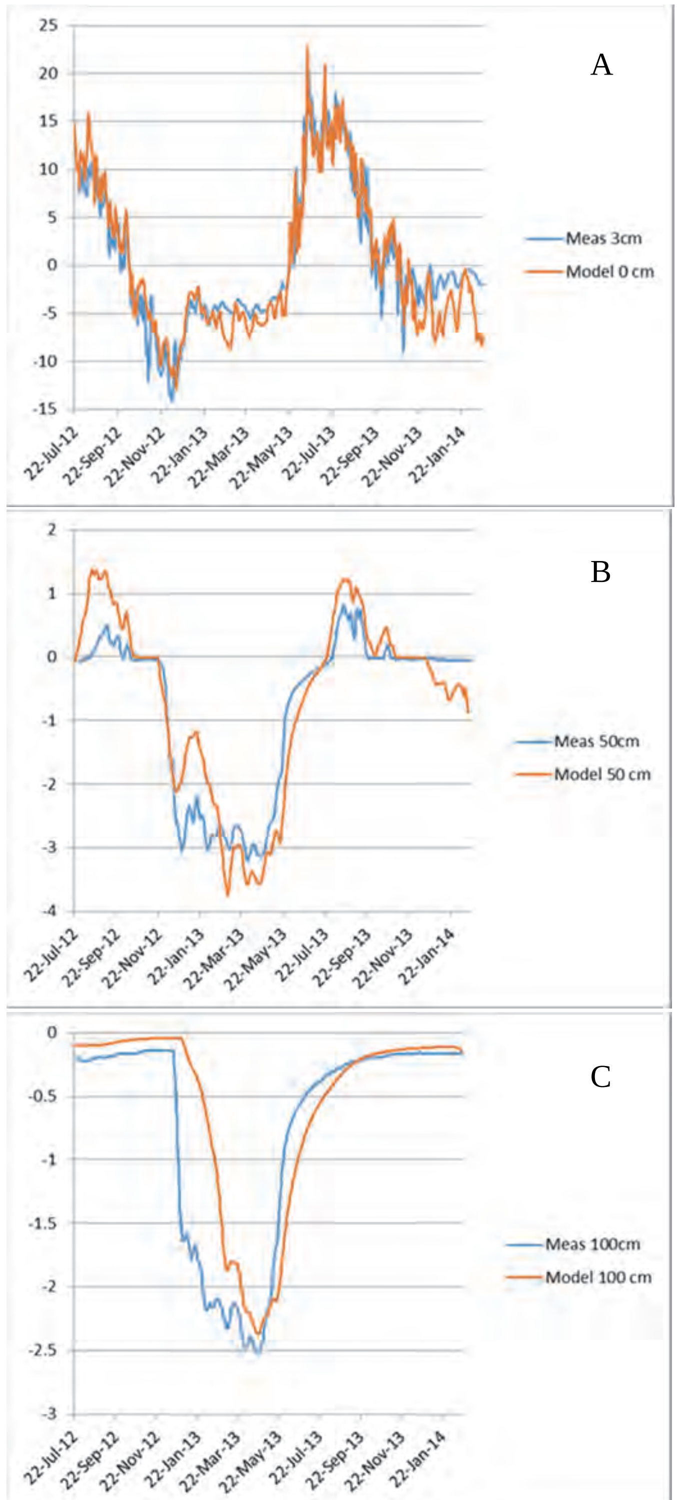

Figure 21. Comparison between measured data (blue) and calculated temperatures (red) near the ground surface (A), at 0.5 m depth (B), and at 1.0 m depth (C) at the Alder-Willow Shrub (S4-AWS) site.

Alder-Willow Shrub (S4-AWS) site

The Alder-Willow Shrub (S4-AWS) site is located about 5 miles north-west of Selawik village within the old floodplain of the Selawik River and about 0.5 miles west of Shogvik Lake. The surface vegetation at the site is represented by tall alder and willow shrubs, grasses, sedges, and occasionally live moss. The organic soil layer at this location is 35 cm thick (Figure 13) and is composed by living moss (1 cm thick), litter (1 cm thick) and peat in different stages of decomposition (20 cm fibric layer and 13m humic layer).

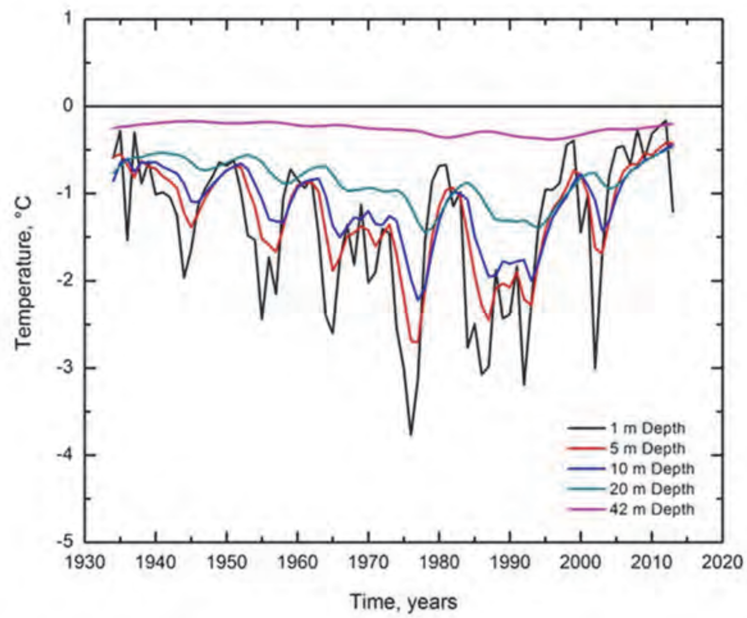

Figure 22. Reconstructed history of changes in mean annual ground temperature at different depths at the Alder-Willow Shrub (S4-AWS) site.

Using Kotzebue air temperature and snow depth adjusted to S4-AWS we calibrated our site-specific numerical model to match the measured subsurface temperature collected from this site during 2012-2014 (Figure 21). The calibrated model produced subsurface temperatures that are in a good agreement with the measured ones.

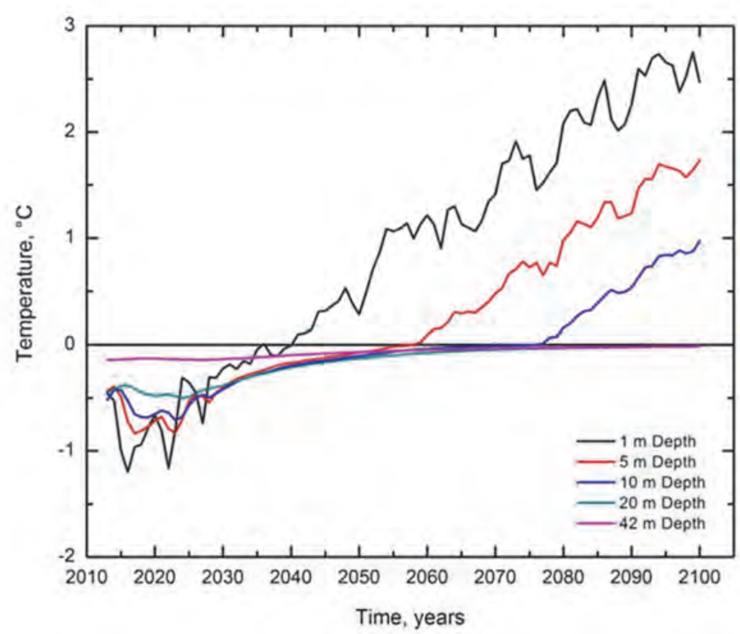

Figure 23. Projected changes in mean annual ground temperature at different depths in the 21st century at the Alder-Willow Shrub (S4-AWS) site.

The calibrated model was then used to reconstruct ground temperature dynamics at the Alder-Willow Shrub (S4-AWS) site for the period 1933-2013 (Figure 22). This reconstruction shows that there has been generally a slight warming trend at all depths since the early 1940s with a total increase of a few tenths of a degree C. However, this increase has been much larger since the mid-1970s (up to 3°C), mostly as a recovery from the colder 1960s and 1970s. The temperatures were generally higher in the late 1930s and 1940s than in the 1950s and 1960s. The ground temperatures reached their minimum by the mid-1970s. A drastic change in permafrost temperatures occurred in the late 1970s, where, in a very short period of time, the temperature in the near-surface permafrost increased by 3°C reaching its local maximum in the beginning of 1980s. The temperature decreased again by the late 1980s to early 1990s and again

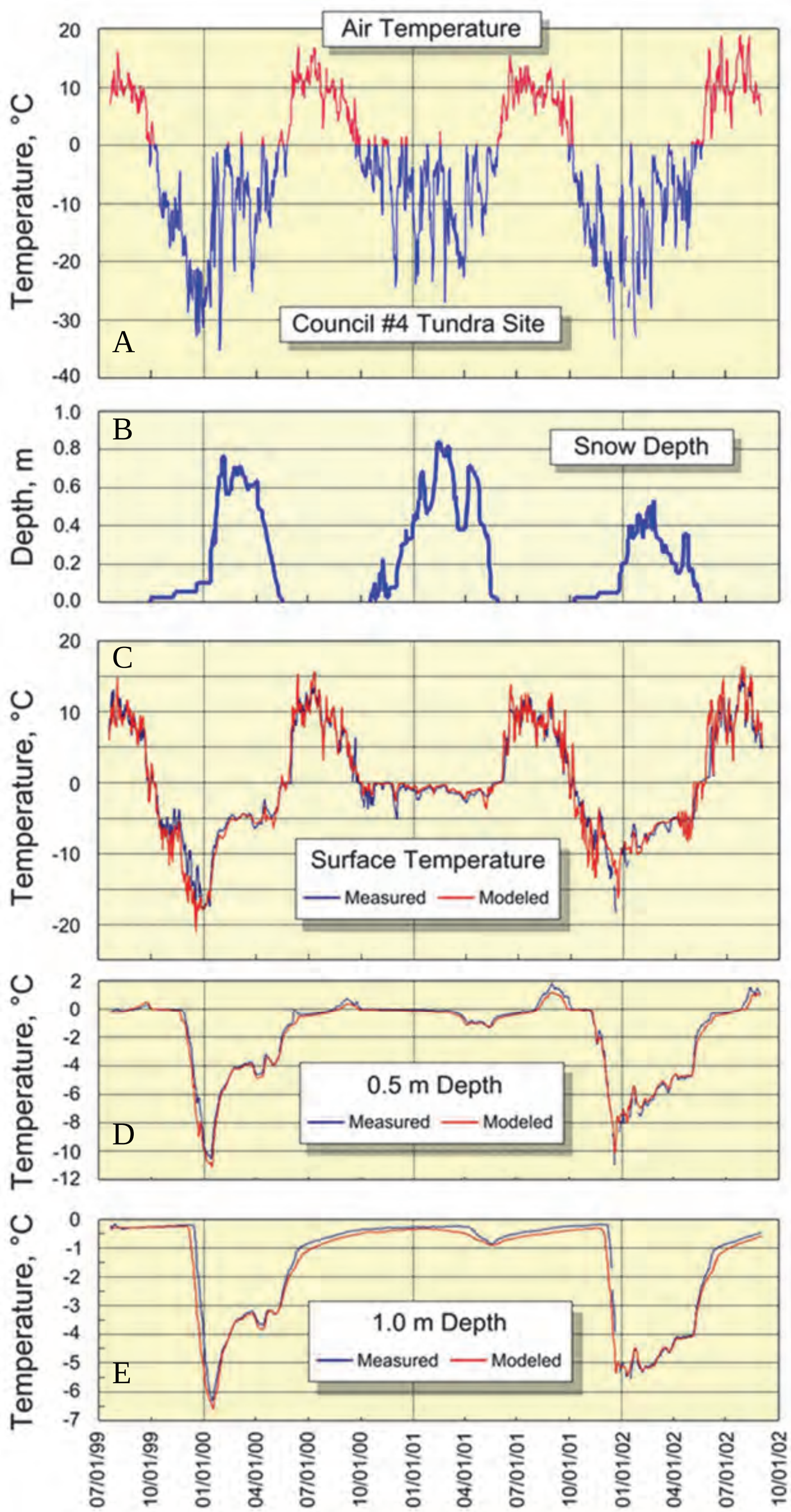

Figure 23. Air temperature (A) and snow depth (B) at the Council sites adjusted from the Nome meteorological station used for the model calibration. Comparison between measured data (blue) and calculated temperatures (red) near the ground surface (C), at 0.5 m depth (D), and at 1.0 m depth (E) at the Council Tundra site.

in the early 2000s. Since the early 2000s ground temperature has been more or less steadily increasing up to the present with a sharp minimum in 2012-2013.

To project changes in the ground temperatures into the future we used a composite of the future air temperature and precipitation scenarios produced by five AR4 GCMs that were found to produce the best results for Alaska (Walsh et al., 2008). This monthly forcing was used to run our calibrated Alder-Willow Shrub (S4-AWS) site model for 2015-2100 time period. The results indicate that a small cooling in permafrost temperatures observed in 2012-2013 and in 2015-2016 will be replaced by more or less steady warming in the late 2010s and onward. However, until the beginning of 2040s there will be no substantial thawing of permafrost at this site. From the beginning of 2040s a more substantial increase in permafrost temperatures is predicted. This steady increase will result in the thawing of near-surface permafrost and a 5 m deep talik formation by 2058. This talik will progressive deepen reaching a depth of 10m by 2077.

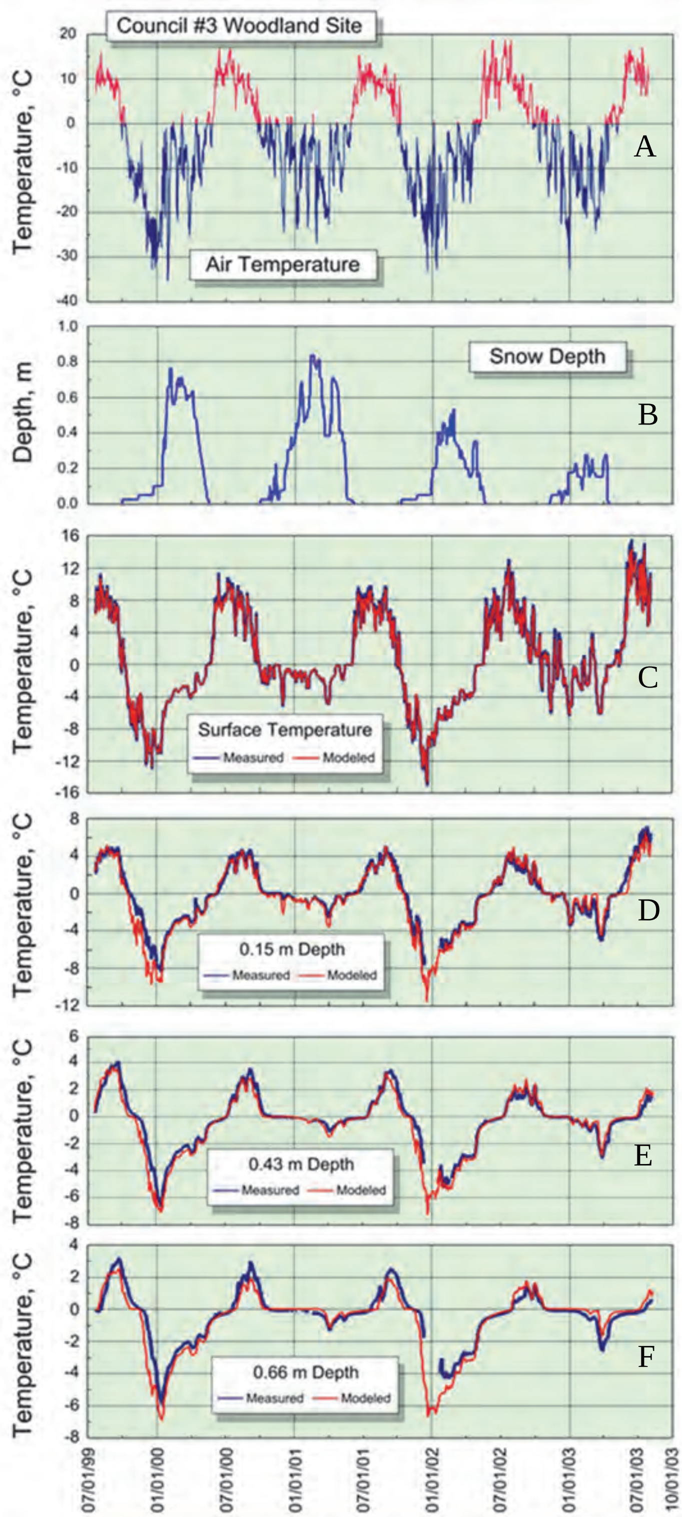

Figure 24. Air temperature (A) and snow depth (B) at the Council sites adjusted from the Nome meteorological station used for the model calibration. Comparison between measured data (blue) and calculated temperatures (red) near the ground surface (C), at 0.15 m depth (D), at 0.43 m depth (E), and at 0.66 m depth (F) at the Council Woodland site.

<u>Council Tundra, Woodland, and Forest sites</u>

We used data form the Council area on Seward Peninsula collected in the 2000s as a part of a previous project to perform our ground temperature reanalysis and produce reconstructed and forecasted ground temperature changes at three sites in this area: Tundra, Woodland, and Forest.

The Tundra site (64°50.499” N, 163° 41’26.21” W) is located about 3 miles south of Council, Alaska to the east of the Nome-Council road and represented by typical tundra vegetation with a thick layer of moss, sedges, grass, lichens, dwarf birch, Labrador tea, and other low shrubs. The organic soil layer at this location is thicker than 30 cm and is composed by living moss (12 cm thick) and peat in the early stages of decomposition (10 cm thick fibric layer and 8 cm thick humic layer). Deeper under the organic layer a layer of gray silt is found and a gravel layer starts at 15 m depth. The Woodland site (64° 53’52.84” N, 163°39’58.54” W) is located 0.5 miles north-east of Council, AK. The vegetation at this site is represented by tall (2 m and higher) alder and willow shrubs and sparse white spruce trees. The organic soil layer at this location is very shallow (less than 10cm) and is composed of litter and humus. Deeper under the organic layer is a layer of silt (50cm thick) and under this silt layer very weathered bedrock is found. The Forest site (64°54’27.73” N, 163°40’43.23” W) is located 1 mile north of Council, AK. The vegetation at this site is represented by medium to tall white spruce trees, live moss, sedges, lichens, dwarf birch, Labrador tea, and other low shrubs. The organic soil layer at this location is 65 cm thick and is composed of living moss (6 cm thick) and peat in different stages of decomposition (fibric and humic layers). Deeper under the organic layer a layer of gray silt is found.

These sites are located relatively close to the Nome meteorological station. Long-term air temperature and snow depth data are available since 1948 from this station. Comparison between air temperatures measured at the Council sites and at the meteorological stations in Nome and Kotzebue during 1999-2004 shows that the air temperature from Nome matches the Council sites much better than the records from Kotzebue. Based on this comparison we decided to use the Kotzebue meteorological data adjusted to the Council area (Figures 23A and 23B) as input data for our modeling.

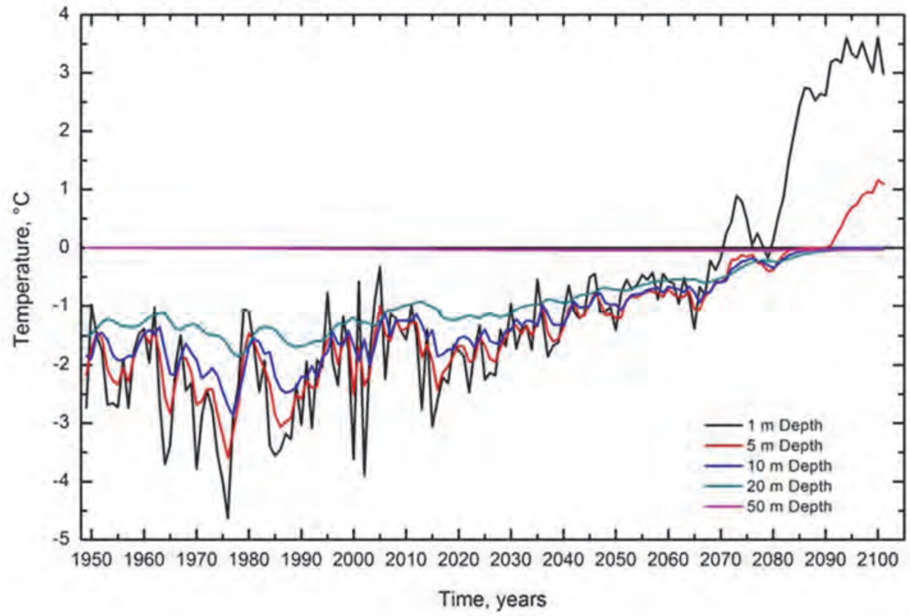

Figure 25. Reconstructed history and projected future changes in mean annual ground temperature at different depths at the Council Tundra site.

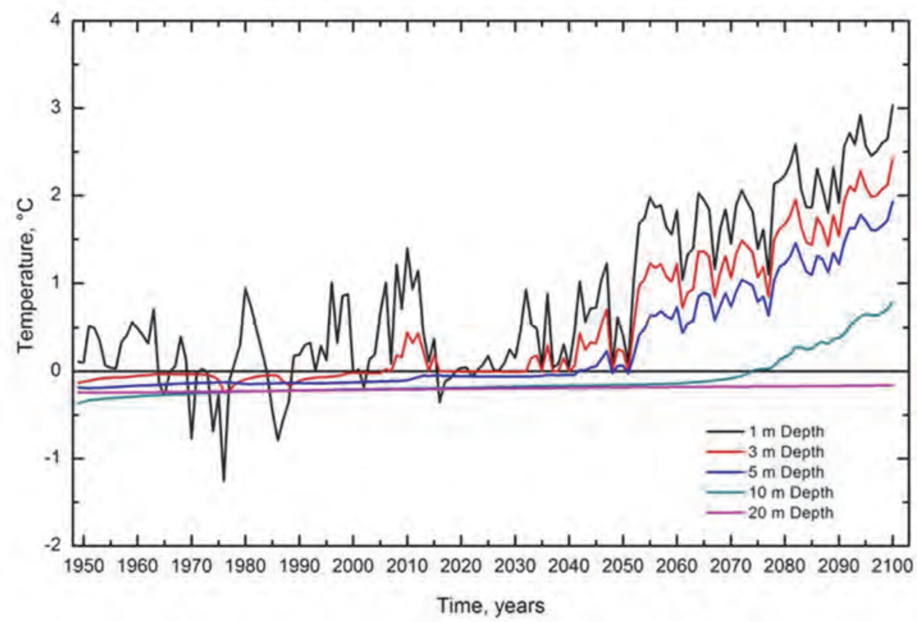

Figure 26. Reconstructed history and projected future changes in mean annual ground temperature at different depths at the Council Woodland site.

Using Nome air temperature and snow depth adjusted to the Council area we calibrated our site-specific numerical model to match the measured subsurface temperature collected from the Tundra, Woodland, and Forest sites in 1999-2003 (Figures 23 and 24). The calibrated model produced subsurface temperatures that are in a good agreement with the measured ones.

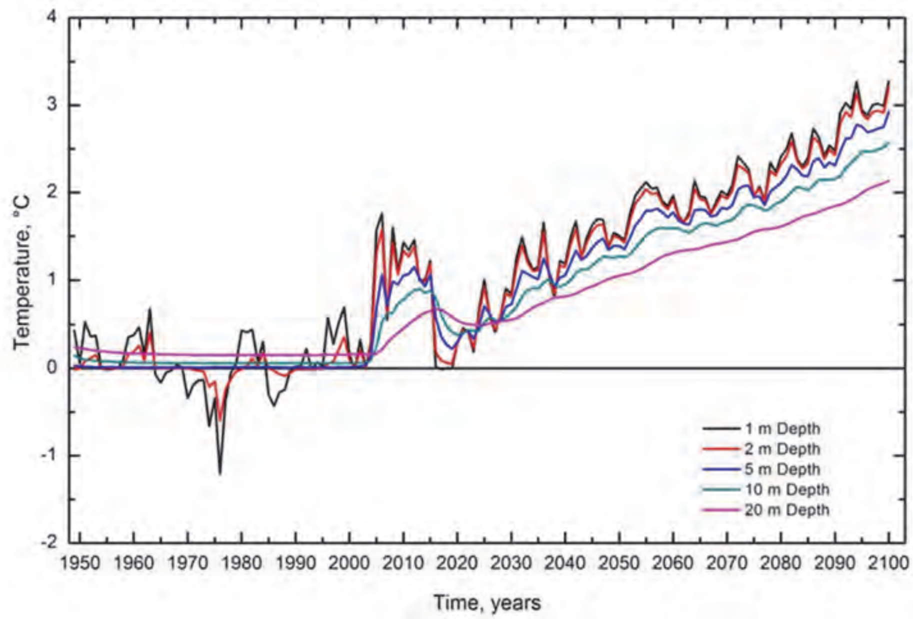

Figure 27. Reconstructed history and projected future changes in mean annual ground temperature at different depths at the Council Forest site.

The calibrated models were then used to reconstruct ground temperature dynamics at the Council Tundra, Woodland, and Forest sites for the period 1949-2013 (Figures 25, 26, and 27). This reconstruction shows that there was generally a slight warming trend at all depths at the colder Tundra site since 1949 with a total increase of a few tenths of a degree C. However, this increase was much larger since the mid-1970s up to the present (up to 3°C), occurring mostly as a recovery from the colder 1960s and 1970s. The ground temperatures reached their minimum by the mid-1970s at this site. A drastic change in permafrost temperatures occurred in the late 1970s. In a very short period of time, the temperature in the near-surface permafrost increased by 3.5°C reaching its local maximum in the beginning of 1980s. Temperature decreased again by the late 1980s and then again in the early 2000s. Since the early 2000s ground temperatures have been more or less steadily increasing up to the present with a sharp minimum in 2012-2013. Much smaller ground temperature variations were reconstructed at two warmer Woodland and Forest sites. At the Woodland site, the mean annual permafrost temperature stayed generally higher than -0.5°C with a shallow (less than 3m) and short-lived talik forming around 1970 and 2000. In the late 2000s and very early 2010s, this talik exceeded 3m in depth. At the Forest site, permafrost was generally absent during 1950-2013. However, a very thin and short-living layer of permafrost (between 1 and 3 m) has formed at this site during 1970-1980 and the again in the late 1980s-early 1990s. Permafrost has been absent since then up to the present day.

To project changes in the ground temperatures into the future we used a composite of the future air temperature and precipitation scenarios produced by five AR4 GCMs that were found to produce the best results for Alaska (Walsh et al., 2008). This monthly forcing was used to run our model calibrated for the Council sites for the 2014-2100 time period. The results indicate that at all three Council sites a cooling in the ground temperatures may occur in 2015-2025

(Figures 25-27). This cooling may produce a short-lived, very thin permafrost layer at the Forest site (Figure 27). This cooling will be replaced by more or less steady warming in 2025 and onward. As a result of this warming, the thin permafrost layer at the Forest site will disappear completely in the early 2020s and will never reappear again. At the Woodland site, this warming will trigger the thawing of near-surface permafrost by 2030. A talik 5 meters deep will form at this site by the early 2040s with a possibility of a partial re-freezing sometime around 2050. From then on, the talik will grow steadily in depth and will reach 10m by the late 2070s. At the same time, there will be no substantial thawing of permafrost at the Council Tundra site until the beginning of 2080s. From the beginning of 2080s a more substantial increase in permafrost temperatures is predicted at this site. This steady increase will result in the thawing of near-surface permafrost and a 5-m deep talik formation by 2090.

DISCUSSION:

The results obtained from this project provide a solid indication that ecotypes can give us information about their ground thermal regime and permafrost characteristics. This is possible due to the way the vegetation and surface soil layers modify the climate (air temperature, snow, shading, etc.) that the permafrost is exposed to. The vegetation and surface soils (most importantly organic layers) can act as insulators for the permafrost, protecting it from the warm summer temperatures. For example, we found that within some ecotypes (Upland White Spruce and Upland Alder-Willow Shrub) the presence / absence of a moss layer often corresponded to the presence / absence of near surface permafrost. This moss layer is important within other ecotypes as well because it acts as an insulator during the summer keeping the thawing front from penetrating too deeply. The tussocks in the Dwarf Birch-Tussock Shrub (TS) ecotype also have an important effect on the permafrost thermal regime. During the winter the tussocks stick up above the snow surface until enough snow has fallen to cover them completely. This creates holes in the snow cover, which would normally be a very good insulator, and allows heat to be removed from the ground, cooling the permafrost. These same tussocks have a shading effect during the summer, reducing the warming of the ground surface and permafrost.

The fact that the ecotypes can tell us about their ground thermal regime gives us the opportunity to translate the ecotype landcover map into a permafrost temperature map. This map is a good first approximation to the distribution of permafrost temperatures across the study area, however, it is only based on data from two years and a limited number of sites / ecotypes. We were fortunate that our two main study years (2012-2013 and 2013-2014) included both a relatively cold (2012-2013) and warm (2013-2014) year giving us an idea of the range of permafrost temperatures to expect. We know that these years bracket the longer-term mean ground temperature because of the slope of MAGT with depth between the two years. An increasing MAGT with increasing depth indicates a colder than average MAGT for that site, while a decreasing MAGT with increasing depth indicates a warmer than average MAGT (Figures 8 and 9).

The second problem with the MAGT1.0 map relates to the fact that not all ecotypes were represented in our measurements. While we were able to cover approximately 63% by areal coverage of the ecotypes (note: 8.5% of the total area is water), it is practically impossible to cover all the ecotypes with the ground temperature measurement sites. We also acknowledge that many of the ecotypes covered by our measurements lacked replication as this simply wasn't possible with a study of this size, however, we believe in this case a well-designed application of a permafrost thermal model can help to overcome these obstacles. Our thermal modeling results (see the "Thermal Modeling" section above) show that with a proper choice of the thermal-physical properties of the subsurface material it is possible to accurately reconstruct the thermal regime of soils. The examples of this reconstruction for the sites where we obtained ground temperature data are described in the modeling section. For the sites where we do not have measured temperature but where the typical profile of the soil texture (including description of the organic layer) and the depth to the bedrock are known from the various maps and existing reports, it is possible to correct the physical properties obtained during the calibration exercises at the site with measured temperature data. These corrected properties may then be used for reconstruction and prediction of the ground temperature dynamics for the entire area of investigations.

PRODUCTS AND OUTREACH ACTIVITIES:

All data from this project have been and will be archived at ACADIS (www.aoncadis.org) and on our website (www.permafrostwatch.org).

As a direct product of this project and with active help and support from our collaborator on this project Michael Brubaker and with help of Moses Tcheripanoff, both from the Alaska Native Tribal Health Consortium, a teleconference/webinar titled "Observing Local Permafrost Change" was organized and delivered on August 20, 2013 to the members of the Local Environmental Observers Program and to other members of the community that participated in this Webinar.

One more webinar was organized by Western Alaska LCC where we presented the major results of this project. This webinar was held on November 20, 2013.

We also reported on our major results from this project during the Conference in Kotzebue on April, 2014 as an oral presentation.

Based in part on the experience and knowledge obtained during the implementation of this project, the following presentations were prepared and delivered:

March 14, 2012. Public Lecture at the Joint Science Day with Cryosphere Group of University of Innsbruck, CliC SSG-VIII, 12-15 March 2012, Innsbruck, Austria

March 30, 2012. Public Lecture at the Geology and Geophysics Seminar, UAF

April 23, 2012. Interview to German Radio during the IPY 2012 Conference: From Knowledge to Action, 22-27 April 2012, Montréal, Canada

June 20, 2012. Public Lecture at the University of Oslo, Norway

August 3, 2012. Observations and Modeling of Changes in Permafrost, Invited Oral presentation at the Toolik Lake Research Station Strategic Planning Workshop, August 2-4, 2012, Portland, Oregon

August 5, 2012. Meeting with a delegation of permafrost scientists and ecologists from China to explain our approaches to development of Distributed Permafrost Observatories in Alaska, including the fabrication of necessary equipment and drilling techniques

November 29, 2012. Filmed interview with the Channel 11 Fairbanks Evening News

March 14, 2013. Live telephone interview with an Australian radio station

May 14, 2013, U.S. Department of State Meeting with the U.S. Climate Negotiation Team, Washington, DC

June 5, 2013. Keynote lecture at the 4th Annual Workshop of the Permafrost Network of Expertise, 5-8 June, Fairbanks, Alaska

August 2, 2013. Interview with Wendy Koch, USA Today reporter

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