



Future Climate Change and Its Threat to Archaeological Resources in Gates of the Arctic National Park

An Annotated Bibliography

Cultural Resource Report NPS/GAAR/CRR—2016/001



National Park Service archaeologists survey a recently drained lake along the Okokmilaga River in 2012. Photograph by: Chris Ciancibelli

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Abstract

This annotated bibliography includes short summaries of more than 80 peer-reviewed publications related to climate change in Arctic and Subarctic northern Alaska and is intended to provide managers of parks in Arctic and Subarctic settings with information needed to focus and prioritize resource inventory and treatment efforts. Gates of the Arctic National Park and Preserve is the focus of this literature survey. The park contains significant archaeological resources that are threatened by processes influenced by a changing global climate. At 8.5 million acres and situated at a geographic crossroads—spanning Arctic and Subarctic, tundra and forest zones, and mountain and riverine environments—Gates of the Arctic is a useful case study for examining not only human adaptations and human-environment interactions over many millennia, but also recent change that affects preservation of the archaeological record. The most important natural and geomorphic processes relevant to archaeological resource management include changes to lakes, mass movements, soil temperature, aeolian sediment deposition, glaciers and snowfields, wildfire, vegetation, human activities, and rivers. A summary table describes both benefits and threats posed to archaeological resources by climate-related processes.

Acknowledgements

Funding for this work derived from the National Park Service Cultural Resources fund. Dan Odess and Ted Birkedal were instrumental in conceiving of the need for a synthesis of climate change effects on archaeological resources in an Arctic and Subarctic setting. Peer-review by Dave Swanson filled important gaps and deepened the treatment of key topic areas.

List of Terms

Active Layer Detachment

Aeolian

Ataxitic cryostructure

Bathymetry

Boreal

Carbonate

Chronozone

Cosmogenic

Cryosols

Cryostratigraphies

Debris lobes

Dendrochronology

Dryas

Eolian

Geomorphological

Glacio-lacustrine or glaciolacustrine

Ground-ice slumps

Holocene

Hydrogeomorphic

Inupiat

Landsat

Laurentide

Lichenometry

Lithologic

Lobate

Loess
Lowstands
Macrophytes
Morainal
Morphometric
Nivation
Ontogeny
Orthophoto
Paleoclimate
Paleoecological
Peatlands
Permafrost
Photogrammetric
Pingo
Retrogressive Thaw Slump
Revegetated
Slump floor
Talik
Thaw Slumps
Thermokarst
Treeline
Waterbody
Yedoma

List of Acronyms

ACP (Arctic Coastal Plain)

ALDS (active layer detachment slides)

AO (Arctic Oscillation)

Ca (calcium)

CALM (Circumpolar Active Layer Monitoring)

CE (Coastal Exposure)

DTLB (Drained Thaw Lake Basin)

GAAR (Gates of the Arctic National Park and Preserve)

GPR (Ground Penetrating Radar)

HI (Herschel Island)

IfSAR (interferometric synthetic aperture radar)

KA (thousand of calendar years)

LGM (Last Glacial Maximum)

LIA (Little Ice Age)

LIS (Laurentide Ice Sheet)

MAAT (mean annual air temperature)

m.a.s.l. (meters above sea level)

Mg (magnesium)

MWP (Medieval Warm Period)

NPR-A (National Petroleum Reserve – Alaska)

NPS (National Park Service)

P-H (Pleistocene-Holocene)

PDO (Pacific Decadal Oscillation)

RTS (retrogressive thaw slumps)

SEAD (Strategic Environmental Archaeology Database)

Sp (species)

TSS (total suspended sediments)

Introduction

Gates of the Arctic National Park and Preserve contains significant archaeological resources that are threatened by processes that are the result of a changing global climate. The archaeological record within Gates of the Arctic National Park and Preserve (Figure 1) is significant due to its high density of sites, great time depth, and excellent degree of overall preservation. With more than 1600 documented archaeological sites, Gates of the Arctic contains roughly a third of the total number of documented sites on National Park Service lands in the Alaska region. The sites span the duration of known human occupation in Alaska (about 12,000 years) and document events of local and national significance such as the initial stages of human settlement of the Americas and subsequent human adaptations to changing Arctic and Subarctic environments since the end of the last Ice Age. Park-associated communities have strong ties to archaeological resources as touchstones for their history and culture. These ties illustrate the ancient connections to these lands. At 8.5 million acres and situated at a geographic crossroads—spanning Arctic and Subarctic, tundra and forest zones, and mountain and riverine environments—Gates of the Arctic offers exceptional opportunities to study human adaptations and human-environment interactions over many millennia.

Recent surveys have documented widespread, but poorly understood impacts to archaeological sites and to landforms of the kind likely to contain undocumented archaeological deposits. Many of the impacts can be linked to climate change and include abrupt lake level changes, thawing permafrost, and melting alpine snow patches. Thermokarsting - changes in surface topography caused by the melting of subsurface ice - is one of the most widespread and significant changes happening to the landscape of northern Alaska and has major potential to affect archaeological resources since it destroys the substrate upon which the archaeological record is written.

In large, remote parks like parks like Gates of the Arctic it is essential that park managers have a means to focus and prioritize resource inventory and treatment efforts. This annotated bibliography is presented as one step in that direction. It includes short summaries of more than 80 peer-reviewed publications related to climate change in Arctic and Subarctic northern Alaska. While Gates of the Arctic and the Central Brooks Range are the primary geographic focus, the findings can readily be generalized to most interior, high-latitude settings throughout the circumpolar world. Focus here was given to identifying the key processes that contribute to landscape instability and change and which have potential to alter or destroy archaeological resources. This bibliography sets the stage for classifying lands according to their vulnerability to landscape change and prioritizing cultural resource inventories and treatments. A summary table describes the most important and relevant geomorphic processes and includes suggestions for monitoring their effects on archaeological resources.



Figure 1. Location of the Gates of the Arctic National Park and Preserve

Literature Reviews

Climate Change Reviews

Bowden, W. 2010. *Climate change in the Arctic—permafrost, thermokarst, and why they matter to the non-Arctic world. Geography Compass 4(10):1553-1566.**

This paper, geared to the non-Arctic community, presents an overview of the arctic environment, permafrost characteristics, and the role of thermokarst features as indicators of current climate change and as possible agents of future change. The paper discusses a limited selection of thermokarst landforms, but does not include information on rates of change or spatial distribution. The paper concludes with a section on thermokarsts in a changing Arctic from a systems perspective. A diagram of the role of thermokarst in the evolution of an arctic landscape in a warmer and wetter climate is also presented.

Francis, J. A., White, D. M., Cassano, J. J Gutowski, W. J., Hinzman, L. D., Holland, M. M., and Vörösmarty, C. J. 2009. *An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life. Journal of Geophysical Research 114 (G4).**

This paper deconstructs the arctic hydrologic system into inter-related components and graphically depicts their relationship with the biological system (marine and terrestrial). The paper also illustrates feedback loops and provides a visual assessment of the arctic hydrologic system in a seasonally ice-free state. Specifically, the authors' divide the hydrologic system into subsystems, emphasizing interactions that occur primarily within the atmospheric, oceanic, terrestrial, or global systems. Hydrological subsystems include factors such as cloud cover, total-column water vapor, surface air temperature, annual-mean net precipitation, and sea-ice thickness/area. Biological subsystems include human well-being, marine primary productivity, and land cover/ecosystem/vegetation. The paper found that the atmosphere drives much of the arctic hydrological cycle, both directly through net precipitation and indirectly through energy transfer processes that affect the surface. Furthermore, at least three of these subsystems have shown demonstrable change in recent decades, which have impacts on all components of the system.

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Hinzman, L.D., Bettez, N.D. Yoshikawa, K. 2005. *Evidence and implications of recent climate change in northern Alaska and other Arctic regions. Climatic Change 72(3): 251-298.*

This is an extensive review of the biophysical evidence of the Northern Alaskan region responding to climate change in the last 100 years, and how different landscape entities have and may interact in the future. In general, direct impacts to the terrestrial regions of the Arctic result from a longer thawing period combined with increased precipitation and/or a decrease of effective moisture. After the little ice age, warming in Northern Alaska ensued until a relatively cool episode between 1940 and 1970. After 1970, warming resumed. Permafrost borehole measurements reflect this climate oscillation. (Note that since this publication in 2005, the rate of climate warming has gone down at sites in the Brooks Range and Toolik Lake with the exception of the unusually warm 2007). There are significant annual temperature trends for a few northern Alaskan sites; the observations are generally limited to the latter half of the 20th century. Increased summer storminess and a decrease of effective moisture in the region are both unequivocally trending over time. Lake drying due to

permafrost degradation and decrease of effective moisture has been observed in the boreal region and the Seward Peninsula. However thermokarst pits and small ponds have formed in coastal plain marine terraces and the centers of drained lake basins over the same time period. This highlights the complexity of permafrost responses depending on soil type, local climate, soils, and topography. Lake alkalinity in the Arctic foothills region has gone up, with permafrost change probably responsible. River discharge has increased in much of Siberia despite a drying trend, which is partly attributed to glacier and permafrost degradation in the watersheds. Snow and glacier responses to climate change include an earlier snowmelt by 10-days in Barrow and nearly every glacier in the Brooks Range retreating since the LIA. Glaciers retreated faster during the warming since the 1970's. Increased shrubbiness and altitudinal/latitudinal advance of spruce tree line by about 10 km in some cases has been observed over the last 100 years. This highlights the long-term climatic trends that dictate these large-scale vegetation changes. These observations are corroborated by experimental warming plots near Barrow and Toolik Lake, which indicate warming causes an increase of shrubs and grasses and a decrease of moss and lichens. Burned area in the boreal forest has doubled in the last 20 years compared to earlier decades. These responses will have a series of interactions including positive and negative feedbacks for other landscape processes and the climate system. The take-home message of this review is that different processes respond differently to short term climate oscillations versus long term trends.

Osterkamp, T. E., and Romanovsky, V. E. 1996. Characteristics of changing permafrost temperatures in the Alaskan Arctic, USA. Arctic and Alpine Research 28(3): 267-273.*

The paper presents results on permafrost temperature readings in northern Alaska from 1983 to 1993 at both deep borehole and shallow ground temperature monitoring sites. The paper also simulates between the 1 m and 20 m deep readings to fill in data gaps associated with lack of monitoring equipment at intermediate depths. The data demonstrate that the permafrost in northern Alaska began to warm at the end of the 1980s.

Smith, M. W., and Riseborough, D. W. 1996. Permafrost monitoring and detection of climate change. Permafrost and Periglacial Processes 7((4): 301-309.*

This paper presents a climate-permafrost model that shows factors that affect temperature at the top of permafrost. The authors demonstrate that permafrost temperature monitoring may be confounded by variations in local surface and lithologic conditions, and by the annual air temperature regime. The authors suggest that 1) temperature monitoring should be concentrated at the permafrost table, 2) active layer depth is not necessarily an indicator of changes in the temperature of permafrost, and 3) that monitoring at exposed bedrock will produce the most direct signal of climate and ground thermal regime.

Thermokarst Lakes and Lake Change

Abbott, M. B., Finney, B. P., Edwards, M. E., and Kelts, K. R. 2000. Lake-level reconstruction and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects. Quaternary Research 53(2): 154-166.

This study describes an extensive lake sediment coring and seismic campaign to determine lake level changes that occurred in Birch Lake. Birch Lake lies in the Alaskan interior at 13.5 m deep. It currently overflows into the Tanana River, but the river has not influenced the lake level in the last

15000 years (radiocarbon years; 15 ka). This study describes the use of horizontally and vertically mapped lake sediment types, and erosional surfaces to determine a sequence of lake level change over the course the lake's ontogeny. Radiocarbon dates of wood, aquatic plant remains and pollen near the boundaries of these deep, shallow and marginal water lake sediment types determine the timeline for these lake transgressions. In addition to sediment descriptions that served to verify the seismic interpretations, geochemical and magnetics also separated out the lithologies based on modern sediment characteristics in the near and far shore environment. The timing of the lake level changes are in radiocarbon years. Birch Lake rose 12.7 ka to almost its current level, but dropped between 11.6 and 10.0 ka. After 10.0 ka the lake rose again to 9 meters below its current level, and then again it rose at 8.8 ka to its current level. There were periodic lowstands until it stayed consistently high after 4.8 ka. The chronozones of Birch Lake level described here are also seen in glacier advances (high lake level early on), increased aeolian activity (low lake levels), and increases in trees and shrubs (high lake levels). Several other lake level records from the region also show similar records of effective moisture during roughly the same periods. The authors point to teleconnections with the Laurentide ice sheet and moisture source proximity as the factors affecting Birch Lake levels before 12.7 ka. The fastest rates of sea level rise coincided with the two-step lake level transgressions in Birch Lake supporting this late glacial aridity hypothesis. The authors associate lower lake levels to the Younger Dryas chronozone, although they also attribute these to greater summer insolation causing increased evaporation. After the P-H transition, warmer conditions from greater insolation and increased storm tracks are to blame for higher lake levels. The age control on this study is rather tentative considering they are dating pollen and aquatic macrophytes, which could be subject to reworking and a reservoir effect respectively.

Arp, C. D., Jones, B. J., Urban, F. E., and Grosse, G. 2011. *Hydrogeomorphic processes of thermokarst lakes with grounded ice and floating ice regimes on the Arctic coastal plain, Alaska. Hydrological Processes* 25(15): 2422-2438.*

This paper uses field surveys, remote sensing, and aerial imagery that spans a 35 year period to assess the relative role of lake depth and level on rates of shoreline erosion of 13 thermokarst lakes on northern Alaska's Arctic coastal plain. The authors distinguished the 13 lakes based on depth and whether the lake experienced floating or grounded-ice conditions during the winter period. Shoreline expansion rates were determined by comparing late-1970s aerial photography with a 2002 orthophoto dataset. Expansion rates ranged from a mean of <0.2 m/yr in shallow lakes to 1.8 m/yr in the deeper lakes, while the mean annual expansion rate for all lakes was 0.9 m/yr. Mean lake depth and mean shoreline erosion rate were found to be correlated in this region. In general, the expansion of these lakes due to permafrost degradation masked the changes in water balance, with the exception of two shallow lakes with stable basins. Based on the modeling results of water balance, the authors indicated divergent longer-term patterns of water balance in shallow versus deep lakes in the region.

Arp, C. D., Whitman, M. S., Jones, B. M., Kemnitz, R., Grosse, G., and Urban, F. E. 2012. *Drainage network structure and hydrologic behavior of three lake-rich watersheds on the Arctic coastal plain, Alaska. Arctic, Antarctic, and Alpine Research* 44(4): 385-398.*

This paper highlights the importance of lakes and drained lake basins on the hydrological response in watersheds located on the low-lying Arctic coastal plain of northern Alaska. The study area

consisted of three primary watersheds: Fish Creek, Judy Creek, and the Ublutuoch River, with a total drainage basin area of ~4600 km². The majority of streams in these watersheds initiate from lake basins, approximately one-third of lakes are connected to the fluvial drainage network, and between 17 and 26 percent of watershed drainage density is through lake basins. Rainfall runoff and drought responses were also affected by the proportion of the landscape covered by lakes relative to drained thaw-lake basins (DTLBs). Comparison of both snowmelt and base flow recession from a broader set of Alaskan North Slope watersheds showed little relationship to drainage area, but significant variation was accounted for by static lake area extent. This high and varied level of stream-lake connectivity likely plays a role in the distribution of aquatic ecosystems and fish communities across this landscape.

Burn, C. R., and Smith, M. W. 2006. Development of thermokarst lakes during the Holocene at sites near Mayo, Yukon Territory. Permafrost and Periglacial Processes 1(2): 161-175.*

This paper describes the formation of thermokarst lakes in the boreal forest region of the Yukon Territory using ground surveys, remote sensing, and dendrochronology. The paper describes the growth of thermokarst lakes through analysis of aerial photography and tree-ring series obtained from submerged trees in the expanding lake margins. Table 1 presents the mean axial growth rate of 16 thermokarst lakes. The mean growth of lakes along their long axis was 0.7 m/yr and it was 0.5 m/yr for their short axis. The maximum observed expansion rate was 1.2 m/yr. The authors noted that the expansion rate of lakes is likely not constant from year to year and, that during particularly warm summers, stable banks may be reactivated and lake expansion may accelerate. Tree ring analysis and measurements of lake talik thickness indicate that the lakes likely formed in the mid-1800s. Estimates to talik formation indicated that vertical degradation of permafrost on the order of 0.5 to 1 m/yr. The authors provide a context in which to interpret the formation of thermokarst lakes in the region throughout the Holocene and suggest that these lakes likely initiated following a forest fire.

Chen, M., Rowland, J. C., Wilson, C. J., Altmann, G. L., and Brumby, S. P. 2012. Temporal and spatial pattern of thermokarst lake area changes at Yukon Flats, Alaska. Hydrological Processes. Available at: <http://onlinelibrary.wiley.com/doi/10.1002/hyp.9642/full>*

This paper provides further evidence that lakes in the Yukon Flats region of Alaska have dynamic surface areas. The authors extract closed basin lakes from Landsat data acquired between 1984 and 2009 for a 422 km² study area. The authors show that 80 percent of the variation in surface water area was explained by local water balance and mean temperature following snowmelt. Nearly 14 percent of the change over the study period was deemed to represent long-term change. The authors conclude by hypothesizing that the majority of the lake change was accounted for by the presence or absence of ice-jam flooding.

Grosse, G., Jones, B. M., and Arp, C. D. 2013. Thermokarst lakes, drainage, and drained basins. Treatise on Geomorphology 8: 325-353.*

In this study, the authors summarize literature on thermokarst lake dynamics; in particular how they form, what their pan-Arctic distribution is, and their morphometric, physical and hydrological characteristics and dynamics. In addition, thermokarst lake drainage is highlighted as an important process in the thermokarst lake cycle of many lake-rich permafrost landscapes. The authors describe

processes which may result in drainage and what processes occur after drainage in basins. A new map of potential thermokarst lake distribution in the Arctic and another map of lake orientation are presented.

Hinkel, K. M., Sheng, Y., Lenters, J. D., Lyons, E. A., Beck, R. A., Eisner, W. R., and Wang, J. 2012. Thermokarst lakes on the Arctic coastal plain of Alaska: Geomorphic controls on bathymetry. *Permafrost and Periglacial Processes* 23(3): 218-230.

This study summarizes the bathymetry of thermokarst lakes across Alaska's Arctic coastal plain in relation to surficial sediments and topography. The authors used lake sensors to estimate water depth and GPS-enabled sonar to collect detailed bathymetric data during the summer months of 2008-2010. Lake depth varied in proximity to the coast. For instance, coastal lowland lakes that developed in marine silts tended to be shallow (~2 m) and of more uniform depth than those developed in fluvial and aeolian sands. Further inland, lakes formed in ice-poor aeolian sand deposits and were generally ~1 m deep, but had deeper central pools (2-5 m). Lakes in the ACP-Arctic Foothills transition zone developed in loess uplands that are extremely ice-rich. Residual lakes inside old lake basins were generally uniformly 2-4 m deep, but at times contained deeper (6-9 m) pools where the expanding lake encroached on the upland at eroding bluffs. The authors speculate these deeper pools were formed by ground subsidence from thawing ice-rich permafrost above ice wedges. The data presented can be used to develop and calibrate models that use high-resolution passive or active remote sensing systems to estimate water depth. Coarse spatial resolution of the data restricts the ability to detect deep pools and steep gradients. This study also highlights the need to incorporate sediment erosion and transport into bathymetry models of thermokarst lakes.

Hopkins, D. M. 1949. Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. *The Journal of Geology* 57(2): 119-131.*

This paper describes thermokarst lakes and sinks in the Imuruk Lake area on the Seward Peninsula of Alaska. The region contains frozen, silty soils with ground ice that exceed the natural porosity of the potentially unfrozen material and melting of this ice leads to land subsidence and ponding of water in the depressions that further promote thaw. The author provides early English definitions of 1) thaw depressions – depressions which result from the subsidence following the thawing of permafrost, 2) thaw (thermokarst) lakes – lakes which occupy thaw depressions; the term includes lakes which originated in other ways but which have been considerably enlarged by thawing at their margins, 3) thaw sinks – closed depressions with a subterranean drainage but believe to have originated as thermokarst lakes. The author noted that thermokarst lakes in the region initiated by a number of different processes: 1) disruption of the vegetation cover by frost heaving, 2) accelerated thaw beneath pools at the intersection of ice wedges, and 3) accelerated thaw beneath pools in small streams. The author also noted that wave erosion becomes an important enlargement process once a water body exceeds about 30 m in diameter. While average expansion rates of lakes are not provided, the author noted some of the faster rates of lake expansion ever recorded in the Arctic, more than 20 m/yr over a two-year period.

Jorgenson, M. T., and Shur, Y. 2007. Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle. *Journal of Geophysical Research* 112 (F2).

This paper takes a closer look at the origin and ontogeny of lakes and lake basins on the Arctic Coastal Plain (ACP) on the North Slope of Alaska. The authors use ice content analysis of different cryostratigraphies across the ACP coupled with radiocarbon dates describing the origin of lakes and drainage basins, and photogrammetric analysis to reveal a new paradigm for ACP lakes. The results have striking implications that revise the former thaw lake cycle hypotheses for the region. Sparse ground ice, minimal ground subsidence due to thaw, stable shorelines, and bathymetry surveys in the regions underlain by sandy sediments, all point to them being depression lakes that filled in during the early Holocene. Because these lakes were observed and assumed to have minimal shoreline migration rates and expansion due to ground ice regimes, they are not known to have cycled in and out of inundation or thawed within the last 10 ka. These depression lakes make up the majority of lakes and basins on the ACP. True thaw lakes with dynamic shorelines and orientated shapes are confined to ice rich deposits in the loess belt near the Arctic foothills. When lakes drain due to river migration or thermoerosion of shorelines, ice aggradation occurs most prominently in basin centers where fine sediment and organics were deposited over millennia. This differential heaving can cause near shore sediments to accumulate small ponds along the former lake margins. Secondary thaw lakes can form in any drained basin, but the majority of secondary ponds are confined to the ice rich centers. Thaw lake cycles are proposed to only occur in a small portion of North Slope lakes.

Marsh, P., Russell, M., Pohl, S., Haywood, H., and Onclin, C. 2008. Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000. *Hydrological Processes* 23(1): 145-158.*

This paper assesses the drainage of thermokarst lakes between 1950 and 2000 for a 10,000 km² study area in the western Canadian Arctic on the east side of the MacKenzie Delta. The authors combined the use of historical aerial photographs and topographic maps to determine lake drainage events in three time periods: 1950 to 1973, 1973 to 1985, and 1985 to 2000. Between 1950 and 2000, 41 lakes drained in the study region for a rate of 0.82 lakes per year; however, when assessing drainage events per time period there has been a reduction from 1.13 to 0.83 to 0.30 lakes per year, respectively. Based on modeling and hydrological observations, one lake that drained in 1989 was believed to result from combination of a warm summer, a resulting deep active layer, and a moderately high lake level.

Parsekian, A. D., Jones, B. M., Jones, M. C., Walter-Anthony, K. M., and Slater, L. 2011. Expansion rate and geometry of floating vegetation mats on the margins of thermokarst lakes, northern Seward Peninsula, Alaska, USA. *Earth Surface Processes and Landforms* 36(14): 1889-1897.*

This paper describes the formation of floating vegetation mats on the margin of expanding thermokarst lakes on the northern Seward Peninsula between 1950 and 2007. These features have been widely described in boreal ecosystems in Alaska but have been seldom described in arctic tundra settings. Based on ground penetrating radar, the vegetation mats had an estimated thickness of 60 cm and based on probing and temperature measurements the water below the vegetation mat remained thawed during the winter and a talik at least 4 m in thickness developed beneath the mat while the lake froze completely to its bottom. The maximum expansion rate of the floating mat

feature into the adjacent tundra through permafrost degradation was 1 to 2 m/yr. Including the area associated with these mats, the land area subject to permafrost degradation increased by 4 percent between 1950 and 2006.

Sannel, A. B. K., and Kuhry, P. 2011. Warming-induced destabilization of peat plateau/thermokarst lake complexes. *Journal of Geophysical Research* 116 (G3).*

This paper uses aerial photography and satellite imagery to assess thaw lake expansion and drainage across a climatic and permafrost gradient. Rates of lake area change were compared to climate variables, and showed some correlation to mean annual air temperature. This study recognizes a temperature threshold, beyond which these landforms rapidly destabilize. This is currently occurring in the sporadic permafrost zone (MAAT ~ -3°C) and will likely occur in the discontinuous permafrost zone over the next century.

Ugolini, F. C. 1975. Ice-rafted sediments as a cause of some thermokarst lakes in the Noatak River delta, Alaska. *Science* 188(4183): 51-53.*

This paper describes the formation of thermokarst lakes as a result of ice-rafted sediment for a 7 km² area on the western portion of the Noatak River delta. The author notes that this mechanism depends on the freezing of shallow lakes and channels to their bed and the incorporation of bottom sediments into the ice. During spring break-up or during fall storms, when sediment-rich ice bodies can migrate onto the landscape, this dirty ice is deposited. Following the melt of rafted ice deposits, entrained sediments melt out and change the surface albedo and the thermal regime of the underlying soil, promoting thaw and formation of thermokarst ponds. The author notes that the entire sequence of the formation of thermokarst ponds through these processes has not been observed.

Yoshikawa, K., and Hinzman, L. D. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost and Periglacial Processes* 14(2): 151-160.

This paper investigates the causes of lake level changes on the Seward Peninsula Alaska over the last 100 years. It was observed that thaw bulbs underneath thermokarst lakes eventually reached the maximum depth of permafrost and then drained into a sub-permafrost ground water zone, which cause the lake levels in the region to lower. Ground photos from 1903 indicate that the lowlands around Southwest Seward Peninsula, Alaska, were once riddled with thaw lakes that are not present or greatly reduced today. Classification of landscape types by soil moisture, topography and vegetation type indicate that the most surface water change occurred in ice rich loess deposits in an elevation zone just above the floodplain. Geophysical surveys using ground-penetrating radar indicated that permafrost underneath the former lakes was nearly absent, while current lakes and adjacent terrestrial soils in this landscape zone were still perched on permafrost. Surface water isotopes indicated that evaporation could not account for the lake level change. Electrical conductivity measurements indicated that a groundwater pool was recharging some lakes and streams in the lowest areas. Thermokarst lakes in areas underlain by relatively thin discontinuous permafrost may have the propensity to drain into sub-surface aquifers under appropriate conditions.

Thaw Slumps, Active Layer Detachments, Gullying

Balser, A.W., Gooseff, M. N., Jones, J. B., and Bowden W. B. 2009. *Thermokarst distribution and relationships to landscape characteristics in the Fenik Lake region, Noatak National Preserve, Alaska. Report to the National Park Service, Fairbanks, Alaska.*

This grey literature publication reports the results of a widespread thermokarst survey in the upper reaches of Noatak National Preserve. Extensive helicopter and aerial-photo campaigns, along with field visits, were carried out in the mid-2000's. Thermokarst features were described, classified, and measured horizontally and volumetrically. Modern aerial surveys were compared with high altitude aerial surveys conducted in the early 1980s. The authors conclude that the numbers of thermokarst features have doubled in the region that now exceeds 500 thermokarst features. The most common today are active layer detachment slides (ALDS), retrogressive thaw slumps (RTS), thermokarst gullies and general thermokarst features of buried glacial ice. Revegetated scars of old thermokarsts were apparent in both sets of images, but not dated. Slides, RTS and gullies were associated with wet sedge meadows, low shrub tundra, and wet sedge meadows with channelized flow respectively. Thermokarst features are not found on carbonate sediments, presumably because these areas undergo carbonate weathering, which makes them better drained sites that have little ground ice. Buried glacial ice is degrading on and around glaciolacustrine deposits from the late Itkillik glacial advance. Retrogressive thaw slumps are typically not associated with any one lithology, but usually occur near lakes and rivers. ALDS' get initiated by the thawing of the ice rich layer on the bottom of the active layer. These may be associated with water tracks because water tracks have more peat and are prone to be infused by ice rich permafrost or increases in summer precipitation is preferentially degrading this ice because wet sedge meadows often drain hillsides. This initial survey is very encouraging for efforts to predict the vulnerability of a large area to thermokarst. These efforts were followed up in Balser, A.W. Retrogressive Thaw Slumps and Active Layer Detachment Slides in the Brooks Range and Foothills of Northern Alaska: Terrain and Timing, PhD Dissertation, University of Alaska Fairbanks.

Burn, C. R., and Friele, P. A. 1989. *Geomorphology, vegetation succession, soil characteristics and permafrost in retrogressive thaw slumps near Mayo, Yukon Territory. Arctic 42(1): 31-40.**

This paper describes two active and one stable retrogressive thaw slump formed along a river cut bank that flows through ice-rich, glaciolacustrine sediments in the Yukon Territory. The authors combined field surveys with aerial photography to document the development of the two active thaw slumps since 1949, vegetation succession on the floors of all three slumps, and the short-term soil development on surfaces of various ages in the slumps. All slumps were thought to have initiated after riverbank erosion exposed the ice-rich sediment. Since the inception of the two active thaw slumps, mean headwall retreat has varied between 12 and 14 m/yr., with maximum retreat rates of 16m/yr. Table 2 in this paper provides measured thaw slump headwall retreat rates for various locations in the Arctic, which range from 1 to 18 m/yr. The authors noted that the reestablishment of plant communities is associated with the initiation of soil development in fresh soil substrata and that after 40 years succession of closed-spruce forest was well advanced.

Burn, C. R. 2000. *The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. Canadian Journal of Earth Sciences* 37(7): 967-981.*

This paper details the formation and stabilization of a retrogressive thaw slump in Canada, through the use of field studies and instrumentation. Data loggers were installed in the slump floor and in undisturbed terrain. The temperature of the slump floor was warmer in both the summer and winter and the net result was 4°C warming of the mean annual ground temperature. The dominant mode of heat transfer in the thaw slump was conduction. The author also presents information on permafrost aggradation occurring in a stabilized thaw slump in the region.

Daanen, R. P., Grosse, G., Darrow, M. M., Hamilton, T. D., and Jones, B. M. 2012. *Rapid movement of frozen debris-lobes: Implications for permafrost degradation and slope instability in the south-central Brooks Range, Alaska. Natural Hazards and Earth System Sciences* 12(5): 1521-1537.*

This paper describes reconnaissance-level investigations of unusual debris mass movement features, termed “frozen debris lobes,” in the south-central Brooks Range of Alaska. The authors combined the use of ground-surveys, remote sensing, field and laboratory measurements, and time-lapse observations to document movement indicators that include toppling trees, slumps and scarps, detachment slides, striation marks on frozen sediment slabs, recently buried trees and other vegetation, mudflows, and large cracks in the lobe surface. Some frozen debris lobe features exceed 100 m in width, 20 m in height, and 1000 m in length. The features have responded to climate change by increasing their downslope movement during the last decades. Mean annual rates of movement were found to be between 2 to 4 m/yr. over decadal time-scales. The features exhibited signs of creep, slumping, viscous flow, blockfall and leaching of fines in warm seasons, and in cold seasons by creep and sliding of frozen sediment slabs. The authors highlighted the potential hazard of one frozen debris lobe feature as it encroaches on the Dalton Highway.

Fortier, D., Allard, M., and Shur, Y. 2007. *Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. Permafrost and Periglacial Processes* 18(3): 229-243. *

This paper describes the rapid development of a lake outlet that incised into ice wedges through the process of thermal erosion moderated by snow-melt over a four-year period on Bylot Island in Canada. This gully system had several features associated with the development of this drainage network including thaw tunnels, sink holes, and saucer shaped divots that can potentially be recognized in the future. The gully evolved from expanded frost cracks causing surface water to flow into underground tunnels, which subsequently widened and led to the collapse of the overlying roof of tundra peat and vegetation. Over the four year period, open gully headwalls retreated at a mean rate of 15.5 m with maximum rates on the order of 5 m/day following snowmelt and subsequent runoff. The drainage gully stabilized after a period of four years. Development of this new drainage network was found to have an impact on the local hydrology of the hillslope in which it formed. Towards the end of the thaw season, the gully system provided a channel in which to route drainage from the active layer, melting ice wedges, and thawing permafrost to the proglacial river at the base of the slope. The authors argue for further studies on a regional scale to assess whether these features and processes are widespread or the result of rare local factors encountered on Bylot Island.

Gooseff, M. N., Balser, A., Bowden, W. B., and Jones, J. B. 2009. Effects of hillslope thermokarst in northern Alaska. *Eos, Transactions American Geophysical Union* 90(4): 29–36.*

This paper describes the possible physical, chemical, and biological changes as a result of hillslope thermokarst in areas of continuous and discontinuous permafrost. Possible changes include increased sediment and nutrient loading into streams and rivers, and changes in vegetation composition near affected areas. Hillslope thermokarst, or thawing of permafrost on hillslopes, results in the failure and mass wasting (downslope movement) of overlying soil and vegetation. Recent hillslope features observed include active layer detachments, thermokarst gullies, and retrogressive thaw slumps. Hillslope thermokarst events are increasing and remote sensing and aerial photographs suggest some areas of the Arctic Coastal Plain have experienced more than a 200 percent increase in hillslope permafrost failures since the 1980s.

Harris, S. A. 2002. Causes and consequences of rapid thermokarst development in permafrost or glacial terrain. *Permafrost and Periglacial Processes* 13(3): 237-242.

This short paper describes some of the fundamental physical properties including the heat capacity of ice, soil, and water that are germane to thermokarst processes. This study is focused on the Fox Lake area of the Yukon Territory, but it can be applied to other periglacial environments. Instrumented soil and water in a nearby lake give the annual pattern of temperature changes for a single year to compare how the different mediums are responding to the same ambient air temperature. Even when frozen, the lake sediment stayed above -3°C while the soil dipped below -16°C. During spring and summer, the soil warmed up quicker than the lake, causing a back and forth temperature gradient over the course of the year. Because water has a greater heat capacity, the shallow lake absorbed five to seven times more heat than the soil. This was enhanced by advection due to water movements and water transparency allowing radiation to penetrate at depth. The larger implication of these properties is that climate change is not always responsible for thermokarst, which can be initiated by a range of factors. Independent evidence of climate change must be brought forth to connect a specific thermokarst with climate change.

Lamoureux, S. F., and Lafrenière, M. J. 2009. Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. *Arctic, Antarctic, and Alpine Research* 41(1): 59-68.

This paper reports the hydrogeomorphic impacts, and meteorology observations and measurements during an unusually warm summer (2007) on Melville Island, Canada. The summer was several degrees warmer than normal conditions, which caused a rapid and deep thaw layer to develop in early summer. Approximately twenty-five active layer detachments (ALD) formed after two significant rain events in July. By the end of the summer, 1.8 percent of the watershed land area was affected. Downstream river sections became increasingly turbid and carried 18 percent more sediment than normal summers. In the sub-watershed with more active layer detachments, stream discharge remained relatively high, probably due to extra permafrost-derived soil water contributing to run-off. Why one sub watershed had more ALDS than another was inconclusive, but probably had to do with differences in slope because they shared many other landscape characteristics. This study shows the extensive downstream effects of ALDS occurring in a relatively small area of the watershed. Additionally, this study supports the hypothesis that these features most likely form from

the combination of warm conditions and severe rainfall events that occur after active layer development. The authors further discuss this event in the context of varied lake records that have archived sediment loading events in a nearby watershed. The conclusion was that this event was unusual, but likely not unprecedented.

Lantuit, H., W. H. Pollard, N. Couture, M. Fritz, M., Schirrmeister, L., Meyer, H., & Hubberten, H. W... 2012. Modern and late holocene retrogressive thaw slump activity on the Yukon coastal plain and Herschel Island, Yukon Territory, Canada. *Permafrost and Periglacial Processes* 23(1): 39-51.

This paper describes the general characteristics and associated landforms of retrogressive thaw slumps on Herschel Island and King Point on the Beaufort Sea coast in the Yukon Territory. Most RTS occur on retreating coastlines of ocean, river, and lakeshores where an underlying body of massive ice (often buried glacial ice) is exposed and thaws. Therefore initial exposure of these ice bodies can be tied to retreating shorelines, but subsequent expansion relies on a range of factors including summer temperatures, shoreline erosion, wave strength, and the amount and nature of slumped material, which can re-insulate the ground surface depth of massive ice near the headwall. Thaw slumps often have evidence for past episodes of activity nearby them and they are thought to cycle on and off. This study looked at the morphology, biogeochemistry, and limiting ages for four active thaw slumps collapsing into the ocean. Rates of headwall retreat were different depending on elevation of the slump above wave influence. When slumps were near the base of the coastline, they were dependent on wave retreat whereas when they started or migrated above the coastline they were found to have different rates of retreat that likely depended on summer temperatures. Slopes and grain sizes of all stabilized and active slumps were very similar. Soil organic carbon seemed to be lost from the ground after RTS activity as did soil moisture. Radiocarbon dating of buried plants on the toe of old and active slumps were limited and inconclusive.

Lewkowicz, A. G. 1987. Headwall retreat of ground-ice slumps, Banks Island, Northwest Territories. *Canadian Journal of Earth Sciences* 24((6): 1077-1085.*

This paper develops an analytical model of headwall retreat that is based on measured energy fluxes, temperature, wind speed, and the ice face and ground slope. Calculated rates were close to maximum rates estimated from 10 years of aerial photographs. Orientation of the slump was found to be an unimportant variable, likely because direct-beam radiation was only a portion of the total input. July was found to be the most important month for ice ablation, however retreat exceeded ablation rates by 1.5 – 2.5 times, depending on slump geometry. Meteorological measurements were used to accurately calculate ablation rates in circumstances when the ice is freely exposed to the inputs.

Lewkowicz, A. G. and C. Harris. 2005. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. *Permafrost and Periglacial Processes* 16(1):115-130.

This paper compares the landscape positions, belowground temperature regimes, and orientation of active layer detachments on Ellesmere Island and the Mackenzie River Valley. Two-thirds of the Mackenzie slides initiated within 2 months of a forest fire. Most of these slides occurred on north-facing slopes, likely because more widespread permafrost was present there. Slides on Ellesmere Island did not necessarily occur when the deepest active layer was observed, just during particularly

warm summers with intense rainfall episodes. High rates of thaw >10 mm/day typically pre-empted a slide initiation on Ellesmere. The authors speculate that ice lenses formed during preceding wet years can prime the ground for landslides in later years if warm conditions happen. Slides therefore initiated within weeks of these meteorological conditions. A thaw index equation was used to hind-cast years with “potential” to have slides resulting in several false positives and three positives where slides occurred. Mackenzie slides appear to be related to 80-120 year fire cycles while Ellesmere slides seem to be much more frequent. The latter have increased in the last 100 years based on repeat photography. Short-term sediment movement estimates were greater in the fire-induced slides, but long-term estimates showed that Ellesmere slides caused more sediment movement due to their higher frequency.

Mesquita, P. S., Wrona, F. J., and Prowse, T. D. 2010. Effects of retrogressive permafrost thaw slumping on sediment chemistry and submerged macrophytes in Arctic tundra lakes. *Freshwater Biology* 55(1): 2347-2358.

This paper tested how recent occurrences of lake-side retrogressive thaw slumping affected water chemistry in five lakes located in the Northwest Territories. All study lakes are within a 53 km area and have the same underlying geology and permafrost characteristics. Lake water, macrophytes, and sediments were analyzed for various physical, chemical, and taxonomic features in lakes disturbed by thaw slumping (n=3) and undisturbed control lakes (n=3). Multiple sampling transects represented varying depths in the 2-5 meter deep lakes with small watersheds. Various statistical analyses were used to test whether significant differences appeared between disturbed and undisturbed lakes, and individual transects that were adjacent and opposite of thaw slumps in the lakes. Disturbed lakes had higher pH, conductivity, macrophyte cover (including benthic mosses), and greater sediment Ca and Mg directly adjacent to the slumps. Alkalinity and conductivity can be heightened by mineral sediment inputs to lakes elsewhere. Undisturbed lakes had more organic matter in sediments and greater light attenuation (more colored water to intercept light). The authors attribute the greater and more diverse macrophyte abundance to increased water transparency and micronutrients in disturbed lakes. They found asymmetry in the bathymetry of the disturbed lakes where underwater slopes adjacent to thaw slumps were steeper than those on the opposite side. Increased macrophyte abundance including low-light and alkaline-loving mosses and calcium-loving *Chara* species have direct effects on aquatic habitats for fish, waterfowl and other species. The authors also remind the reader that the presence of macrophytes feeds back to affect nutrient status and erosion by moderating sediment re-suspension and wave energies in the littoral environment.

Swanson DK. 2014. Mapping of erosion features related to thaw of permafrost in the NPS Arctic Inventory and Monitoring Network, Alaska. Natural Resource Technical Report. NPS/ARC/NRTR—2014/912. National Park Service. Fort Collins, Colorado. Published Report-2216465

This report presents results on the survey of active layer detachment slides and thaw slumps in the National Parks of northwestern Alaska using high-resolution satellite imagery acquired from 2006 to 2009. A total of 2,246 detachment slides and 724 thaw slumps were found. The topographic situations, associated vegetation, and regional distribution of these features were summarized.

Swanson, D. K., and Hill, K. 2011. *Monitoring of retrogressive thaw slumps in the Arctic network, 2010 baseline data. National Park Service, Fort Collins, Colorado. Natural Resource Data Series NPS/ARC/NRDS—2011, 70 p.*

This NPS report describes the whereabouts, activity, and landscape situation of 24 retrogressive thaw slumps in Noatak National Preserve and Gates of the Arctic National Park and Preserve. There are over 200 slumps known in these parks today and are most abundant in the eastern part of Noatak Preserve. Three-Dimensional aerial photos were taken of these slumps to quantify the amount of sediment subsidence and head-wall retreat for future years. Three-dimensional models were obtained for fourteen slumps to quantify the volume of ice and sediment affected by the mass movements. Slumps occurred exclusively on glacial till deposits. Slumps covered a one to four hectare area, and consisted of a headwall, sediment transport zone that was sparsely vegetated and an alluvial fan downhill. Most of the headwalls had what is described as buried glacial ice topped by unconsolidated gravel and till from the last glacial maximum. Some of the slumps were from older glaciations and had buried glacial ice topped by till and then ice wedges. The latter landscape situations were home to slumps with higher headwalls sometimes reaching eight to ten meters. Many of the slumps that are active today were also active in the 1980s. In addition, many slumps were near scars from stabilized and re-vegetated slumps, or even encroaching into old scars, which indicates just surficial ice can be thawed and re-thawed to form these features. One out of the 24 slumps was on a south-facing slope, which raises the question of whether or not buried glacial ice on the warmer south facing portions of the landscape thawed in the past.

Thermokarst Pits

Jorgenson, M. T., Shur, Y.L., and Pullman, E. R. 2006. *Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters 33(2): L02503.**

This paper describes the degradation of ice wedges between 1945 and 2001 on a portion of the Arctic Coastal Plain of northern Alaska, west of the Colville River delta. Ice wedges here are thought to have been stable for thousands of years. Ice wedge degradation was evaluated at three spatial scales: 1) field surveys at two sites 2) manual change detection with aerial photography at two intensive sites and 3) automated change detection using spectral characteristics of a larger area. In the field, ice wedge degradation was classified into several stages: 1) intact ice wedges with no evident surface changes; 2) initial degradation with barely evident settlement associated with thawing of the transient layer and greening of tussocks; 3) intermediate degradation with obvious settlement, shallow standing water, and robust green tussocks; 4) advanced degradation with deep, water-filled pits and dead submerged tussocks; 5) initial stabilization with robust aquatic sedges in shallow water; and 6) advanced stabilization associated with thick peat accumulation, reestablishment of a permafrost layer above the ice wedges, reduction of surface water, and establishment of mosses. Aerial photography identified ice wedge degradation and stabilization at the two intensive study sites. The area of thermokarst pits increased slowly from 0.5 percent in 1945 to 0.6 percent in 1982, then increased abruptly to 4.4 percent by 2001. In contrast, the percent area of stabilizing pits showed only gradual changes over the three dates (1.6 percent, 2.2 percent, and 3.0 percent, respectively), as earlier degrading pits became stabilized. The automated classification of the larger area revealed similar patterns. By combining the field studies with the aerial photography the authors show that initial and advanced degradation can happen within 20 years and that advanced stabilization is achieved within

another 20–30 years. The authors attributed the abrupt increase in ice-wedge degradation after 1982 to warm summer temperatures that occurred between 1989–1998; however they did not consider potential increases to winter temperatures nor to increased snowfall. The degradation of ice-wedges at their study site has caused a substantial redistribution of surface water from the adjacent tundra. The authors indicate that these processes may impact 10–30 percent of the arctic lowland terrestrial landscapes.

Pingos

Jones, B. M., Grosse, G., Hinkel, K. M., Arp, C. D., Walker, S., Beck, R. A., & Galloway, J. P. 2011. Assessment of pingo distribution and morphometry using an IfSAR derived digital surface model, western Arctic Coastal Plain, Northern Alaska. *Geomorphology* 138(1): 1–14.*

This paper mapped the distribution and morphometry of pingos in a 40,000 km² area on the western of Arctic Coastal Plain of northern Alaska using a ca. 2005 digital surface model derived from airborne IfSAR imagery. The authors identified 1,247 pingo-like features between 2 and 21 m high, 400 more than previously mapped in the region. The highest pingo density (0.18/km²) occurred where streams had reworked aeolian sand deposits. Morphometric analyses indicated that most pingos were small to medium in size (<200 m diameter), gently to moderately sloping (<30°), circular to slightly elongate (mean circularity index of 0.88), and of relatively low height (2 to 5 m). However, 57 pingos were higher than 10 m, 26 have a maximum slope greater than 30°, and 42 are larger than 200 m in diameter. Comparing the ca. 2005 derived pingo dataset with the pingo dataset created from mid-1950s stereo-pair aerial photography revealed that 66 may have partially or completely collapsed during the 50 year period. The authors only positively identified two pingos to have formed over the same period. However, the authors indicate that caution should be taken when comparing contemporary and legacy datasets derived by different techniques.

Lobdell, J. E. 2011. North Alaskan pingos: Ephemeral refugia in prehistory. *Arctic Anthropology* 32((1): 62–81.

This paper describes cultural remains found on two pingos in the Kuparuk Oil Field on the Central Coastal Plain in Alaska. More relevant to this review, pingos are potential hotspots of human activity in pre-history as well as geomorphic change. People likely used them for excellent views of the otherwise flat landscape, to intercept animals that congregate at pingos, or to catch wind and get away from mosquitos in the summer. Interestingly, cultural remains from atop pingos and their associated features can aid in determining the minimum age of pingo initiation. The Kuparuk Pingo had a range of artifacts with dates on burned bone going back to the mid-Holocene, while Central Pingo had post-contact Inupiat artifacts. Thermoerosion processes from adjacent lakes and rivers were eroding both of these pingos. This is not surprising because pingos are vulnerable to geomorphic change for many reasons. (1) They protrude from the centers of drained lake basins, which often drained because of active thermoerosion or fluvial processes in the vicinity, (2) They are very ice rich and are ice-cored, making them inherently unstable, (3) The south sides of pingos have high solar insolation and thin organic mats that would otherwise insulate this ice rich core. (4) Pingo uplift causes the margins of the former lake basin to be low ditches that fill up with water and, once big enough, threaten the pingo's persistence. For all these reasons, this is an interesting geomorphic feature to study in relation to high-risk archaeological remains.

Mackay, J. R. 1998. Pingo growth and collapse, Tuktoyaktuk Peninsula area, western Arctic coast, Canada: A long-term field study. *Géographie physique et Quaternaire* 52(3): 271-323.

This paper presents results from repeat topographical surveys on eleven pingos in the western Canadian Arctic over a 20 year period. The author focuses on pingo genesis; the role of pore water expulsion when saturated sands freeze; long-term pingo growth data; sub-pingo water lenses; hydrofracturing, peripheral faulting, and spring flow; and pingo collapse. One pingo in the study area grew by 4.5 m over the study period. Two pulsating pingos show sign of increased and decreased height over the study period. The author also discusses several mechanisms responsible for pingo collapse.

Soils and Geomorphology

Allard, M. 1996. Geomorphological changes and permafrost dynamics: Key factors in changing Arctic ecosystems. An example from Bylot Island, Nunavut, Canada. *Geoscience Canada* 23(4): 205-212.

This paper summarizes several soil and geomorphological factors formed since the Holocene that may affect arctic ecosystems and could be used to inform studies seeking to investigate patterns of soils in permafrost regions. The author uses Bylot Island, Nunavut, Canada as an example site. Peat-rich soils can assist in interpreting past changes related to the intensity of geomorphological processes. Accumulation of peat and sand is closely related to aggradation of permafrost and frost cracking, leading to tundra polygons. Buried vegetation layers beneath drained lake sediments show changes to lake inundation and drainage, and pingo formation. Aeolian activity may increase in colder and drier periods. Soil core samples obtained from numerous sites on Bylot Island show that areas of the island support a dynamic and sensitive assemblage of polygons, thaw lakes, and pingos that have changed continuously over the last 3000 years. Surface changes including geomorphology and vegetation in a network of sensitive sites, along with climate and permafrost temperature monitoring, constitutes a comprehensive method to assess the impact of climatic changes on land systems. However, precision mapping of polygon and vegetation types, and measurements of peat thickness and composition are vital components to adequately monitoring permafrost feature changes.

Benninghoff, W. S. 1952. Interaction of vegetation and soil frost phenomena. *Arctic* 5(1): 34-44.*

This paper describes the influence of frozen soils on the establishment and propagation of vegetation communities and vice versa. Frozen soils exert great force and trauma on root systems of plants through repeated freeze-thaw cycles, differential frost heaving, cracks caused by rapid freezing, etc. Plants have adapted shallow root systems due to impervious permafrost, which make trees and shrubs easy to overturn in inclement weather or windstorms. In fact, insufficient depth for the proper function of roots limits spruce forest, and species with flexibility of their root habits have the greatest likelihood of establishment in permafrost areas. Furthermore, plants may be subjected to severe water loss by exposure to drying winds, and roots that are encased in frozen soil cannot readily absorb water and may also limit tree growth in permafrost areas. Thermokarst features caused by the melting of variable amounts of ice in the soil change the physical environment for vegetation occupying a site. Margins of lakes with high permafrost tables are particularly susceptible to

destruction – in Nebesna, Chisana, and Tanana river valleys of eastern Alaska, previous research estimated mean shore retreat of 2.3 – 7.5 inches/year. The oriented lakes of the Arctic Coastal Plain were shown to be constantly changing owing to calving of shores, draining, filling with peat, and initiation of new thaw cycles. All permafrost areas are characterized by the instability of the surface and consequent transience of site conditions. Vegetation also influences frozen soils. It shields the soil from maximum penetration of heat by shading, decreases air circulation, retains moisture in and just above the soil, prevents thaw through root systems, intercepts rain, and cools soil through evaporation of moisture on plant surfaces. Mosses may play an important part in this effect. Removal of moss, thick turf, and surface peat greatly hastens thawing of frozen ground. However, vegetation can also warm soils by impeding heat radiation from the soil to the cold air and retaining snow cover, which insulates the ground from lower temperatures. Vegetation may be important for reducing frost disturbance in tundra through anchoring roots to the soil and insulating effects of the above ground plant parts. Disturbances to the vegetation such as burning and clearing in severe frost climate regions do much more than initiate plant succession that will culminate in the return of the original type of stand. Because of soil frost changes following disturbance, the affected surface and the local environment may be so greatly modified that entirely different communities occupy the site for unknown periods of time.

Kanevskiy, M., Shur, Y., Jorgenson, M. T., Ping, C. L., Michaelson, G. J., Fortier, D., Stephani, E., Dillon, M., and Tumskey, V. 2013. Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska. *Cold Regions Science and Technology* 85: 56-70.*

This work quantifies ice structures in the five dominant terrain units on the Arctic Coastal Plain: primary surface (silty deposits in the west to gravelly sand in the east), low yedoma foothills, drained lake basins, deltas and tidal flats, and aeolian sand dunes. Wedge ice volumes and total volumetric ice were calculated. Wedge ice was the dominant form of massive ice, ranging from 3 to 50 percent, and occurring in nearly all terrains. Other types of massive ice included thermokarst cave ice, ice core pingos, and folded massive ice. Most of the soils were found to be frost-susceptible silts, resulting in extremely ice-rich permafrost dominated by ataxitic cryostructure. Ice content was notably lower in young drained lake basins, deltas, and tidal flats. The authors discuss formation and calculation of the size of the transition layer, which is the ice-rich upper-part of the permafrost, the formation of which greatly elevates the landscape.

Koch, J. C., Ewing, S. A., Striegl, R., and McKnight, D. M. 2013. Rapid runoff via shallow throughflow and deeper preferential flow in a boreal catchment underlain by frozen silt (Alaska, USA). *Hydrogeology Journal* 21(1): 93-106.*

This paper investigates seasonal changes in runoff lags, ratios, and pathways from a hillslope in a north-facing, continuous permafrost silty hillslope in interior Alaska. The data presented in this study, combined with soil moisture data and infiltration modeling, indicates the presence of rapid preferential flowpaths that drain the hillslope quickly. Uranium isotopes indicate that these flows are contacting virgin permafrost, which may occur as streams incise into their beds, and (or) associated with slumps. This effect may be maximized at this study site due to a recent fire that increased the active layer.

Swanson, D. K. 1996. Soil geomorphology on bedrock and colluvial terrain with permafrost in central Alaska, USA. *Geoderma* 71(1): 157-172.

This is a soil classification survey near Hughes Alaska to determine how geomorphic features dictate soil types in the discontinuous permafrost zone of Alaska. By surveying a variety of soil indexes in the field along a diverse array of geomorphic and mapped soil-class transects, it was found that three soil classes existed based on various ranks of soil classes. These were wet, moist and dry, and have shared features such as vegetation, pH, texture, O-layer thickness etc. Slope shape was the most significant determinant for the distribution of these three classes, and slope, aspect and position were also important. Permafrost occurred on lowlands with thicker organic layers and wet soils promoted by the below ground thermal offset of wet organic rich soils. These soils likely formed in concave slope shapes due to fine grain sediments settling in these areas and becoming poorly drained over time and more likely to accumulate peat. This work can refine our understanding of the distribution of thin and thick soils and the presence of permafrost at any given location from mere surface observations. This may prove useful when assessing an archaeology site for the significant controls on stability or nature of sub-surface layers.

Active Layer Deepening and Warming Soils

Grosse, G., Harden, J., Turetsky, M., McGuire, D. A., Camill, P., Tarnacai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., 2011. Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research* 116(G4): G00K06.*

Though the authors focus on the vulnerability of soil organic carbon, important thermokarst and thermo-erosion processes are summarized and their impacts on soils and ecosystem characteristics are described. The authors quantify that areas of 73,000 km² and 814,000 km² with Cryosols are underlain by ice-rich permafrost in Alaska and Canada, respectively. The authors define pulse disturbances affecting soils as rapid processes such as thermokarst, thermo-erosion, and wildfires, and differentiate these from press disturbances that are representing more gradual changes such as slow active layer deepening or changes in soil wetness. Approaches for predicting soil and soil carbon changes due to such disturbances are shown and research and data gaps are also highlighted.

Liu, L., Schaefer, K., Zhang, T., and Wahr, J. 2012. Estimating 1992–2000 average active layer thickness on the Alaskan North Slope from remotely sensed surface subsidence. *Journal of Geophysical Research* 117(F1): F01005.*

This paper demonstrates the utility of deriving active layer thickness measurements from thaw-season surface subsidence based on InSAR. The authors developed an algorithm that accounts for the vertical distribution of water content in the active layer factoring in soil texture, organic matter, and moisture content which can be used to estimate active layer thickness based on the measurements of vertical surface deformation from the InSAR data. This algorithm was applied to ERS-1 and ERS-2 satellite InSAR derived measurements for an 80 x 100 km area centered on Prudhoe Bay, Alaska between 1992 and 2000 to determine average active layer thickness at relatively high resolution. Active layer thickness values were reported to be within 10-20 cm of what was interpreted as reality and based on the Circumpolar Active Layer Monitoring (CALM) program grids in the region. In moist tundra areas the estimated active layer thickness was 30-50 cm and in wet tundra areas the

estimated active layer was 50-80 cm. The authors note that this method could complement ground-based measurements and be useful for filling the spatial gaps of in situ measurements in remote permafrost areas and to advance our understanding of changes in the active layer and permafrost system.

Nelson, F. E., Hinkel, K. M., Shiklomanov, N. I., Mueller, G. R., Miller, L. L., & Walker, D. A. 1998. Active-layer thickness in north central Alaska: Systematic sampling, scale, and spatial autocorrelation. *Journal of Geophysical Research* 103(D22): 28963-28973.*

This paper measured active layer depth at numerous sites with a wide range of terrain, soil, and vegetation characteristics across the Arctic Coastal Plain and Arctic Foothills, Alaska. Along 100 m grids at 7 sites, authors placed a graduated steel rod into the soil to measure active layer depth. They evaluated their approach and found that the depth at probe resistance corresponds closely to the frost table. They found high spatial, but low temporal heterogeneity in active layer depth that varied between the coastal plain and foothills. They sampled in 2 years with similar air temperatures, which may explain the low temporal variability in active layer depth. Active layer thickness was influenced by microclimate, hydrology, soil moisture, and vegetation. This study attempted to use a network of monitoring sites that were established to collect a wide range of ecological data across northern Alaska. They found, however, that although the 100 m scale was suitable for the coastal plain, narrow water tracks and tussock tundra in the foothills led to variations in thaw depth over short lateral distances. The authors recommend reconnaissance sampling in this area to determine the appropriate sampling scale for particular variables.

Pullman, E. R., Jorgenson, M. T., and Shur, Y. 2007. Thaw settlement in soils of the Arctic coastal plain, Alaska. *Arctic, Antarctic, and Alpine Research* 39((3): 468-476.*

This paper describes a synthesis of field surveys and observations of thaw strain and thaw depth derived from soil cores taken between 1998 and 2003 in a study region spanning from Prudhoe Bay to west of the Colville River delta, Alaska. Thaw strain was determined for each of the 108 core samples, and mean thaw strain was calculated for each of the sampled terrain units. Potential thaw settlement was estimated as the decrease in volume a frozen soil sample undergoes when thawed for individual soil horizons and the potential change in the active layer thickness caused by surface disturbance. Thus, thaw settlement is a function of the original thickness of the active layer, the increase of the active layer as it adjusts to disturbance at the surface, and the thaw strain of the underlying permafrost. The authors then divided the study area into 12 terrain units and provided an estimate of potential thaw settlement for each one. Mean thaw settlement associated with a thickening of the active layer to 1.1 m in sandy soils associated with active meander river channels resulted in zero thaw settlement; however the same thickening of the active layer in very ice-rich silty soils would result in a thaw settlement of ~0.9 m. The authors also scaled-up their estimates to cover the various ecotypes that represent the larger Coastal Plain region. These estimates are representative of the centers of ice-wedge polygonal terrain and do not factor in thermokarst that would result from degrading ice-wedges and other massive ice bodies.

Shur, Y.L., and T. E. Osterkamp. 2007. Thermokarst. Institute of Northern Engineering.. University of Alaska Fairbanks, Fairbanks, AK. Rep. INE06.11, 50 p.

This is a review of the extensive Russian literature concerning thermokarst processes. The review details the development and current definitions of various types of ground ice. Primary ice masses form during freezing and they include intrusion, and pore-water ice and even lenses. Secondary ice masses include ice wedges that form from the ground contracting and then filling in with water. The active layer of permafrost sits on a transitional zone called the transient layer, which thaws about once every decade. This layer can buffer the underlying permafrost, and typically has a high ice and water content. Modifiers of permafrost include vegetation, water, soil, and relief. These potentially alter the air to soil climate relationship. Modifiers are more important for the persistence and formation of permafrost in warmer areas, but at some point along a climate gradient permafrost's presence doesn't rely on modifiers. Two types of thermokarst are discussed, local and climatic. Local thermokarst are more common and potentially more rapid.

Glacier and Snowfield Wasting

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S. and Valentine, V. B. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 297(5580): 382-386.

This study uses repeat laser altimeter measurements of glacier thicknesses in the 1950's, 1990's and early 2000's to determine the volume of ice loss in recent decades. The authors focused on coastal range glaciers, but conducted additional repeat surveys in the eastern Brooks Range. The results are unanimous and are included in this literature review to provide a sense of glacial retreat in the last several decades; this study may prove useful for assessing the impacts of wasting glaciers on archaeological material in GAAR. Ninety-five percent of the glaciers observed have thinned since the mid-20th century, some by several hundred meters. Glacial thinning occurred twice as fast during the late 90s-early 2000's compared to the previous several decades. Although there was overwhelming evidence for glacier volume change, areal extent of thinning glaciers did not always diminish over the same time periods. Therefore, when considering glacier-wasting measurements in relation to marginal areas of interest, one must be cautious in drawing conclusions. Repeat photography may be a more appropriate method.

Barclay, D. J., G. C. Wiles, and P. E. Calkin. (2009). Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* 28(21):2034-2048.

This is a review that updates Calkin et al., (1988, below) about Holocene changes in glacier extent on a statewide scale. The authors classify glaciers based on their landscape positions and response to climatic factors. Cirque and mountain valley glaciers are most responsive to climate, but tidewater and foreland glaciers near the Gulf of Alaska are also observed. Methods used in order of resolution are: age of glacially over-run forests using tree-ring cross dating and sprouting data in the southern ranges, radiocarbon dating wood of foreland features, lichenometry, and cosmogenic dating. The extent and distribution of Alaska glaciers during the period classified globally as the last glacial maximum (LGM) indicate that the Gulf of Alaska was the main moisture source for glaciers in the past, as it is today. Glaciers were at their maximum extents between 20 and 25ka, and there is some evidence of multiple standstills and potential re-advances leading up to the deglacial period. During

the early Holocene there is only spurious evidence for glacial advances and most glaciers seem to be at today's extent or slightly larger. During the mid to late Holocene, ice advances began again in nearly every range. The Brooks Range has numerous pre-little ice age (LIA) moraines that lichenometry dates to three clusters of advance with mean ages at 4.1, 3.3, and 2.6 ka. Between 2 ka and 1 ka, lichenometry indicate that moraines were being built in the Brooks Range. There are no discussed conclusions of what is happening to the Brooks Range during the MWP. LIA moraine building events in the Brooks Range are centered on 1210, 1560, and AD 1840. Nearly every forefield valley observed by Calkin (1988) had moraines that dated to AD 1560.

Calkin, P. E., Kaufman, D. S., Przybyl, B. J., Whitford, W. B., and Peckl, B. J. 1998. *Glacier regimes, periglacial landforms and holocene climate change in the Kigluaik Mountains, Seward Peninsula, Alaska, U.S.A. Arctic and Alpine Research 30(2): 154-165.*

This study surveys the last remaining glaciers in the Kigluaik Mountains of the Seward Peninsula. Historical observations in the Kigluaik Mountains indicate that at least three more glacier bodies in the region were present at the beginning of the twentieth century. Glaciers occur at elevations from 600-900 m on north facing and canyon-like cirques. There are obvious LIA moraines at the front of all three glaciers. Lichenometry on morainal features dates these retreats to the 17th and 18th century. Limited examples of Late-Holocene moraines occur down valley from the LIA advances that date to 3 ka. This paper gives a good review about the formation and classification of the two types of rock glaciers: lobate, formed in steep-sided cirques prone to accumulation of rock-falls covering snow and ice patches, as well as tongue shaped, associated with buried glacier ice, mobilized ice-cored moraines or buried ice by streams and ice caves. Lichen ages on seven rock glaciers indicate that they formed or stabilized around 3-4 ka. The authors discuss these data in the context of past and present climate change. They conclude that glacier advances during the mid to late Holocene and LIA correspond to rock glacier formation and pingo formation, other indicators of a colder climate probably from lower insolation. Glaciers were likely not present during the early Holocene warm period in the study region.

Dixon, J., C., Manley, W. F., and, Harrison. W. D. (2007). *The frozen past of Wrangell- St. Elias National Park and Preserve. Alaska Park Science 6(1): 24-29.*

This park service science article introduces "ice patch" archaeology, the study of ancient cultural artifacts emerging out of cirque glaciers and permanent snowfields, in Wrangell St. Elias National Park. Surveys in 2001-2003 have found that archaeological resources are only in select sites, and often rare. However, sites that do yield cultural material are unique and valuable. Due to the preservative nature of ice, organic material such as wood, bone, or sinew that may otherwise be fragmented, degraded or absent, can preserve radiocarbon ages on organic material have extended back to 2.8 k 14C years before present. Repeat aerial and satellite photography, traditional ecological knowledge, and radiocarbon dating indicate that these ice and snow features are wasting with increases in summer temperatures. The ice that these artifacts are embedded in is at least as old as the 14C dating, speaking to the temporary and dwindling resource. There are no mentioned efforts of ice patch archaeology in other Alaskan National Parks, but the potential for these resources to occur in GAAR is likely.

Ellis, J.M. and Calkin, P.E. 1979. Nature and distribution of glaciers, neoglacial moraines, and rock glaciers, East-Central Brooks Range, Alaska. *Arctic and Alpine Research* 11(4): 403-420.

This study presents the results of a survey detailing the distribution, orientation, and landscape characteristics associated with current and recent cirque and rock glaciers in the Atigun Pass area of Brooks Range, Alaska. The glacier history of the study region is summarized as having several, north-south symmetrical glacier advances in the Brooks Range during the Pleistocene that ended with the Itkillik II advance sometime around 12 to 14 k y.a. Neoglacial deposits from the mid to late Holocene were observed using lichenometry methods. Today, the nivation hollows and cirques that are occupied with exposed glacier ice are confined to north-facing aspects. Holocene cirque glaciers almost always had end moraines with 400-800 m of the toe, which means that today's glaciers are on average half as large as those occurring at the height of the neoglacial. Rock glaciers occurred where the head-wall of the glacier ended in a cliff that would provide debris and rocks to cover the downslope glacial ice. Five of the 133 cirque glaciers had no moraine deposits downslope. These are likely the ones that would have well-preserved artifacts or other material exhumed from the retreating toe of the glacier. Ninety-seven percent of glacier ice was found to be north of the continental divide and greater than 80 percent of the rock glaciers occurred north of the continental divide. Glaciers occurred above 1500 m while rock glaciers were slightly lower due to the insulating capacity of the debris buffers the warmer temperatures. Many glaciers had downslope lobes that terminated into a rock glacier, which can be unstable relative to their lobate shaped rock glacier counterparts. All glacial features had mean aspects of >330 and <20 degrees indicating they were confined to north facing slopes. Direct solar radiation appears to be a significant control on the presence of exposed glacier ice today, inferred by the asymmetry of cirque glaciers. However, there is an apparent interaction with moisture as evidenced by the southern cirques that had ice in them at lower elevations because they were more proximal to moisture-laden maritime air masses.

Farnell, R., P. G. Hare, E. Blake, Bowyer, V., Schweger, C., Greer, S., & Gotthardt, R. 2004. Multidisciplinary investigations of Alpine ice patches in southwest Yukon, Canada: Paleoenvironmental and paleobiological investigations. *Arctic* 57(3):247-259.

This paper describes an inventory and paleoecological interpretation of organic remains emerging out of dwindling ice patches in the southwest Yukon Territory. Seventy-two ice patches containing visible organic remains on top of them were identified by aerial survey in late summer in between Whitehorse and the coastal mountain ranges between 1550 and 2075 m elevation. Ice patches are found in small cirques and generally north facing slopes or toes of north facing slopes. The majority of organic remains that are found on ice patches are caribou dung. Biological specimens were recovered at 35 ice patches and 18 ice patch surveys had archaeological remains. Three well-studied ice patches have stratigraphically organized organic/dung layers from the mid Holocene to present. There was a mid-Holocene hiatus in ice deposition, and ice contraction and expansion is associated with the MWP and the LIA. Paleoenvironmental results of the region can be gleaned from plant macrofossils, pollen, and soft tissue of animals and bones. The ability of ice patch stratigraphy to correlate during melting events requires extensive radiocarbon dating to determine precise ages of plant and animal remains. Retreating ice patches can expose once buried plants including dead lichen "rings" which may be targeted to date ice patch advances.

Hinkel, K. M., and Hurd, J. K. 2006. Permafrost destabilization and thermokarst following snow fence installation, Barrow, Alaska, USA. *Arctic, Antarctic, and Alpine Research* 38(4): 530-539.*

This paper describes the impact of a snow fence on permafrost temperature and land subsidence in Barrow, Alaska from 1999 to 2005. Data loggers were installed at depths of 5, 30, and 50 cm in the ground on the downwind side of the snow fence and in tundra sites not impacted by the snowdrifts that formed as a result of the snow fence. Active layer thickness and snow depth were measured annually in August and April. As a result of the snow fence, the ground temperature in the downwind strip have warmed by 2 to 14°C in the winter and cooled by 2 to 3°C in the summer, the latter due to the time it takes to melt the drifted snow (3 to 4 m in thickness). The net effect has been a warming of the ground surface, thawing of the permafrost, subsidence on the order of 10 to 20 cm, and development of thermokarst ponds. This study highlights the importance of snow accumulation and thickness on the ground thermal regime and how snow accumulation can contribute to thermokarst formation.

Meulendyk, T., B. J. Moorman, T. D. Andrews, and G. MacKay. 2012. Morphology and development of ice patches in Northwest Territories, Canada. *Arctic* 65(5): 43-58.

This paper describes the morphology, origin, and ontogeny of ice patches in the Northwest Territories (NWT) of Canada using GPR and ice core methods and compares these ice patches with other ice patches around the world. The study area is the Backbone Mountains west of the Mackenzie River where ice patches occur between 1600 and 2000 m in hollows and north facing or leeward slopes just below the peaks of ridges. GPR and ice core profiles of two ice patches showed that snow/firn depths in July were from 50 to 100 cm. The base of the snow layer was saturated with unfrozen meltwater in lenses above an ice layer that continued to the bedrock. Several organic layers and sediment layers composed mostly of caribou dung were found in the ice cores, some of which could be detected by GPR methods (depending on the resolution and separation between organic layers). Radiocarbon ages on distinct organic layers range from near modern to ~3 ka with significant age gaps between layers. Varying depths of these age gaps implies that accumulation rates of ice change over time. Only a small proportion of the ice patch was observed to be converting snow into more permanent ice. The outer perimeter of each feature was exclusively snow that contracted during the growing season. Repeat GPR and ice core surveys for three summers showed that some individual areas and an individual snow patch may respond differently to the same climatic conditions in a given period. Both features did not significantly grow or contract over three years. Overall the mid to late Holocene ages on the oldest organics in the two ice patches are consistent with the neoglacial period and the contraction of treeline in the region. The NWT ice patches are formed in locations that have southwesterly winds during the winter, causing north facing slopes to accumulate more snow.

Stieglitz, M., Déry, S. J., Romanovsky, V. E., and Osterkamp, T. E. 2003. The role of snow cover in the warming of arctic permafrost. *Geophysical Research Letters* 30(13): 1721.*

This paper highlights the role of snow cover on the permafrost thermal regime. Through the use of modeling, the authors show that snow cover variability can impact the temperature of permafrost to the same extent as near-surface air temperature. The authors conclude that trends in permafrost

temperature in northern Alaska from 1983 to 1998 can in a large part be explained by variability in snow cover.

VanderHoek, R., E. J. Dixon, N. L. Jarman, and R. M. Tedor. 2012. *Ice Patch Archaeology in Alaska: 2000-10. Arctic 65(1), 153-164.*

This is a summary of ice patch archaeology in the state of Alaska that highlights extensive surveys in Wrangell St. Elias and Lake Clark National Park, and briefly touches on limited surveys in Katmai, Denali, and Gates of the Arctic National Park. Ice patches were observed to be <1000 m.a.s.l. in the northerly Brooks Range and snow-ridden Katmai National Park, and >1000 m.a.s.l. in most of the coastal range parks and southern half of the state. Snow patches can be classified into three categories: 1) round or cirque types 2) longitudinal ice patches in gullies 3) transverse ice patches running parallel with a ridgeline in the lee side of the slope where snow drifts and collects. Type three has been observed to have the most archaeological finds. Numerous organic artifacts were found at various ice patches in these surveys. Notable items include caribou antler projectile points, a birch basket, animal hides, and bones, as well as wooden samplings that may have been transported to the site. Most finds were found on the footprint or the retreating front of the wasting ice patches. At least two of the surveyed ice patches disappeared completely at least once during one of the summers surveyed. Numerous radiocarbon dates are reported here ranging from modern to 4 k ¹⁴C BP. The significance of these diverse finds are that, while ice patches are known for being locations for good caribou and sheep hunting by indigenous groups, a wide array of activities were also conducted in these higher altitude regions, mainly during the summer. This is consistent with ethnographic records from these regions and the interpreted use of many of the objects found.

Wiles, G. C., R. D. D'Arrigo, R. Villalba, P. E. Calkin, and D. J. Barclay. 2004. *Century-scale solar variability and Alaskan temperature change over the past millennium. Geophysical Research Letters 31(15): L15203.*

This short paper is a synthesis of several studies on glacier advances from the three major mountain chains in Alaska. The authors look at tree-ring, radiocarbon, and lichenometry-dated moraines to bracket LIA glacier advances, and compare a glacier advance index to a sun activity proxy (production of ¹⁴C in the upper atmosphere). There was distinct correlation between glacial advances and minimums of sun activity (170-210 year cycles) indicating that century scale changes in glacier mass balance across the state is generally dependent on a celestial cycle experienced all over the world at the same time. However some of the solar minimums have variable response by some or all of the glaciers in the state. The authors suggest that there is an interaction with solar minimums and the Arctic Oscillation in the Brooks Range and the Pacific Decadal Climate cycles in the southern ranges. Today, negative PDO indexes are associated with cooler temperatures in the coastal ranges of Alaska. When comparing periods of solar minimums and negative PDO's over the last 1000 years enhances glacier advance. The authors hypothesize that the cold summers that happen during a negative AO phase is required along with solar minimums to trigger glacial advances in the Brooks Range. To date there does not seem to be a good long-term record of the AO. The Brooks Range glaciers were more sensitive to the Sporer and Dalton sun minima beginning in the early 15th and 19th centuries respectively. One-third of the glaciers studied in the Brooks Range (n=27) advanced during

the Sporer minimum with a peak centered around 1450 and another around 1500. The earliest advances in these records occurred after what is thought of as the medieval warm period (MWP).

Paleo-Thermokarst

Fritz, M., Wetterich, S., Schirrmeister, L., Meyer, H., Lantuit, H., Preusser, F., and Pollard, W. H. 2012. Eastern Beringia and beyond: Late Wisconsinan and Holocene landscape dynamics along the Yukon Coastal Plain, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 319-320: 28-45.

This paper compares the cryostratigraphic, geochemical and proxy records of two permafrost exposures on the Yukon Coastal Plain. The sites differ in that the exposure on Herschel Island (HI) was affected by the LGM limit of the Northwestern extent of the Laurentide Ice Sheet (LIS), while a coastal exposure (CE) was not. Radiocarbon dates on plant detritus sampled just below an unconformity in the HI exposure indicate that the earliest arrival of the LIS glacier was around 16.2 ka. Buried glacier ice is evident on HI, which is observed to be vulnerable to widespread retrogressive thaw slumps. Oxygen and hydrogen isotope data on ice wedge water could distinguish sediment-rich Pleistocene ice wedges from Holocene ice wedges. After glacier retreat, the former footprint of the LIS may have been a source for increased aeolian deposition in the CE during the late glacial. The late glacial period (>11.2 ka in this study), was associated with ice wedge formation that are eventually truncated by early Holocene thaw in the unglaciated CE. The landscape symptoms of the early Holocene warm period are ice wedge casts, thermokarst lake sediments, truncated ice wedges, and basal peats. Increased TOC contents in HI layers corresponding to the early Holocene indicate that reworked organics congregated in thaw deposits. This work highlights how sites adjacent and under the ice sheets have varying responses to glacial interglacial climate change, sea level rise, and the legacy of permafrost development that continues today.

Irvine, F., Cwynar, L., Vermaire, J., and Rees, A. 2012. Midge-inferred temperature reconstructions and vegetation change over the last ~15,000 years from Trout Lake, northern Yukon Territory, eastern Beringia. *Journal of Paleolimnology* 48(1): 133-146.

This paper is a report of two lake sediment cores from Trout Lake in the northernmost reaches of the Yukon Territory, just west of the Mackenzie River. Today the lake lies in shrub and tussock tundra zones. The sediment cores were analyzed for loss on ignition, radiocarbon chronology and midge-inferred July temperatures over the last 15,000 years. Trout Lake was cored in 9.5 and 3.7 m of water to get a sediment record of around 3 meters. The deepwater and shallow water cores had nine and five dates analyzed, respectively. Some dates were on "moss" samples, which at times can be difficult to interpret. Delay of shallow lake core initiation indicates that lake levels rose around 9.9 ka. Regarding temperature zones in the core, a four-degree warming occurred out of the LGM beginning roughly 14.4 ka. The authors indicate that the increase in shrubs around 14.4 ka in the region can be attributed to this warming. They record a ~1-2 degree cold reversal between 12.2 and 11.2 that they attribute to the Younger Dryas (YD) chronozone. Note though that this work does not constrain the YD chronozone very well. With moderate dating errors, this could be very true, or completely wrong. This record indicates that the HTM lasted from 11.2 - 9.6 ka in the record. The HTM is recorded as 2 degrees warmer than present in both the deep and shallow cores. The fact that both cores in vastly different water levels are estimating similar temperatures is very encouraging for

the technique. One of the main criticisms for this approach is varying lake levels would alter the summer temperature regimes experienced by midges, while not necessarily change the temperature. Typical pollen records are presented from this record. There are traces of cottonwood pollen in the early Holocene. Dry tundra steppe indicators are replaced by shrubs rapidly starting with willow around 14.4 ka and then birch ~14 ka. However, around 16 ka there is a spike in birch and the authors do not comment on this. Alder comes in rapidly at 6 ka.

Kanevskiy, M., Shur, Y., Fortier, D., Jorgenson, M. T., and Stephani, E. (2011). *Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure. Quaternary Research 75(3): 584-596.*

This paper provides an overview on the nature and distribution of yedoma in the Arctic, describes the characteristics of a yedoma exposure in northern Alaska, and provides an overview map of the potential distribution of yedoma in Alaska. Yedoma permafrost deposits typically refer to late Pleistocene syngenetic permafrost, which are typically very high in ground-ice content. The exposure that was studied in northern Alaska represents 40,000 years of undisturbed yedoma formation. The lack of yedoma in certain regions of northern Alaska form the basis of the hypothesis that portions of the Arctic Coastal Plain were glaciated during the Pleistocene.

Mann, D., Peteet, D., Reanier, R. E., and Kunz, M. L. 2002. *Responses of an arctic landscape to Late-glacial and early Holocene climatic changes: the importance of moisture. Quaternary Science Reviews 21(8): 997-1021.*

This is a summary of several years of paleoecology and history of fluvial geomorphology research in the arctic foothills and coastal plain regions of Alaska's North Slope (NPR-A). Part one describes the biophysical gradients in the region today, including cooler summers near the coast, a glacial, aeolian, marine transect of surficial geology from south to north, and the unusual state of waterlogged aridity that the arctic tundra has during the summer. Part two describes past studies that have focused on the paleoecology of the region including fluvial terraces, sand dune activity, paleobotany and other climate proxies alluding to the fact that widespread changes occurred during the Pleistocene-Holocene transition from ~14-8 ka. The original research of this paper relies on four sources of paleoenvironmental archives: a) the lithology and pollen record of a drained lake basin in the arctic foothills, b) the ages of the lowest organic material from peat cores near the Mesa archaeological site, c) geologic sections indicating fluvial aggradation and incision, and thermokarst deposits across the study region, and d) the radiocarbon ages of cottonwood remains found in various environments. Lake levels and shrub pollen increase ~14.5 ka and remain high for the majority of the record (ending ~5 ka), but are interrupted by low lake levels and vegetation reminiscent of the mammoth steppe during a well dated Younger Dryas period. Basal peat ages (n=48) indicate that the oldest peat started forming around 15 ka, but slowed down during the Younger Dryas, only to resume between 11 and 8 ka. The ages of cottonwood trees follow this general pattern, which is corroborated by the *Populus* pollen identified in the lake sediment record. Streams were flushed with sediment and aggraded during the Bolling Allerod and early Holocene, but incised during the Younger Dryas. Thermokarst deposits dated during times of aggradation support increased sediment loads in rivers during periods of supposed warming. This dramatic warm-cold-warm climate oscillation is nearly identical to well accepted northern hemisphere climate archives including the Greenland ice, and Atlantic marine

cores, as well as local sand dune and glacier activity. Due to the widespread breadth of this precisely dated work that records nearly synchronous and wholesale landscape change, it has become the cornerstone of P-H climatic accounts for this region. These widespread landscape changes are attributed to the interaction of moisture changes, thick organic soils and permafrost on the landscape. Peat is thought to have taken control of the below-ground environment for the rest of the Holocene after around 8.5 ka.

Mann, D., Groves, P., and Reanier, R. E., and Kunz, M. L. 2010. Floodplains, permafrost, cottonwood trees, and peat: What happened the last time climate warmed suddenly in arctic Alaska? *Quaternary Science Reviews* 29(27): 3812-3830.

This paper is the result of a several year, multi-disciplinary investigation that recorded various landscape responses to two distinct warming events that occurred at the end of the last ice age in Northern Alaska. Cottonwood trees expanded beyond their current latitudinal limit between 14.8 and 12.8 ka (Bolling Allerod) and then again between 11.5 and 9.5 ka (Holocene Thermal Maximum). Floodplain aggradation is also evident during these two episodes on two coastal plain rivers (also corresponding to floodplain aggradation recorded on four other rivers in Mann et al., 2002). River downcutting and the absence of *Populus* plant macrofossils characterize the younger Dryas chronozone and the later Holocene. Because summer temperature limits cottonwood expansion and sediment supply to North Slope Rivers, the mechanisms causing these changes are shown to be related to climate oscillations during the Pleistocene-Holocene transition. The authors hypothesize that after 9.5 ka the spread of peatlands takes control on the below-ground temperature regime by buffering soils from permafrost thaw events in the Holocene. This peat-covered Holocene landscape state has caused the uplands to be relatively disconnected from depositional environments such as lakes and floodplains. The authors note that to reconnect sediment communication between these two landscape types would require even greater warming than occurred during the BA/HTM, or some disturbance event such as fire, because more peat on the landscape has a buffering capacity against permafrost thaw.

Oswald, W., Gavin, D. G., Anderson, P. M., Brubaker, L. B., and Hu, F. S. 2012. A 14,500-year record of landscape change from Okpilak Lake, northeastern Brooks Range, northern Alaska. *Journal of Paleolimnology* 48(1): 101-113.

This is an investigation of vegetation, floodplain behavior, and glacial advances seen through the a 14.5 ka lake sediment record. Okpilak Lake is situated on the foothills (600 m alt.) of the Eastern Brooks Range in Arctic National Wildlife Refuge (ANWR). The lake is located adjacent to the outwash plain of the glacier-influenced braided plain of the Okpilak River amongst tussock and shrub tundra. Its location makes the lake vulnerable to clastic input from the adjacent Okpilak River, alluvial fans affecting the inlet, and lakeshore bank erosion. Pollen, lithology/magnetics, and radiocarbon analyses were conducted on two, side-by-side cores (~11 m thick) collected from the deeper half of the lake (11.5 m water depth). Age control was moderately precise (avg. 1 sample per 1 ka), however no identification of the ^{14}C samples was reported, nor were the $\delta^{13}\text{C}$ values, which does not rule out aquatic plant ^{14}C ages tainted by a reservoir effect or reworked wood. The sediment lithology was very dynamic, recording deposition of clastic material alternated by organic rich gyttja recording autochthonous productivity. Birch dominated the tundra after 11.6 ka, where it was briefly

among cottonwood trees in the early Holocene. The typical moist acidic tundra indicators such as Ericaceae, (11.6 ka), Sphagnum moss (11 ka), and *Rubus chamaemorus* (9 ka) are well established by this time. Alder comes on the scene around 6 ka. Inorganic layers record river aggradation events on the Okpilak River during the late-glacial, early Holocene transition (10.9-10.0 and 9.4-9.2 ka), and again at 6.8, 5.5 ka and during the Little Ice Age. Some of these correspond to known warming events in the region (early Holocene), while others are coincident with glacial advances during the mid-Holocene. The suspect dating on this record prevents precise correlation with other river aggradation event studies (i.e. Mann, et al., 2010), but it is interesting that there is undisputable evidence for dynamic floodplain aggradation events during the Holocene. It is also interesting to note the sequence of different moist acidic tundra indicators.

Wildfire

Swanson, D. 1996. *Susceptibility of permafrost soils to deep thaw after forest fires in interior Alaska, USA, and some ecologic implications. Arctic and Alpine Research 28(2): 212-227.*

This study describes active layer, soil characteristics and flora before and after wildfires recorded at nearly 200 sites across Kobuk Valley National Park. Survey points were along transects that went over various topographic positions to get a sense of how the collected data interacted with slope azimuth and geology. Permafrost thaw occurs after a fire due to lack of ground shade, increase in runoff from up valley, and combustion of organic layer. Lowland areas and north facing slopes typically did not thaw after fires. These places also had the thickest O layers before and after the fire. In many cases hillsides, ridge shoulders, non-north facing slopes and convex slopes with moderate organic layers had active layers that were greater than a meter. Many of these places showed evidence of near-surface permafrost that was likely present prior to the fire. This evidence included micro-scale cryoturbation, and periglacial features. Areas lacking post-fire thaw generally did not show a lot of vegetation change from that which likely occurred before the fire. The methods employed and potential sample bias in different sites prevented a quantitative estimate of the landscape area thawed after burn. In general this paper provides a good classification system that declares where wildfire would cause enhanced post-fire thaw and where thaw would be lacking.

Yoshikawa, K., Bolton, W. R., Romanovsky, V. E., Fukuda, M., and Hinzman, L. D. 2003. *Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. Journal of Geophysical Research 108(D1):FFR-4.**

This paper examined the impact of wildfires on permafrost in the boreal forest of interior Alaska by studying eleven fire sites, including two controlled burns, with years of ignition ranging from 1924 to 2000. In particular, the authors focused on quantifying the impacts of fire on 1) direct heat conduction and convection to the ground, 2) removing moss as an insulating material, 3) heat budget, 4) soil moisture characteristics, and 5) active layer thickness and talik formation. Immediately following fire, ground thermal conductivity may increase 10-fold and the surface albedo can decrease by 50 percent depending on the extent of burning of the surficial organic soil. The authors found that if the organic layer thickness was not reduced during the burn, then the active layer did not change after the burn in spite of the surface albedo decrease. However, for sites with a high burn severity and combustion of the organic layer, the active layer increased to a depth that did not refreeze each

winter after a period of 3-5 years. At a site that burned in 1983, a talik thickness of 4m was already present. Table 1 provides an overview of the instrumentation involved in the study.

Vegetation Change

Billings, W. D., and Peterson, K. M. 1980. Vegetational change and ice-wedge polygons through the thaw-lake cycle in arctic Alaska. *Arctic and Alpine Research* 12(4): 413-432.

This paper provides an overview of the thermokarst lake cycle through the study of vegetation succession in a chronosequence of drained thermokarst lake basins located near Barrow, AK. Pioneer species in recently drained lake basins consisted of *Dupontia fischerii* and *Arctophila fulva*. As time passes since drainage, *Carex aquatilis* becomes more abundant as does the development of ice wedge polygonal networks.

Jorgenson, M. T. and Osterkamp, T.E. 2005. Response of boreal ecosystems to varying modes of permafrost degradation. *Canadian Journal of Forest Research* 35(9): 2100-2111.*

This paper describes the many modes of permafrost degradation, associated land features before and after thaw, and the ecological and geomorphological consequences occurring in the years after thaw. Thermokarst lakes form in the boreal forest, and can expand laterally by thermomechanical erosion at rates of 0.1-2 m/year. Kettle lakes on ice cored moraines in glacial features can similarly form near Alaska's formerly glaciated mountain chains. Their expansion is more localized to ice rich moraines. Scar-fens form when spring water from nearby mountains rise to the surface and melt ice rich floodplain deposits, creating a linear oriented subsidence scar with dead forests. Collapse scar bogs are a more localized subsidence process and are usually rounded features that form on old floodplain deposits. Because boreal forests have limited shallow ice wedge networks, features like troughs, pits and polygonal mounds are rare relative to northern Alaska. Upon thaw, boreal ice wedges may have different routes and rates of stabilization because of increased productivity laying down thicker soils that insulate deeper ice wedges. Thermokarst pipes can form on steeper slopes and is also a precursor to rapid Holocene or Pleistocene ice degradation about to ensue. Active layer detachments (ALDs) and thaw slumps are uncommon but can form rapidly. It is said that ALDs in the boreal forest can be enhanced on particularly warm summers or following a fire. Climate gradients and snow depth from south to north affect permafrost degradation and its history. Warmer areas with more snow are more likely to have enhanced degradation, while northerly areas with thin snow packs are only vulnerable to surface degradation. Lowland areas with finer, and more ice rich sediments are the most vulnerable to more dramatic degradation. Sub-surface groundwater flow is probably the biggest mystery of detecting the landscape's vulnerability of degradation. Due to the distinct successional responses of vegetation and aquatic habitats after permafrost degradation, one can interpret recent history of landscapes using a variety of observations, which would be helpful when assessing the threat to archaeology sites.

Lloyd, A. H., Yoshikawa, K., Fastie, C. L., Hinzman, L., and Fraver, M. (2003). Effects of permafrost degradation on woody vegetation at arctic treeline on the Seward Peninsula, Alaska.. *Permafrost and Periglacial Processes* 14(2): 93-101.*

This paper examined how climate-induced changes in active layer thickness and soil drainage influences advancement of the treeline on the Seward Peninsula, Alaska. The authors measured active layer thickness, soil moisture, density of tall shrub species, cover of low shrub species, and

reconstructed white spruce establishment history along transects across the banks of a network of thaw ponds. Transects covered topographical types including: channels (low-lying depressions at the elevation of the thaw ponds), banks (the scarp at the edge of the thaw ponds and low-lying depressions), and flats (the level terrain at the top of the banks) and included sites with and without trees and shrubs. The authors counted and tagged each tree and measured tree characteristics and took core samples to examine growth patterns, counted density of tall shrub stems, and counted other shrub species as a visual estimate of percent cover. Active layer depth was measured in late August using a thaw depth probe. Soil moisture was measured as volumetric soil water content using a dielectric constant measuring device inserted into the soil. Active layer thickness didn't vary along transects, but soils on thaw pond banks were much drier than those on level tundra or thaw pond channels. Furthermore, thaw-pond banks were the only sites in which trees successfully established, and shrubs were taller and more dominated by tall shrub species (e.g., willow and shrub birch) than other areas. The authors speculate that tree and shrub advancement in the tundra depends on well-drained microsites, like those on thaw pond banks, and thus treeline advancement is contingent on further degradation of existing permafrost.

Shur, Y. L., and Jorgenson, M. T. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes* 18(1): 7-19.

This paper presents a classification system for describing the complex interaction of climate and ecological processes on permafrost formation and degradation. The authors distinguished five types of permafrost: climate-driven; climate-driven, ecosystem-modified; climate-driven, ecosystem protected; ecosystem-driven; and ecosystem-protected. Climate-driven permafrost forms under modern climatic conditions in recently exposed land surfaces and is found primarily in the continuous permafrost zone. Climate-driven, ecosystem-modified permafrost occurs in the continuous permafrost zone when vegetation succession and organic-matter accumulation lead to development of an ice-rich layer at the top of the permafrost. Climate-driven, ecosystem-protected permafrost refers to permafrost currently located in the discontinuous permafrost that initially formed as climate-driven but its stability is now a result of overlying vegetation and organic material. If this permafrost thaws it cannot reestablish under current climatic conditions. Ecosystem-driven permafrost forms in the discontinuous permafrost zone in poorly drained, low-lying and north-facing landscape conditions, and under strong ecosystem influence. Finally, ecosystem-protected permafrost persists as sporadic patches under warmer climates, but cannot be re-established after disturbance. The authors note that these distinctions are important since these various types of permafrost react differently to disturbance and climate change.

Tsuyuzaki, S., Ishazaki, T., and Sato, T. 1999. Vegetation structure in gullies developed by the melting of ice wedges along Kolyma River, northern Siberia.. *Ecological Research* 14(4): 385–391.*

This paper examined the relationship between thermokarst gully characteristics and vegetation communities in northern Siberia, Russia. The authors surveyed 5-10 randomly selected plots within each gully. Height, width and slope of each gully were measured with a transit compass while soil moisture and pH were tested using a portable soil tester. Soil compaction was tested at five points in each plot using a soil hardness tester. Percent cover of each plant species was visually estimated. In

gullies surveyed, ~50percent of the area was vegetated. Cluster analysis revealed 4 vegetation community types: flixweed (*Descurainia sophia*)-dominated grassland, chamomile (*Matricaria matricarioides*)-dominated forbland, purple dropseed (*Agrostis purpurascens*)-dominated grassland with fire moss (*Ceratodon purpureus*) carpet, and fireweed (*Chamaenerium angustifolium*) and chamomile-dominated forbland. Gully height, width, and elevational differences influenced dominant vegetation types. The authors' determined these differences were mediated by the influence of gully height on soil pH and compaction and soil stability, which then influenced vegetation establishment. Dominant species were all long-distance dispersers and the authors' suggest re-vegetation of thermokarst features like gullies favor species with long-distance dispersal mechanisms. Soil moisture was positively associated with soil pH and soil compaction. Steep slopes consisted of softer soils (i.e., less compact and stable). Flixweed established in large gullies, while common horsetail (*Equisetum arvense*) and feltleaf willow (*Salix alaxensis*) established in small gullies. Siberian dock (*Rumex sibericus*) did not establish on compact soils, where fire moss was common. Fireweed and chamomile did not establish on small gullies with soft soil and low soil pH.

Archaeology

Blankholm, H. 2009. Long-term research and cultural resource management strategies in light of climate change and human impact. *Arctic Anthropology* 46(1-2): 17-24.

This review gives a brief, yet broad synthesis on the impacts that global change will likely have on archaeological resources in the circum-arctic and Antarctic. Blankholm divides these processes into climate change and human disturbances. Climate change effects on archaeological sites include sea level, wind ablation, glacier and snowfield wasting, lake levels, tree-line expansion covering up visible sites, and permafrost thaw causing ground subsidence or decomposition of organic artifacts. The author notes that prehistoric people congregated near shorelines, treeline, wind exposed areas, and other places on the edge of landscape types vulnerable to change. Several human impacts were highlighted including mineral exploration, drilling and mining, hydroelectric dams, the fishing industry, and tourism such as camping locations. The supporting activities of these industries, such as road access and pipelines, also have direct and often greater impact on landscape disturbance. Blankholm ends the paper with a call for action to polar archaeologists and environmental change scientists to better understand the effects of these processes on archaeology.

Buckland, P. I., Eriksson, E., Linderholm, J., Viklund, K., Engelmark, R., Palm, F., Svensson, P., Olofsson, J. 2011. Integrating human dimensions of Arctic palaeoenvironmental science: SEAD—the strategic environmental archaeology database. *Journal of Archaeological Science* 38(2): 345-351.

This paper starts with a review of human impacts on the local environment during prehistoric periods in the arctic, and then goes on to introduce a paleoenvironmental database to ultimately summarize and provide data for these occurrences. Based in the countries lining the North Atlantic, this database, the Strategic Environmental Archaeology Database Project (SEAD), will focus on several different types of paleoenvironmental data relevant for archaeology. Unlike other databases, such as PAGES, and Neotoma, this will take the human-environment view by incorporating a wide range of data and describing the archaeological implications. The arctic was chosen because it was and will be most vulnerable to climate change and the ecological impacts of climate and human-induced

landscape change that has resounding effects on ecological communities in the far north. Interesting notes include farming impacts of Greenland Norse, Sami reindeer herding and chemical impacts on soils and adjacent hydrology. Buckland also describes the arctic as a place on the fringe where long records and multi-proxy evidence for paleoenvironmental impacts are sparse. This motivates the compilation and gathering of the arctic literature to make it more powerful and allows a destination for summarizing some grey literature mentioned from Scandinavian countries. The paper concludes with a rallying cry for getting data into this system so people can use it.

Human Disturbances

French, H. M. 1975. Man-Induced thermokarst, Sachs Harbour Airstrip, Banks Island, Northwest Territories. Canadian Journal of Earth Sciences 12(2): 132-144.

This paper describes the degradation of ice wedges associated with the installation of an airstrip on Banks Island in Canada. The silts, sands, and gravel that underlie the surface are ice rich with values ranging from 20-95 percent excess ice content. Degradation of ice wedges and development of thermokarst rapidly occurred in the first three years following construction of the airstrip and subsidence on the order of 10 cm was measured using survey equipment. Repeat surveys at the site in the first decade following disturbance indicate that thermokarst is still progressing actively at the site.

Lawson, D. L. 1986. Response of permafrost terrain to disturbance: A synthesis of observations from northern Alaska, U.S.A. Arctic and Alpine Research 18(1): 1-18.

This paper examines thermokarst effects by drilling activities during the 1940s and 1950s in the NPR-A. Three locations were examined, Fish Creek, Oumalik and East Oumalik. Each were intensive drilling locations for at least one year, but vary in their surficial geology and permafrost characteristics. Observing how these sites responded differently to the similar disturbances allowed a wider inference of how the wider region will respond to near surface disturbance. The disturbances were grouped into trampling of vegetation, killing of vegetative cover, removal of the vegetative mat, and removal of the vegetation and soil. Areas with coarse-grained sediments, lower ice content and minimal breadth of ground ice complexes (i.e. ice wedges) had less and more localized disturbances than areas with higher ground ice, widespread ice wedges, and finer sediments, which had more widespread disturbance. Removing vegetation and surface soils were responsible for the most widespread disturbances. In general the former types of landscapes had disturbances that did not spread beyond the localized subsidence due to thaw, whereas, in the latter landscape type disturbance was extensive due to slumping, sediment flow, and thermal and mechanical erosion after subsidence. Upon subsidence, an area was more prone to extensive erosion if drainage or higher relief was associated with that area. Lawson introduces a stability index that is based on the initial disturbance area and the affected area. In general, degradation processes were most complex at the Oumalik fine silt upland site and least complex in the stabilized dunes at Fish Creek. After disturbance, physical stability of the ground, which usually happens after some subsidence, is required for vegetation stabilization. This can take upwards of 30 years in the case of the Oumalik site. Ice-poor, thaw-stable materials in undrained or low relief areas required an estimated five to ten years for stability. This is an excellent study showing how different terrain representative of Arctic Alaska responds to disturbance and subsequently recovers.

Mackay, J. R. 1970. Disturbances to the tundra and forest tundra environment of the western Arctic. *Canadian Geotechnical Journal* 7(4): 420-432.

The author defines the terms thermokarst and thermo-erosion and highlights differences between these two terms - in particular the importance for thermal degradation and vertical subsidence for thermokarst versus the importance for thermal degradation, mechanical erosion, and lateral expansion under the influence of flowing water for thermo-erosion. The author uses multiple examples from Northern Canada to explain his views of these processes. Examples include the impact of man-made disturbances from seismic exploration, a wildfire, a seepage in a channel, and a dog kennel patch on underlying permafrost. Field measured rates of thermokarst and thermo-erosion are reported for each of these examples. The paper seems to be the only example of canine-caused thermokarst in permafrost regions and highlights the possible role of cumulative small-scale man-made impacts.

Fluvial Geomorphology

Bowden, W. B., Gooseff, M. N., Balser, A., Green, A., Peterson, B. J., and Bradford, J. 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. *Journal of Geophysical Research* 113(G2): G02026.

Thermokarst features are increasing near the Toolik Lake Natural Research Area, and these features are delivering nutrients and sediments to headwater streams. These additions are at levels that are well above background levels, and at concentrations that have been found to significantly affect primary and secondary production in water bodies. While thermokarst features only affect a finite area on the terrestrial landscape, their effects may be felt through a very large fraction of the stream network. Thermokarsting increased small stream total suspended sediments (TSS) by several orders of magnitude, and increased Toolik River TSS by approximately one order of magnitude. Nutrients increased below thermokarst features, and remained elevated for several hundred meters downstream. Sampling of another nearby feature indicated that nutrient outflow from thermokarst features elevated stream concentrations over the period of record (1999-2005).

Costard, F., Gautier, E., Brunstein, D., Hammadi, J., Fedorov, A., Yang, D., and Dupeyrat, L. 2007. Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. *Geophysical Research Letters* 34(14): L14501.*

This paper links climatic changes in Central Siberia to fluvial erosion of the Lena River. The authors note three major changes since the 1980s: reduced winter ice thickness, increased spring water temperature (up to 2° C), and a slight increase in spring discharge. Areal and satellite maps are then used to observe the effects of these fluvial changes on the river banks and vegetated islands. The most obvious change was accelerated head retreat in vegetated islands, which increased by 21 percent to 24.5 percent. These rates are consistent with predictions from an ablation model, which found that the water temperature increase was a 4-fold more important explanatory variable than the discharge increase. Deposition of sediments on wide bars and long islands suggests that eroded sediment is not transported far, but will mean that islands migrate faster.

Dupeyrat, L., Costard, F., Randriamazaoro, R., Gailhardis, E., Gautier, E., and Fedorov, A. 2011. Effects of ice content on the thermal erosion of permafrost: Implications for coastal and fluvial erosion. *Permafrost and Periglacial Processes* 22: 179-187.*

This paper considers the relative importance of thaw versus ablation in eroding frozen, non-cohesive riverbanks using mathematical models and laboratory experiments. The authors find that their experimental results can be matched by an ablation model above a critical ice content threshold (depending on the Reynolds number of the water). Below this threshold, sediments will thaw but may or may not move depending on the erosive power of the water and strength of the medium. The authors find that the main factor controlling thermal erosion is usually water temperature, as opposed to ground temperature. This model may explain apparently contradictory field observations of erosion potential of the banks of the Lena River.

Goudie, A. S. 2006. Global warming and fluvial geomorphology. *Geomorphology* 79(3): 384-394.

This general review paper delivers some broad concepts and connections about future climate change's effects on runoff, sediment transport, and the outcomes for geomorphologic features. Due to the paper's broad nature, I discuss what is relevant for our studies in this report. A relevant process that is expected with warmer temperatures is the ability for air to hold more water, which implies greater thermodynamic instability and increased extreme precipitation events. This scenario could affect areas in GAAR that are proximal to moisture sources such as in the southeastern portion of the Park. Run-off coefficients (the amount of runoff occurring for any given rise or fall of precipitation) will be more sensitive in historically arid regions, and will depend on the ability for increased productivity to respond to warmer/wetter climates and intercept precipitation. This lag period of disequilibrium is said to be the most dynamic time for a basin. Specific to cold regions, run-off will be affected by the general model of climate change, but also thermokarst depressions acting as storage basins for precipitation, changes in ice jams, the timing of run-off and soil thaw, and the ability for deeper active layers to store water. Many of these symptoms of climate change will affect the rate of channel bank erosions, sinuosity, braided networks, floodplain colonization by plants, and many other factors. Fire is also a relevant geomorphic agent, which seems to be understudied at high latitudes.

Hamilton, T. D. 2001. Quaternary glacial, lacustrine, and fluvial interactions in the western Noatak basin, Northwest Alaska. *Quaternary Science Reviews* 20(1): 371-391.

This paper describes extensive work on Quaternary sediment exposures in the Noatak River Basin that are representative of four glacial advances and as a result glacial dammed lake deposits of varying extent occurring in the Noatak Basin. At times glacial lobes came south out of the Delong Mountains to dam the Noatak River, forming an extensive lake that overflowed into the north-flowing Etivluk River. During the LGM this "Lake Noatak" existed, but was thinner and confined to the lower valleys as a result of less extensive glaciation. The result is multiple bands of glacial alluvial deposits alternated with extensive glacial lacustrine sediments. The depth and distribution of many of these layers have important implications for ground ice regimes in the Noatak Basin and environs. Glacio-lacustrine sediments have a distinct ability to retain water, which, upon lake drainage and permafrost aggradation, can form ice-rich deposits that are vulnerable to subsequent thaw. The distribution of these deposits is mapped in this paper, and the topographical framework is

described in a manner that these scenarios could be identified in other Brooks Range valleys. The LGM or Anisak glacial advance in this region corresponds to the timing and nature of the Itkillik II glaciation. It is said that source areas for this western Brooks Range glacial advances are lower, which implies more proximal moisture sources than the Central and Northern Brooks Range source areas that are much higher.

McNamara, J. P., D. L. Kane, and L. D. Hinzman. 1999. *An analysis of an arctic channel network using a digital elevation model. Geomorphology* 29(3): 339-353.

This paper compares the results of temperate fluvial geomorphology models that predict the point at which stream channels form on the Imnaviat watershed in the Arctic Foothills of the North Slope of Alaska. The goal of the paper was to observe whether this watershed, which is underlain by continuous permafrost, behaved the same as watersheds without permafrost, to better understand the controls on stream distribution. The focal feature of this paper is water-tracks, drainage channels that are not incised, but drain substantial portions of the upper watersheds in arctic tundra regions. The heads of channels were observed to begin in a critical area that the modeling classified as the transition from hill-slope to valley processes. Modeling predicted channels where poorly developed watertracks should have been. Water-tracks do not follow other fluvial geomorphology of mature watershed models that observe fractal tendencies of channels. The authors attribute the unique watershed characteristics that they observed to the fact that permafrost has stabilized much of the slopes and has not allowed the watertracks to incise and become a more channelized watershed. The models indicate that this channelized watershed would have been created in a more temperate region. The authors say that the consequence of this “frozen” state of pre-mature basins is large valleys with extensive, relatively un-dissected hillslopes. The implications for this literature review are the following: 1) In a warmer climate, water tracks are vulnerable to incision, and are a potential supply of sediment sources. 2) Perhaps there are basin characteristics indicating a period of past incision that occurred because of a warming event. 3) The landscape morphology that occurs for people and archaeology is dependent on these rather unique basin characteristics.

Toniolo, H., Kodial, P., Hinzman, L. D., and Yoshikawa, K. 2009. *Spatio-temporal evolution of a thermokarst in interior Alaska. Cold Regions Science and Technology* 56(1): 39-49.*

This paper describes the rapid development of a thermokarst gully in interior Alaska over a two year period with a focus on the role of sediment transport and its associated geomorphological processes. The study combined the use of fieldwork and laboratory work. Fieldwork consisted of topographical surveys, discharge measurements, systematic water sampling, and abundant visual documentation of morphologic changes through digital photographs. Laboratory work mainly consisted of water sample analyses to obtain suspended solid concentration and suspended sediment grain-size distribution. The processes responsible for the rapid development of the features consisted of fluvio-thermal erosion and cryogenic piping. Headward erosion of the gully was 3.5 m/yr over the study period and lateral slumping of the gully walls was 0.5 m/yr. Active sedimentation from the thermokarst has led to initial infilling of a pond in the drainage. The authors noted that since groundwater flow in the study site was found to be an important part of the accelerated thermokarst growth, future work should look more closely at the subsurface flow network.

Walker, J., Arnborg, L., and Peippo, J. 1987. Riverbank erosion in the Colville delta, Alaska. *Geografiska Annaler Series a-Physical Geography* 69(A), 61-70.*

This paper summarized the erosion rates of the Colville River delta, Alaska. The delta is ice covered for over eight months per year and is subjected to high discharge rates and periodic flooding events during break up each year. The authors suggest bank erosion is likely to occur along as much as 60 percent of the banks of the main river channels during that 3-4 week period. Erosion is the result of hydromechanical and thermal impact of water as well as other factors including bank composition and height, snow and ice cover, stage and velocity of discharge, air and water temperature, and wind. Thermo-erosional niches form and large blocks break off into the river. The banks were measured during irregular time intervals from 1961-1987. Echosounding traces were used to monitor the shifting of the channel and changes in channel form. Stakes were placed 25 or 50 ft. from the bluff edge to measure erosion rates. One year later erosion ranged from 0 to 10.9 m, 5-years later erosion had destroyed two stakes, three others were found over the bluff edge, and two were missing. Most erosional banks were peat (75 percent), followed by laminated silts (15 percent), Gubik silts, sands, and gravels (7 percent), and sand dunes (3 percent). Average erosion rates may reach 4 m per year, but rarely exceeded 3 m per year, although there is high spatial and temporal variability. Block collapse can result in as much as 12 m of instantaneous retreat. The rate of breakup impacts erosion rates – fast breakup may result in faster erosion rates.

Warburton, J. 1990. An alpine proglacial fluvial sediment budget. *Geografiska Annaler Series a-Physical Geography* 72(A):261-272.

This paper reviews the concepts and defines a sediment budget for suspended and bed-load transport over the course of the wasting season in an Alpine glacier catchment. This budget involves the productions transport and discharge of detritus. Although other studies have focused on total yield, this is not sufficient, because it does not explain how sediment yield changes in different conditions preventing any forecasting. Unlike continuous permafrost environments where mass movements can occur, slope processes can be minimal in this environment so the author focused on fluvial transport. This study is relevant for assessing the relative amount of channel change and sediment deposition in glacier-fed and formerly-glacier-fed floodplains in GAAR. Sixty-five percent of transport was in the form of bed-load, while the remainder was estimated to be suspended transport. Sediment transport was positively related to runoff and was at a maximum during the ablation period. A 10 percent increase of sediment yield occurred downstream in the study area, indicating an amount of sediment from side-valleys and slopes. A flood that occurred over a four-day period had drastic implications for channel morphology that affected the stream differently in various up or downstream positions. In this study, channel erosion and to some extent bluff erosion was the main supplier of sediment yield along this stretch of river. Although evidence for channel degradation and net loss of channel material was observed in the two years of this study, most proglacial streams are aggradational in nature over long term periods. Based on this study, for that shift to take place would involve changes in discharge, increased sediment supply from side-channels, and the reduction in flood events, and the increase of sediment supply by a retreating glacier.

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