Long-term observations of active layer thawing and freezing, Barrow, Alaska

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ABSTRACT
Beginning in the early 1950s and continuing to the present, Barrow has been a region of numerous active layer and permafrost investigations. The average active layer thickness (ALT) obtained by physical probing at two, permanently gridded sites for the periods (1962 -1970) and (1991-present) was 35 cm, with mean minimum of 22 cm in 1992 and a maximum of 45 in 1968. Additional 1970s ALT data from the nearby U.S. Tundra Biome sites are compared with these long-term data. ALT values based on measured soil temperatures from 1997 to present ranged from 33 to 63 cm with final freezeback dates ranging from October 9 to November 12. Average ALT calculated from modeled soil-permafrost temperatures (1924 to present) was 34 cm with a minimum of 18 cm in both 1945 and 1969 and a maximum of 54 cm in 1998. Modeled ALT values are comparable to those determined by temperature point measurements.

RÉSUMÉ
Des années 1950 jusqu'à présent, Barrow est une région où de nombreuses investigations de la couche active et du pergélisol ont été faites. L'épaisseur moyenne de la couche active (ALT) obtenue par des sondages à deux sites quadrillés permanemment, de 1962 à 1970 et de 1991 à aujourd'hui, était de 35 cm. L'épaisseur moyenne minimale était de 22 cm en 1992 et l'épaisseur maximale de 45 cm en 1968. Les valeurs d'ALT basées sur la température du sol, de 1997 jusqu'à aujourd'hui, sont comprises entre 33 et 63 cm avec des dates de regel final allant du 9 Octobre au 12 Novembre. L'ALT moyenne calculée selon la température du sol-pergélisol modélisé (1924 à 2015) était de 34 cm; le minimum était de 18 cm (1945 et 1969) et le maximum de 54 cm (1998). Les valeurs d'ALT modélisées sont comparables à celles déterminées par les points de mesures de température.

1 INTRODUCTION

Understanding variations in active layer thickness (ALT) over multi-decade periods is critical to both engineering and environmental interests. This paper reports on the collective active layer measurements obtained over the past six decades near Barrow Alaska. In the early 1950s investigations by the U.S. Geological Survey (Brewer 1958) demonstrated the influence of lakes, ocean and buildings on near-surface permafrost temperature regimes and illustrated the characteristic zero curtain during the annual freeze-thaw cycles of 1951 and 1952. During the 1960s, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) frozen ground projects included the establishment of a series 10 x 10 m plots along a 2.1 km transect that spanned multiple land cover types and microtopographical units that comprise the generally wet tundra landscape of the area (Brown 1969, Brown and Johnson 1965). ALT was probed seasonally between 1962 and 1970, and observations were resumed on an annual basis beginning in 1991 under the Circumpolar Active Layer Monitoring (CALM) program. In the early 1970s under the International Biological Programme (IBP) Tundra Biome studies, thaw measurements were conducted at a series of plots, grids and shallow ponds. (see section 3.2 for additional background). In the early 1990s the CALM program established a 1000 x 1000 m grid near the CRREL sites, and it has since probed both sites on an annual basis. In conjunction with the CALM program, the Natural Resources Conservation Service (NRCS) established in 1997 a soil temperature site in close proximity to the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL). In 1998, the International Tundra Experiment (ITEX) initiated a program of year-round soil temperature measurements (Hollister et al. 2006, 2008). Starting in 2002 soil and near-surface permafrost temperature measurements began under the Global Terrestrial Network for Permafrost (GTN-P) at two new boreholes sites (Romanovsky et al. 2002, Yoshikawa et al 2004). Other more recent projects with active layer measurements

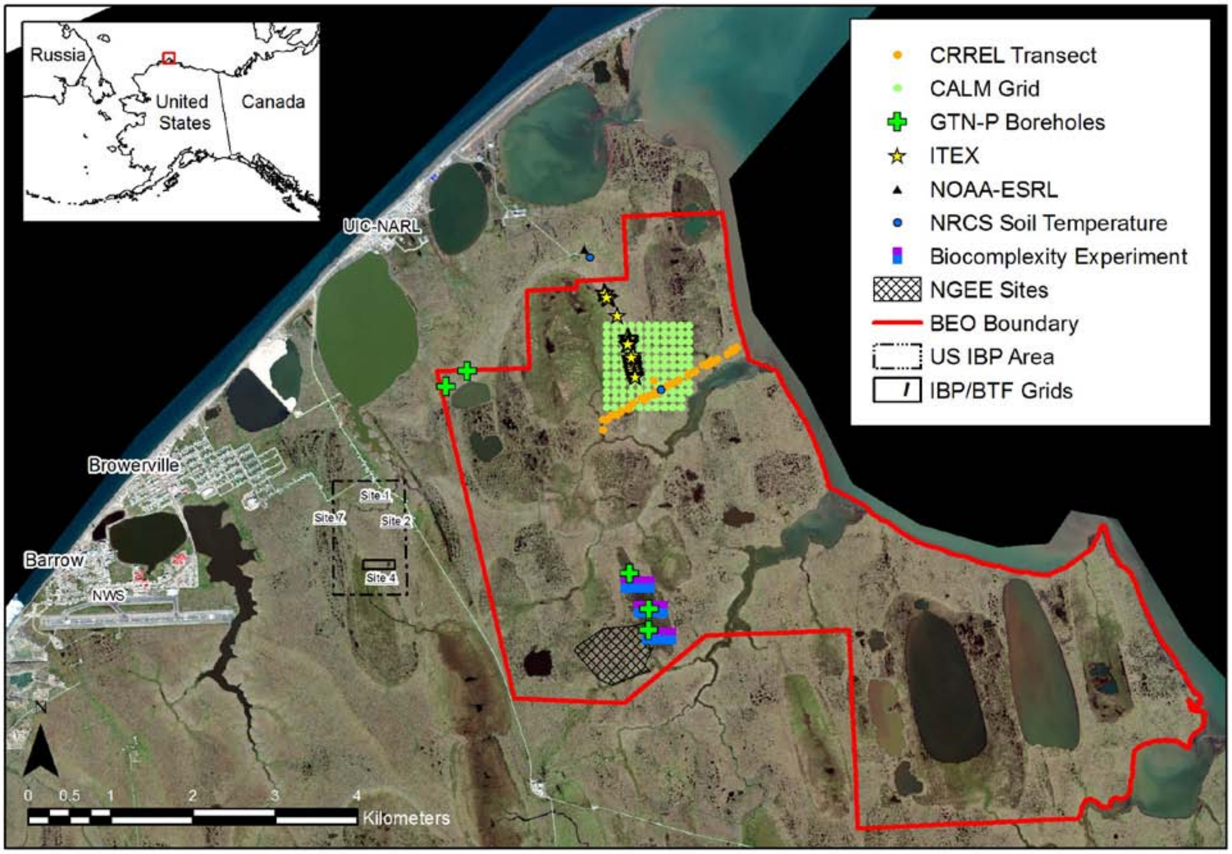

Figure 1. Location of research and active layer thickness sites in the Barrow, Alaska area.

include the National Science Foundation (NSF) Biocomplexity (Zona et al. 2012) and Back to theFuture (BTF) (Lara et al. 2012) projects, and the Department of Energy (DOE) Next-Generation Ecosystem Experiments (Hubbard et al. 2013, Gangodagamage et al. 2014). In August 2013 Shaeffer et al. (2015) explored the use of the Remotely Sensed Active Layer Thickness (ReSALT) product that uses Interferometric Synthetic Aperture Radar technique to measure seasonal surface subsidence and inferred ALT (see Appendix 1 for inventory of projects).

Figure 1 shows the locations of many of the active layer sites. With the exception of the Tundra Biome studies, long-term monitoring sites are located on the Barrow Environmental Observatory (BEO), a 7466-acre scientific reserve established in 1992 on lands owned by the Ukpeaġvik Iñupiat Corporation. Brown (2001) presented a historical review of terrestrial bioenvironmental research activities at Barrow during the period 1957-1997 that included results of some of the active layer measurements.

This paper provides an updated summary of Barrow ALT observations and trends and reports for the first time an analysis of soil temperature data for the determination of dates of complete freezeback of the active layer. We also compare annual modeled ALT data with measured values.

2. METHODS

The majority of ALT measurements at Barrow were obtained by probing, i.e., by inserting a narrow-diameter metal rod into the thawed soils to the point of refusal, interpreted as the position of the upper limit of ice-bonded sediment. Maximum summer thaw generally occurs by mid-August. Soil temperature in the uppermost permafrost is recorded at varying depth intervals with thermistors imbedded in a 1.2 m long rod, or by individual thermistors positioned at intervals along improvised support rods. Temperatures in shallow boreholes are measured by lowering a thermistor down a narrow-diameter, nonfreezing, liquid filled polyethylene tube. Methodological details can be found in the references cited in the bibliography; CALM's measurement protocols are detailed in Nelson and Hinkel (2003).

3. RESULTS

3.1 SUMMARY AND UPDATE OF PUBLISHED RESULTS

This report builds on the 2010 Barrow publication documenting recent decadal variations in ALT in moisture-controlled landscapes (Shiklomanov et al. 2010) and includes an extensive literature review.

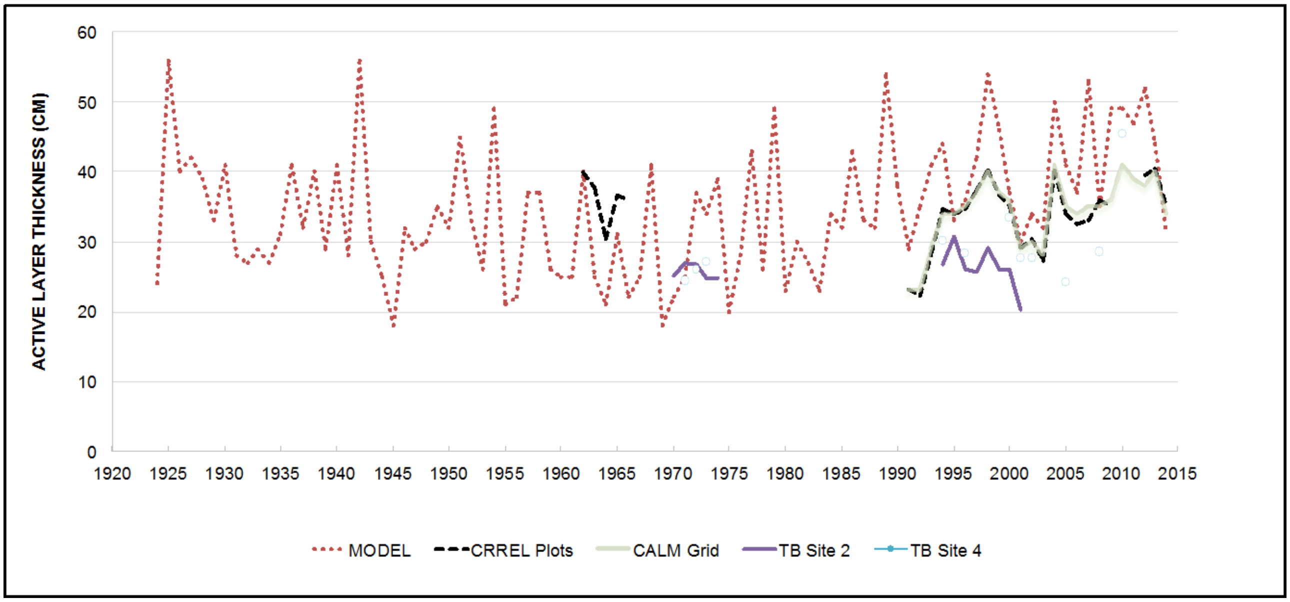

Figure 2. Modeled and observed active layer thickness, Barrow, Alaska.

Earlier papers, published in the Proceedings of the International Conferences on Permafrost (McGaw 1978, Nelson et al. 1998, 2008) and in journals (Kelley and Weaver 1968; Hinkel and Nelson 2003) have provided details about active layer observations at Barrow. Brewer and Jin (2009) concluded that observations in Arctic Alaska over the last 50 years indicate that there has been a net warming of the upper portion of the permafrost temperature profile but no noticeable thawing of the permafrost had occurred. This recent warming has been well documented (Romanovsky et al. 2002).

Figure 2 includes a summary of the average ALT record for the Barrow CALM grid and CRREL plots, over the period of record. Following Shiklomanov et al. (2010), the ALT record on the CALM grid shows large interannual variability, but no clear trend from 1995 to 2014. The spatial variability of ALT shows a large degree of co-variation with the thickness of the organic layer. ALT is also closely related to landscape type (low-centered and high-centered polygons, drained lake bottom, beach ridge), a complex integration of vegetation, substrate properties, soil moisture, and microtopography. The record from the CRREL plots shows a distinct decrease from the deeper ALT in the 1960s to more shallow values in the early 1990s. From the mid 1990s onward both mean annual values and interannual variability are similar for the CALM grid and CRREL plots.

Nelson et al. (1998) postulated that the active layer exhibits Markovian behavior ascribable to breaching or penetration through and subsequent re-formation of the ice-rich layer at the top of permafrost. Conceptual developments by Shur et al. (2005) recast this phenomenon in terms of a *transient* or *transitional* layer that, owing to its ice-rich nature, resists very large short-term increases in ALT. The transient layer, where it exists, effectively freezes and thaws at a very different temporal interval than the active layer or permafrost, and cycles between an alternating status of permafrost and seasonally frozen at intervals measured in decades to millennia.

Shiklomanov et al. (2013), at other study sites on the Alaskan North Slope, demonstrated that penetration of thaw into the ice-rich transient layer and accompanying thaw consolidation result in subsidence at the ground surface that is not apparent from observations based only on probing or temperature. Measurements near Prudhoe Bay and Sagwon, showed that the addition of subsidence values to ALT resulted in pronounced improvements in the statistical correlation between air temperature and the depth of thaw. Moreover, when subsidence measurements were added to ALT measurements, a steady increase in thaw depth occurred over the 11-year period of record. Unpublished subsidence data from several of the Barrow CRREL plots and nearby frost boils indicate that a similar relation holds at Barrow (D. Streletskiy, personal communication, 2015).

3.2 TUNDRA BIOME SITES

During the 1970-1974 field seasons, Barrow was the intensive site for the U.S. IBP Tundra Biome program. In Canada, the intensive IBP site was the Truelove Lowlands on Devon Island with permafrost and active layer investigations by R.J.E. Brown (1977). The primary objective of the U.S. program was to develop a predictive understanding of how a wet Arctic tundra ecosystem functions. The soil thermal studies included models and their validation (Nakano and Brown 1972, Ng and Miller 1977, McGaw, Outcaalt and Ng 1978). Numerous publications and dissertations and three synthesis books document the research designs and

Table 1. Average end of summer Active Layer Thickness (cm) on US IBP Tundra Biome plots and grids (data from Brown et al. 1974, unless otherwise indicated).

1a. Ordination plots (1973 data, Webber 1978)

Nodum	I	II	III	IV	V	VI	VII	VIII
No. plots	1	5	11	6	6	8	2	4
8/16/1972	27	44	32	27	25	26	37	76
8/18/1973	37	54	36	32	32	32	37	75
8/13/1974	32	50	31	28	28	30	34	74

1b. Control plots (number of plots probed)

Site 2	ALT	Site 4	ALT
8/13/1970 (10)	25		
8/14/1971 (10)	27	8/6/1971 (12)	25
8/14/1972 (10)	27	8/14/1972 (13)	26
8/14/1973 (10)	25	8/14/1973 (13)	27
8/13/1974 (10)	25		
8/26/1994 (7*)	27	8/26/1994 (7)	30
8/29/1995 (7)	31		
8/18/1996 (7*)	26	8/18/1996 (6)	28
8/9/1997 (10)	26		
8/22/1998 (10)	29	8/8/2010 (10**)	45
8/18/1999 (10)	26		
8/18/2000 (9)	26		
8/23/2001 (10)	20		

1c. Site 4 grids

390 x 110 m grid	ALT	34-m long grid	ALT
8/13/1973	26	8/12/1973	27
		8/23/2000**	33
8/24/2001**	24	8/11/2001**	28
8/12/2008**	29	8/2/2008**	27
4 rows, 40 points each		3 rows, points at 50 cm	

* F.E. Nelson; 1995; 1997-2001 data by CALM

* * Craig Tweedie

results (Brown et al. 1980; Hobbie 1980, Tieszen 1978).

The U.S. Tundra Biome research design included a series of repetitive observations on plots of various sizes and across several grids, as well as a series of experiments in shallow ponds. The locations of the four major sites are shown in Figure 1. A series of 43 vegetation plots or ordination nodum (Webber 1978) were distributed across the 110 hectare area, which was also mapped for soils, landforms, and vegetation (see Brown et al. 1980). Except for some selective reporting of ALT (see Brown et al. 1980 and Webber 1978), there are no publications in the open literature exclusively addressing the Biome program's ALT observations. A seven-page, internal U.S. Tundra Biome Data Report (Brown et al. 1974) presented summary results for the terrestrial sites. Many of the plots were remeasured in recent years under the CALM and Back to the Future projects, and some of these comparative measurements are reported in Table 1.

The 43 ordination plots (1m x10m) characterize the range of ALT across the entire study area (Table 1a). During the 1972-74 summers, the maximum seasonal ALT ranged between 25 and 74 cm. ALT was greatest in 1973 at all ordination plots.

Thaw measurements on the ten Site 2 control plots (6m x 6m) offer the best time series (1970 -1975), and subsequently were supplemented with data obtained by the CALM project (1994 to 2001) (Table 1b). The 1970 summer data also include measurements on ten of the 1960s CRREL plots, facilitating direct comparison of these data with those from the 1990s and later.

Average ALT on the experimental sites was generally less than that observed at the CRREL and CALM sites (Fig. 2). During the Tundra Biome period, late-season ALT was relatively uniform on the Site 2 plots and less than the historical data from the CRREL and CALM sites. This area is relatively uniform, non-polygonized terrain with average values for the 10 plots falling within a narrow range (25-27 cm). For the same plots from 1995 to 2001 average thaw ranged between 20 cm in 1998 and 29 cm in 2001. These shallow and deep thaw summers correspond to similar extreme values on both the CRREL and CALM plots (Fig. 2).

Several grids or composite transects were located on Site 4 (Table 1c), an area characterized by a range of well-developed polygonal ground morphology (Walker 1974, Lara et al. 2012). A larger range in ALT would be expected on this highly variable terrain. However, as on Site 2 the average range of ALT for both grids is relatively narrow; 24-29 cm for the large macrotopographic grid and 27-33 cm for the microtopographic grid. The deeper value on the microtopographic grid for year 2000 of 33 cm is anomalous and may reflect changes in moisture or subsidence on this site.

During the Tundra Biome years ALT transects under the shallow ponds were measured (Hobbie 1980). Despite a decrease in pond area, no statistically significant changes in water depth were found between the 1970's and 2010's in IBP pond C. However, thaw depth was on average 11cm deeper by the end of August in 2011-2013 as compared to 1970-1972 (Andresen, and Lougheed 2015).

In summary, we find the ALT for the US Tundra Biome sites during the 1970s and more recently are less than ALT occurring on the CALM and CRREL sites and show less intraseasonal variation, possibly a reflection of subtle difference in terrain characteristics.

3.3 MODELLED VS OBSERVED

Changes in ALT can be modeled using a numerical permafrost model. The GIPL2 model of the University of Alaska's Geophysical Institute Permafrost Lab was used to reconstruct Barrow permafrost temperatures and ALT dynamics at a specific location near the North Meadow Lake (NML2) site.

The model and the procedure of its application were described in previous publications (Romanovsky et al., 2002 and 2007; Nicolsky et al., 2007). The model was calibrated using soil temperature data from a shallow (one meter) thermistor cable obtained by Ken Hinkel (Hinkel at al., 2001) at a Barrow site with surface conditions very similar to the NML2 site. No data from the NML2 site were used for the calibration. The daily air temperatures and snow cover thickness during the entire period of measurement (1924-2014) at the Barrow meteorological station were used as a climate forcing for this calibrated model. A time series of ALT for the 1924-2014 time interval was obtained (Fig. 2).

To validate the modeling results the calculated ALT was compared with the measured values at the same site. The measured values were derived from the high-resolution ground temperature measurements that began at this site in 2002. From 11 years of comparison (measured data in 2005 and 2006 were not available), six years show a difference of 3 cm and less and two years less than 5 cm difference. Only in 2007, 2009, and 2014 was the difference between calculated and measured ALT more than 5 cm. From this comparison it seems that the model has a tendency to under predict ALT during years with cold summers. One of the explanations may be the use of the same thawed soil thermal conductivities for all summers in the model. In reality, the colder summers are usually wet and the thawed thermal conductivity may be larger than during warmer and drier summers. The higher soil thermal conductivity may compensate for the lower summer temperatures and the ALT may not be as low as the model predicts.

Modeled ALT shows no significant trend during the entire 1924-2014 period (Fig. 2). However, there is a noticeable decrease in ALT from 1920s toward the 1960s. Since the 1970s, the ALT increased gradually with some decadal time-scale variability. It also can be concluded from the modeling results that average ALT during the last ten years was larger than any other decade during the last 90 years.

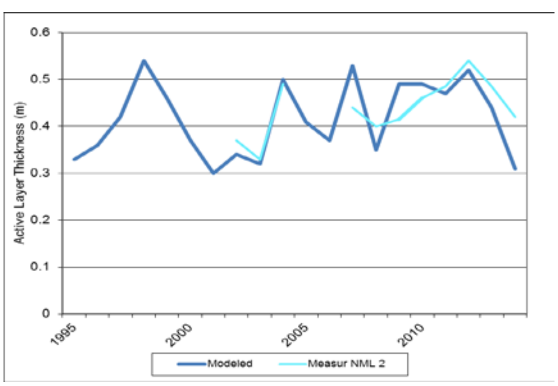

Figure 3. Comparison between calculated (dark blue) and measured (light blue) ALT at the NML2 site.

The Barrow weather station records indicate the time period for the first 30 years until about 1950 was relatively warm, specially the 1920's (Wendler, Moore, and Galloway 2014). This warm period was followed by a cold period of about 25 years until the mid-1970's. The time period from 1976 until present observed a strong and fairly consistent warming of 2.7°C. All months, with the exception of January, display a warming, which is especially strong in autumn (6.3°C), followed by spring (1.8°C), summer (1.5°C) and winter (1.2°C). October displays the maximum temperature increase (7.2°C) with a November increase of 6.1^{0}C. During the period of the last 34 years annual decreases in sea ice coverage by 16% for the Chukchi Sea and 14% in the Beaufort Sea were observed.

3.4 ANNUAL SOIL FREEZEBACK

At Barrow, soil freezing can start in early- to mid-September and extend into November. The freezeback process is characterized by development of a “zero curtain,” an effect by which the temperature of the unfrozen soil remains constant at or very close to 0^{o}C owing to the latent heat of fusion and other nonconductive heat-transfer processes (Outcalt et al., 1990). The duration of the effect varies from year to year depending on the Fall climate and to some extent on interannual differences in soil moisture. Brewer (1958) illustrated the zero curtain operating in 1951 and 1952 at the 25 cm depth. For 1951 the zero curtain occurred between late September to early November and for 1952 from early September to early October. Those observations are similar to those seen in recent decades. Variations in the freezeback of the active layer have been previously reported by Romanovsky et al. (2003) for several other locations on the Alaskan North Slope and more recently at the U.S. Geological Survey's climate monitoring sites (F. Urban, personal. communication. 2015; see also DOI: 10.3133/ds892).

As noted above (Wendler et al. 2014), Fall air temperatures at Barrow have increased dramatically, a function likely related to delayed freezing of the adjacent Arctic Ocean. These warmer temperatures may result in longer periods of active layer freezing as measured by the duration of the zero curtain effect. For this study, soil temperatures were analyzed at four Barrow locations (NML2, two ITEX sites and NRCS-CALM; see Figure 1 for general locations) using -0.2 as the zero curtain threshold.

At the NRCS site, where average ALT from 1997 to 2013 was 52.4 cm, the earliest freezeback was October 9, 2001 and the latest dates were between November 1 and 13 in the last four years of record (2010-2013) (Table 2). For NML2, the site of the permafrost temperature profile, ALT between 2002 and 2014 averaged 44.2 cm with essentially the same November freezeback dates as the NRCS site.

Average ALT for the dry and wet ITEX sites between 1997 and 2014 are based on readings at 24 control plots (Hollister et al. 2006, 2008). The average thaw for the dry sites was 81.4 cm and for the wet sites 44.6 cm. Freezeback for these drier sites that are underlain by fine gravel ranged from early to late October. The ITEX wet sites had the latest freezeback dates with most years extending into late November. Freezeback for the last four years of record exceeded the NML2 and NRCS by about three weeks with the

Table 2. Freezeback dates for Barrow soil temperature sites.

Year	NRCS ALT[1]	NRCS	NML ALT[1]	NML	BD ALT[1]	ITEX BD-1	ITEX BD-2	BW ALT[1]	ITEX BW-1	ITEX BW-2
1997	61.4	10/25/1997	ND	ND	92.3	ND	ND	50.0	ND	ND
1998	63.4	10/30/1998	ND	ND	ND	10/19/1998	10/18/1998	ND	11/16/1998	11/22/1998
1999	59.2	10/16/1999	ND	ND	91.8	10/8/1999	10/4/1999	53.9	10/26/1999	10/28/1999
2000	56.3	10/25/2000	ND	ND	80.5	10/7/2000	10/5/2000	48.3	10/21/2000	11/20/2000
2001	45.6	10/9/2001	ND	ND	80.4	10/4/2001	10/4/2001	43.0	10/21/2001	10/22/2001
2002	50.8	10/23/2002	37	10/19/2002	32.8	10/16/2002	10/11/2002	33.5	11/11/2002	11/17/2002
2003	39.1	10/16/2003	33	10/15/2003	66.0	10/13/2003	10/12/2003	40.0	10/28/2003	10/28/2003
2004	58.2	10/28/2004	49	10/25/2004	ND	10/14/2004	10/11/2004	ND	ND	ND
2005	54.5	10/16/2005	ND	ND	ND	10/7/2005	10/2/2005	ND	10/19/2005	10/27/2005
2006	49.0	10/28/2006	ND	10/27/2006	85.8	10/16/2006	10/14/2006	39.7	ND	ND
2007	51.7	10/24/2007	44	10/25/2007	91.5	10/11/2007	10/10/2007	44.3	11/27/2007	11/29/2007
2008	45.7	10/20/2008	40	10/23/2008	80.8	10/8/2008	10/7/2008	39.4	ND	11/21/2008
2009	48.2	10/20/2009	42	10/20/2009	88.4	10/8/2009	10/7/2009	43.6	ND	11/7/2009
2010	51.1	11/1/2010	46	11/2/2010	93.0	10/27/2010	10/29/2010	46.7	ND	11/24/2010
2011	52.5	11/5/2011	49	11/7/2011	94.5	10/26/2011	10/27/2011	50.6	ND	11/25/2011
2012	54.0	11/11/2012	54	11/12/2012	89.5	10/24/2012	10/21/2012	48.6	11/28/2012	12/2/2012
2013	50.5	11/3/2013	49	11/5/2013	89.8	ND	ND	51.2	ND	11/26/2013
2014	ND	ND	42	10/29/2014	64.0	ND	ND	36.8	ND	ND
Ave	52.4		44.1		81.4			44.6		

[1] ALT in cm

2012 zero curtain extending to December 2. These later dates may be furthered enhanced by a deeper snow cover in contrast to the drier and more exposed upland sites.

4.0 DISCUSSION AND CONCLUSIONS

Results of multi-decadal measurements of ALT in the Barrow, Alaska, area show large interannual variability, but no clear-cut trends over the past two decades. The 1960s ALT data from the CRREL plots are not unlike those from the 1990s, although both the early 1990s and 2000s had annual values of ALT smaller than those of the 1960s. For all practical purposes the average annual CRREL and CALM measurements from the 1990s onward are identical. Over the same period, the temperature of permafrost has increased several degrees at the depth of zero amplitude.

For the first time we can compare the early 1970s, the IBP Tundra Biome years, with the overall ALT record. Although considerable variability occurs in ALT and terrain types across the IBP research area, 1970s values for the Site 2 control plots have a relatively thin active layer with a narrow interannual range. The variation in the 1990s IBP thaw generally follow the annual range seen in observations from the CALM and CRREL sites.

It is important to note that our average values mask the variability in ALT due to changes across small distances in micro-relief, vegetation, and soil organic matter and related soil moisture conditions. This also applies to modeled ALT, where good agreement is obtained between modeled thaw when compared with ALT determined from point measurements of temperature.

Analysis of the Barrow weather data reveals a significant warming in the months of October and November. The question is how this warming affects the annual refreezing of the active layer. Based on our available observations of soils temperature, a delay of freeze back into November was measured in four out of the last five years.

The role of the ice-rich transient layer and related subsidence in controlling ALT has yet to be fully understood. As indicated, at several sites east of Barrow, average ALT and summer air temperatures correlate well when subsidence has been considered. In a recent paper on the shallow Biome ponds, ALT was reported to be 10-20 cm greater as compared to the 1970s values. We might speculate that the transient layer beneath the ponds may have diminished over the decades, thus facilitating deeper thaws.

The transient layer freezes and thaws at a very different temporal interval than the active layer or permafrost, and cycles between perennially frozen ground and seasonally frozen soils at intervals measured in decades to millennia. Ongoing and future observations and research are needed to more completely understand the role of the transient layer and its relation to ALT (e.g., Bockheim and Hinkel 2005). The CALM program is actively investigating this topic at Barrow.

ACKNOWLEDGEMENTS

Prior to 1980 logistical support for field projects at Barrow were provided by the Naval Arctic Research Laboratory. These projects included the CRREL studies and the U.S. Tundra Biome program. In 1992, the landowners, Ukpeagvik Iñupiat Corporation (UIC), approved the creation of the Barrow Environmental Observatory (BEO). During the 1990s and into the 2000s, the Barrow Arctic Science Consortium (BASC), a not-for-profit organization dedicated to scientist/community collaboration, was designated by UIC to manage the BEO and provide logistical support to projects with funding from the U.S. National Science Foundation (NSF). We acknowledge UIC for use of its lands for research and collectively all those involved in the collection of field data over the years (including CRREL, Tundra Biome, ITEX, and CALM personnel). Figure 1 was prepared by Stephen Escarzaga and Ryan Cody.

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Appendix 1. Historical and current ALT projects and data sets for Barrow, Alaska.			
Project/ data	Years	Parameter	Primary References*
USGS	1950s	temperature	Brewer unpub., 1958, Brewer and Jin 2009
CRREL	1962-66, 68, 70, 1991 to present	probe	Nelson et al. 1998, 2008 *
IBP Tundra Biome	1970-74**	probe	Tundra Biome Data Report 74-18 (Brown et al. 1974)
IBP Tundra Biome ponds	1970-72; 2011-13	probe	Hobbie 1980; Andresen and Lougheed 2005
CALM	1993 to present	probe	Shiklomanov et al. 2010
ITEX	1994 to present	probe & temperature	Hollister et al. 2006, 2008*
NRCS	1995 to present	temperature	Shiklomanov et al. 2010
GTN-P	2002 to present	temperature	Romanovsky et al. 2002 */ Yoshikawa et al. 2004
Biocomplexity	2006 to 2011	probe & temperature	Shiklomanov et al. 2010
Back to the Future	1972-2010	probe	Lara et al. 2012
NGEE	2012 to present	temperature	Hubbard et al. 2013, Gangodagamage et al. 2014
Model	1924 to present	modeled ALT	Romanovsky et al. 2002
Legacy beach ridge	1993 400m transect	probe	Elias et al. 1996
Korando beach ridge transect	1954 (resampled 1960s, 1990s)	probe	Korando 1954
Drew beach ridge transect	1958	probe	Drew et al. 1958
* ALT and/or permafrost data presented and discussed in 2010 paper (Shiklomanov et al.)			
** remeasured 1994-2001; MSU/UTEP: 2000, 2001, 2008, 2010			