Regional patterns of ice-wedge degradation since the mid-20th century across northern Alaska

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Abstract

Ice-wedge polygons are abundant in permafrost landscapes of Alaska's North Slope, creating complex microtopography and meter-scale contrasts in hydrology, vegetation, and ground-ice conditions. Rapid and dramatic landscape changes have occurred in recent decades on the eastern North Slope coastal plain due to thaw of the uppermost portions of ice wedges. Direct impacts include ground subsidence (thermokarst), vegetation mortality and a landscape pock-marked with small flooded pits along polygon margins. Secondary impacts include further thermal degradation of permafrost and rearrangement of subsurface water flow on the landscape, affecting areas well beyond the thermokarst pits themselves. Archives of historical (1948, 1955, 1971, 1977–1985) and modern high-resolution imagery support change detection in polygonized landscapes along regional gradients of climate and geomorphology spanning the North Slope.
To characterize the timing and extent of ice-wedge degradation, we delineated small waterbodies in historical and modern imagery for a network of eleven 43 km^2 study areas across the North Slope utilizing high-resolution, multi-spectral aerial photography (1979–1985), and modern satellite imagery (2009–2012). We iteratively set a threshold near-infrared reflectance value to each image to discriminate small waterbodies from land on old, residual upland landscapes in each study area. Spatial analysis of water extent indicated increase in the area occupied by flooded pits at 8 of 11 landscapes since circa 1980 (median +10.6%; maximum 134.6%). The 3 landscapes where water extent decreased are all located on the western North Slope, where historical photography indicates that widespread thermokarst began before ~1950. Recent thermokarst pit increase was prevalent on the eolian sand sheet and ice-rich silt (yedoma), but not on alluvio-marine deposits near the Chukchi coast. Because the ice wedges underlying residual uplands have developed over millennial timescales, the changes observed over the past few decades appear to represent a directional change that cannot be offset on decadal timescales by ice aggradation elsewhere. The regional pattern of ice-wedge degradation is intriguing, in that thermokarst appears to have initiated earlier on western, alluvio-marine deposits and progressed further east. Future work involves field-based and modeling approaches to identify physical and climatic mechanisms that could corroborate the spatial changes observed since the mid-20th century.

Introduction & Methods

Numerous reports of ice-wedge thermokarst have emerged over the last decade from across the Arctic, including the Alaska North Slope (Jorgenson et al. 2006), the Canadian High Arctic (V. Romanovsky, unpubl. data), and the forest-tundra ecotone in northeast Siberia (Frost and Epstein 2014) (**Figs. 1, 2**). Ice-wedge thermokarst often results in an irregular land surface with a multitude of small flooded waterbodies. Here we evaluate regional patterns of ice-wedge degradation across the Alaska North Slope, where ice-wedge polygons are abundant, and extensive archives of historical high-resolution photography exist to identify spatio-temporal patterns of landscape change. The study area encompasses three broad geomorphic environments with differing substrates, landscape histories, and ground-ice conditions: (1) alluvio-marine deposits along the Chuckchi Sea coast; (2) the eolian sand sheet southeast of the Barrow arch; and (3) ice-rich eolian silt (yedoma) of the northern Brooks Range foothills (**Fig. 3**).

We quantified the extent of small (< 500 m^2) thermokarst pits evident in color-infrared (CIR) photography from the Alaska High Altitude Photography Program (AHAP) (1977–1985), and in modern very-high-resolution satellite imagery (2010–2012) across a network of eleven 43 km^2 study areas. To distinguish thermokarst pits, we exploited near-infrared (NIR) reflectance values, which are much lower for open water than for tundra vegetation. For this analysis, we focused on old, residual upland landscapes, where ice wedges have developed over long periods of time and surface water is usually only present in thermokarst pits. We used 5-m resolution IFSAR DEMs to mask low-lying areas, such as drained-lake basins, where there is high inter-annual variability in water level, ice wedges are smaller, and changes difficult to interpret. We also referred to older (1948–1955), black & white aerial photography to estimate surface water conditions in prior decades.

Figure 1. Thaw of large, old ice wedges can lead to dramatic landscape change over a matter of years. Initiation of thermokarst (at left) triggers ground subsidence, vegetation mortality, ponding, and the alteration of flowpaths. Over time, pits become stabilized by colonizing wetland vegetation and the development of an organic mat.

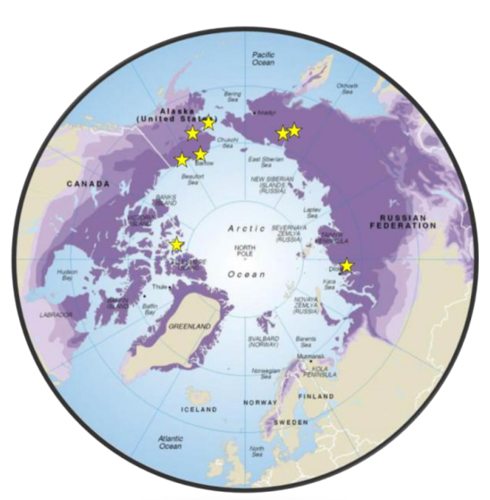


Figure 2. Reports of recent ice-wedge degradation span most of the circumpolar Arctic. From Liljedahl et al. (2013).

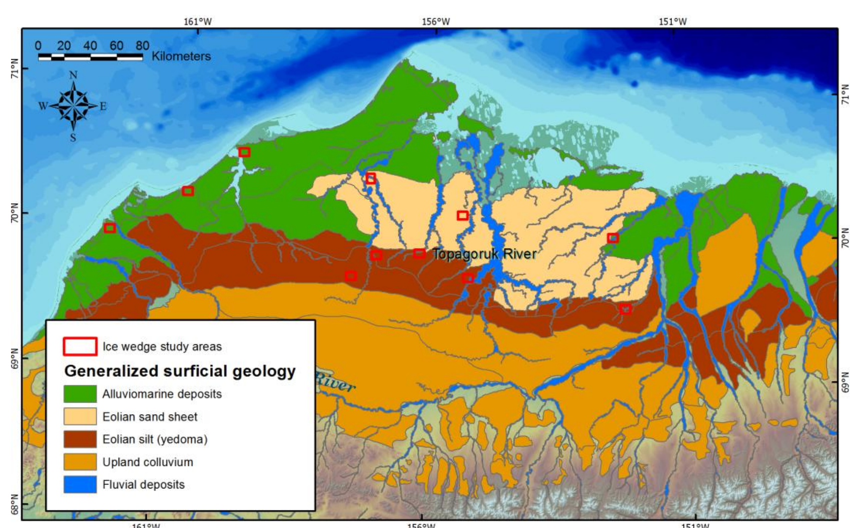


Figure 3. Study sites (red boxes) are distributed in three broad geomorphic environments: alluvio-marine deposits, eolian sand sheet, and ice-rich silt (yedoma) in the foothills. Mapping after Jorgenson and Grunblatt (2013).

Results

Spatio-temporal analysis revealed increase in the total area of flooded thermokarst pits at 8 of 11 study landscapes since ~1980 (**Table 1, Figs. 4–7**). Across the study area, percent change in the cover of flooded pits ranged from -27.3% to +134.6% (median +10.6%). The overall extent of flooded pits was highest in both historical, and modern periods on old alluvio-marine deposits near the Chukchi coast, where thermokarst was already well underway before ~1950. However, pit extent has declined since the early 1980s at 2 of 3 alluvio-marine sites. Pit extent increased at all 3 sites on the eolian sand sheet, and at 4 of 5 yedoma sites. The most dramatic changes by far occurred on ice-rich yedoma in the eastern part of the study area, with pit extent more than doubling at the southeasternmost site (Kogosukruk River); however, pit extent decreased substantially at the westernmost yedoma site (Upper Meade River). Overall, a regional pattern is evident from west to east. Changes in thermokarst pit extent were predominantly negative at the westernmost sites, and there is a sharp rise in recent thermokarst rates moving from west to east across the study area (**Fig. 8**).

Table 1. Summary of study area locations, imagery dates, and observed changes in thermokarst pit extent (circa 1980–2010). Negative values are shown in parentheses.

Study area	Lat (°N)	Long (°E)	Geomorphic setting	AHAP imagery date	Modern imagery date	Total pit area (ha) AHAP	Total pit area (ha) Modern	% change	% change decade^{-1}
Kugachiak Creek	70.0	-162.3	Alluvio-marine	16 Jul 1982	08 Aug 2010	176.3	161.5	(8.4)	(13.6)
Ongorakvik River	70.3	-160.9	Alluvio-marine	02 Aug 1985	05 Jul 2012	166.6	196.7	18.1	6.5
Wainwright	70.6	-159.8	Alluvio-marine	18 Jul 1982	08 Jul 2012	30.7	23.9	(22.1)	(7.4)
Upper Meade	69.8	-157.5	Yedoma	16 Jul 1982	19 Jul 2009	16.6	12.1	(27.3)	(3.1)
Atqasuk East	70.5	-157.2	Sand sheet	02 Aug 1985	22 Jul 2012	0.8	0.9	11.3	4.2
Piksiksak Creek	70.0	-157.0	Yedoma	16 Jul 1982	22 Jul 2012	3.8	6.1	61.0	20.3
Topagoruk River	70.0	-156.2	Yedoma	16 Jul 1982	09 Jul 2010	12.4	13.0	4.7	1.7
Oumalik River	70.3	-155.4	Sand sheet	16 Jul 1982	15 Jul 2009	43.3	47.6	10.0	3.7
Titaluk River	69.8	-155.2	Yedoma	16 Jul 1982	25 Jun 2010	25.7	45.6	77.8	27.8
Judy Creek	70.1	-152.4	Sand sheet	13 Jul 1979	22 Jul 2012	5.0	7.8	55.8	16.9
Kogosukruk River	69.6	-152.2	Yedoma	1 Aug 1977	22 Aug 2011	7.5	17.7	134.6	39.6

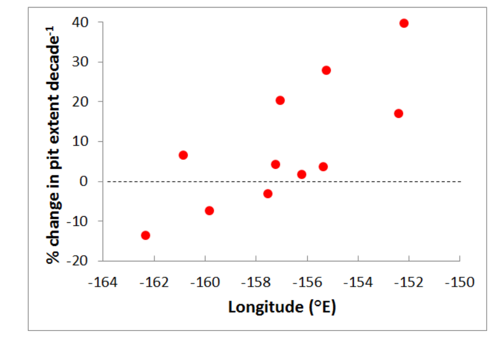


Figure 8. Decadal rates of change in thermokarst pit extent exhibit a regional pattern, with stabilization of pits prevalent in the west, and highest rates of increase in the east.

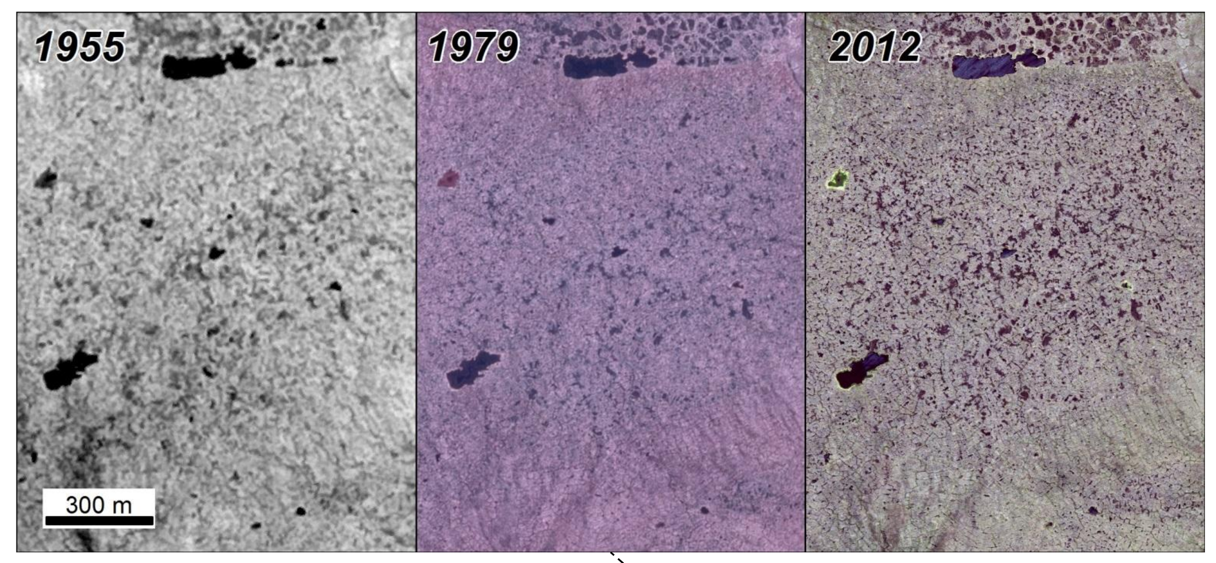


Figure 4. Thermokarst pit evolution at Wainwright, 1955–2010. Most of the thermokarst pits present in 2012 were already evident in 1955 imagery. Surface water extent decreased overall at 2 of the 3 westernmost study areas, on alluvio-marine deposits. In contrast to sites further east, thermokarst pits were already widespread at the 3 alluvio-marine sites as of 1955.

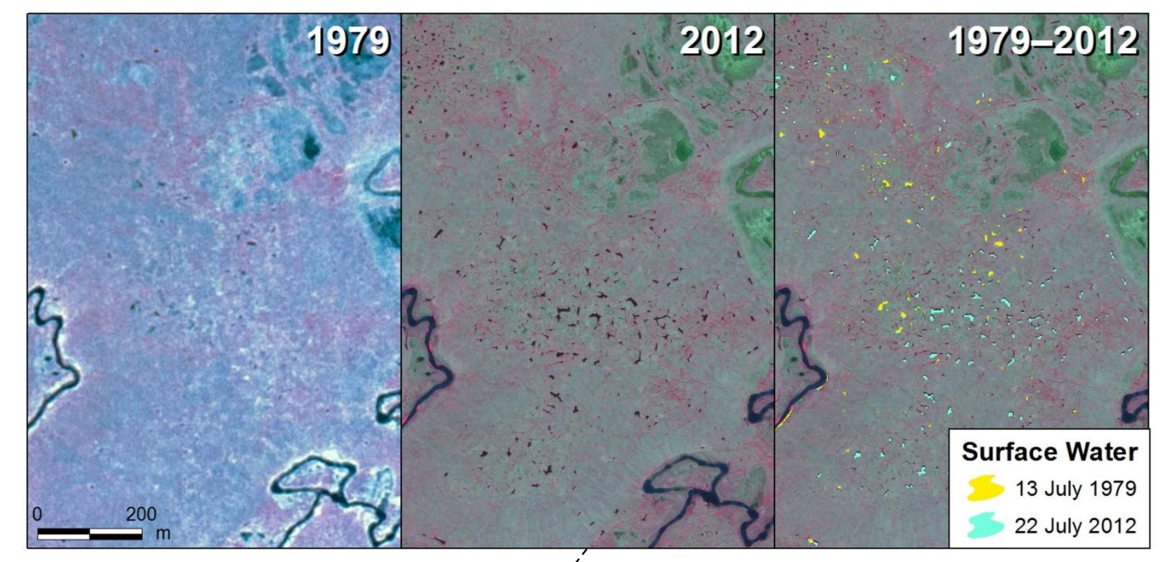
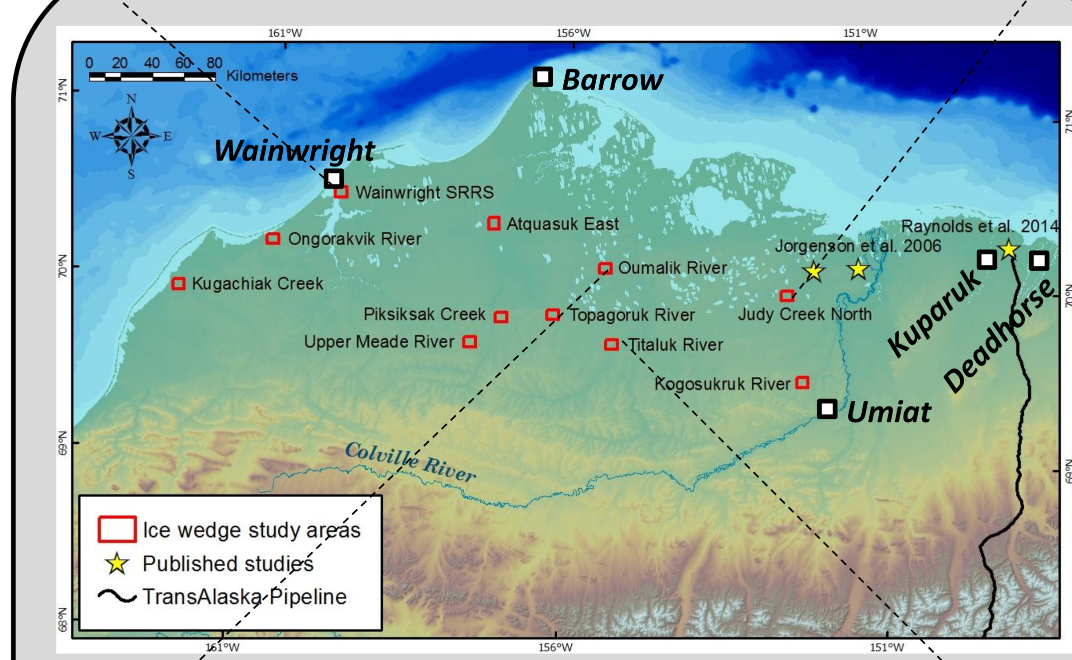


Figure 6. Thermokarst pit development on eolian sand sheet at Judy Creek study area, 1979–2012. The extent of flooded pits increased by 56% at this study area. Note that some of the pits evident in 1979 have become colonized by vegetation. Published reports of recent ice-wedge thermokarst come from sand sheet and alluvio-marine environments to the northeast (Jorgenson et al. 2006).



Study sites (red boxes) span the western two-thirds of Alaska's North Slope. Yellow stars show published reports of ice-wedge degradation.

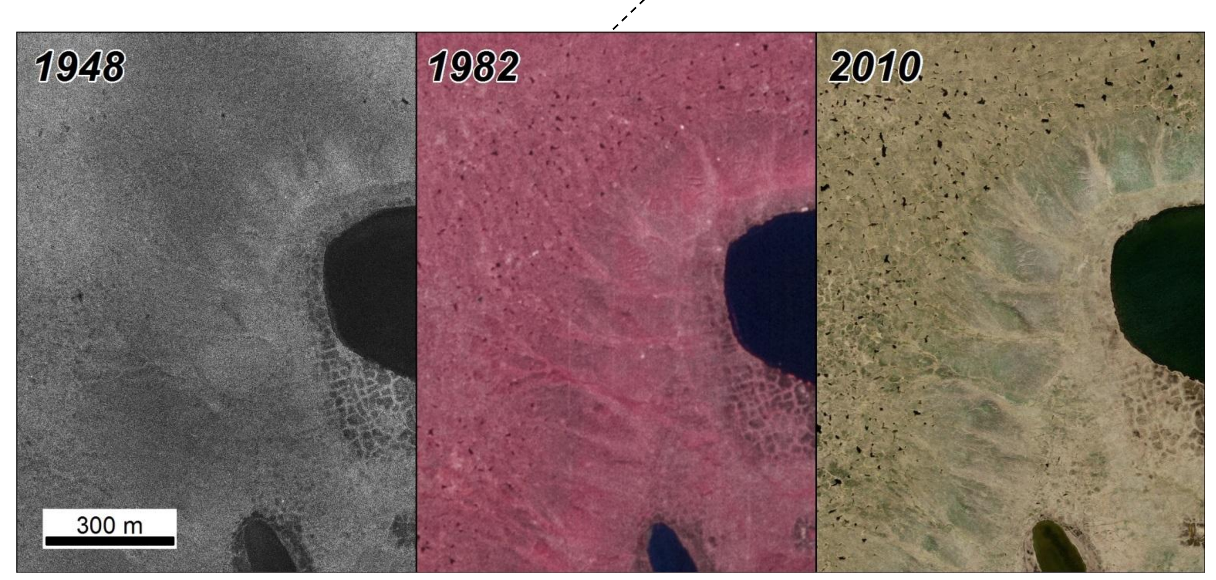


Figure 5. Timeline of ice wedge degradation at Oumalik River study area on the eolian sand sheet, 1948–2010. Very few thermokarst pits were evident in 1948, but the landscape has since become pock-marked with thermokarst pits. Recent changes in pit area, and their overall abundance are quite variable on the sand sheet, perhaps reflecting high variability and ground-ice content; ice content is often very low in sandy substrates.

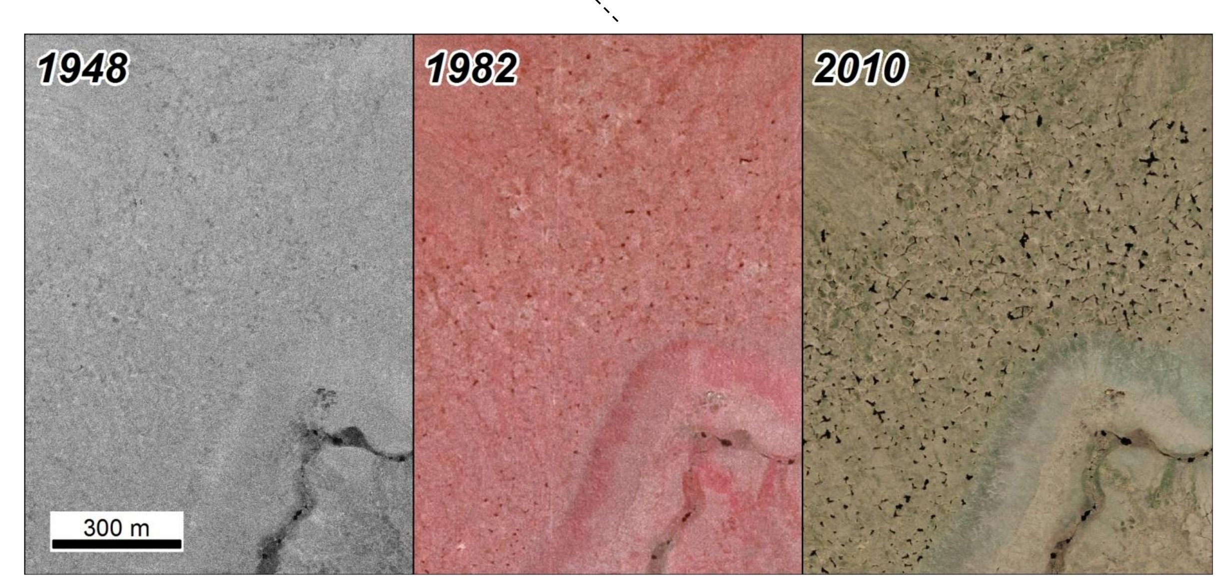


Figure 7. Timeline of ice wedge degradation at Titaluk River study area, in the foothills yedoma belt, 1948–2010. Only a few flooded pits are evident in the 1948 photo. Initiation and growth of thermokarst pits accelerated dramatically after 1982. The "yedoma belt" of the Brooks Range foothills is characterized by very large ice wedges which developed during the Pleistocene (see Figure 10, above right).

Discussion

Although we only quantified changes in surface water extent, the secondary impacts of ice-wedge degradation extend well beyond the footprints of thermokarst pits themselves. Changes in the relative elevation of polygon troughs usually results in complex patterns of drying in some areas (e.g., greater connectivity of polygon troughs) and wetting in others (redirection of flow paths) (**Fig. 9**). These secondary impacts strongly affect the composition and productivity of vegetation at local scales. Ice-rich yedoma is potentially subject to dramatic subsidence (**Fig. 10**).

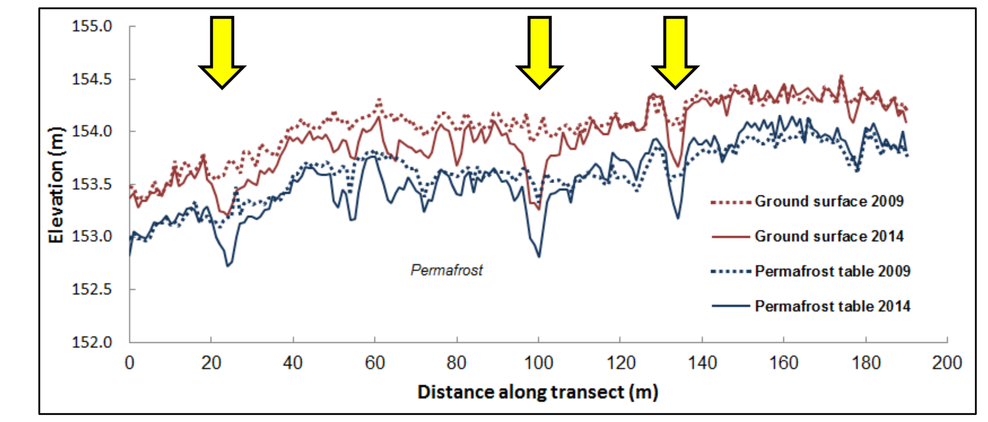


Fig. 9. Field-measured elevations of ground surface and permafrost table along a ~200 m transect spanning newly-developed thermokarst pits (yellow arrows) and remnant high-center polygons near Kogosukruk Creek, in 2009 and 2014. Rapid subsidence is evident at several locations (arrows), and has created new flowpaths for soil water atop the permafrost table.

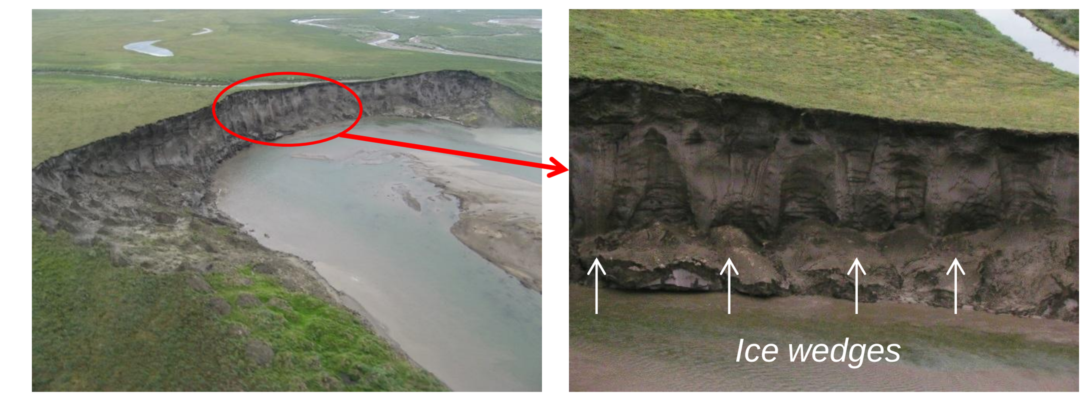


Fig. 10. Large yedoma exposure near Umiat, showing large Pleistocene ice wedges underlying residual uplands (see Kanevskiy et al. 2013). These ice bodies developed over long periods and have remained protected from thaw by the surface organic mat and a thin layer of segregated ice and mineral soil.

To what extent is recent ice-wedge degradation linked to longer-term climate changes? Can thermokarst be triggered by extreme events, such as a sequence of warm and wet summers? If so, did the recent period exceed the climate variability of the recent past? What is the susceptibility of different geomorphic environments to ice-wedge degradation in the future? What are ongoing and future impacts to North Slope communities, industrial infrastructure, and wildlife? These, and other questions remain unresolved and require integrated studies grounded by field-based observations.

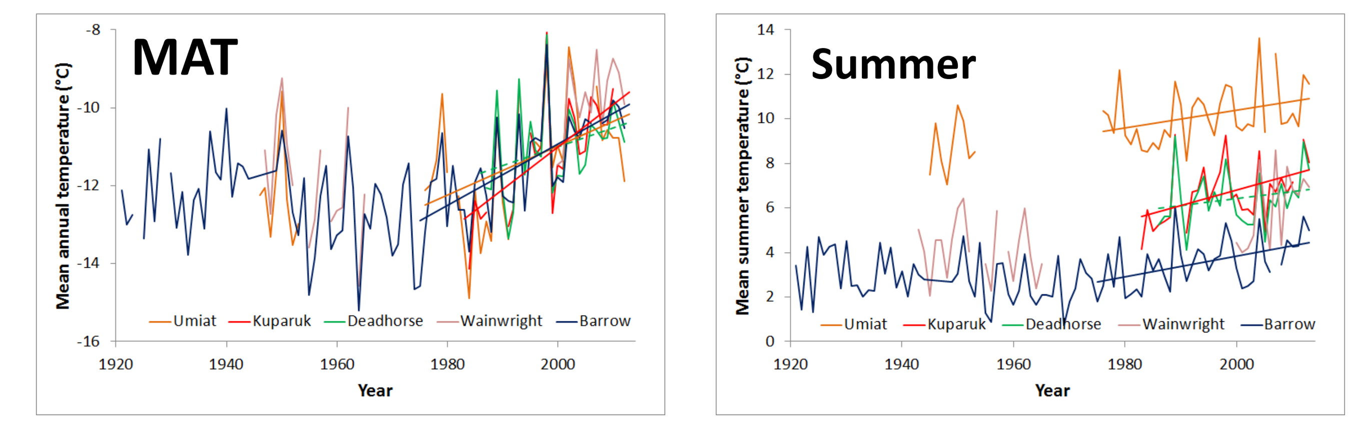


Fig. 11. Specific climate drivers of ice-wedge degradation remain uncertain and likely include rainfall and snow conditions. Station data are sparse, but indicate an upward trend in mean annual and mean summer (June–Aug) temperatures since the late 1970s. There were several exceptionally warm years from the late 1980s to mid 2000s. Although there is little regional variation in MAT across the North Slope, a strong latitudinal climate gradient exists in summer.

Conclusions

1. The extent of thermokarst pits increased in residual upland landscapes at 8 of 11 study sites (overall median +10.7%; maximum 134.6%)
2. Initiation of thermokarst occurred well before ~1950 at sites in the western part of the study area (Chukchi coast), but later in areas to the east
3. On the coastal plain sand sheet and in the foothills, thermokarst mainly began after ~1950, and accelerated after ~1980; this is consistent with reports from alluvio-marine deposits father to the east
4. Regional variability in the timing and extent of thermokarst may be partly explained by local/regional differences in the physical properties and ice content of surficial materials
5. The strong increase in recent thermokarst rates from west to east warrants further investigation and suggests complex interactions with coastal-continental climate gradient

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