Ice-wedge degradation: Why Arctic wetland are becoming wetter *and* drier

UNIVERSITY OF ALASKA FAIRBANKS

Anna K. Liljedahl[1], *akliljedahl@alaska.edu*, J. Boike[2], R. P. Daanen[3], A. N. Fedorov[4], G. V. Frost[5], G. Grosse[2], L. D. Hinzman[6], Y. Iijima[7], J. C. Jorgenson[8], N. Matveyeva[9], M. Necsoiu[10], M. K. Raynolds[11], V. Romanovsky[12], J. Schulla[13], K. D. Tape[1], D. A. Walker[11], C. Wilson[14], H. Yabuki[7]

1 Water and Environmental Research Center, University of Alaska Fairbanks, USA
2 Alfred Wegener Inst. Helmholtz Centre for Polar and Marine Research, German y
3 Alaska Department of Natural Resources, USA
4 Melnikov Permafrost Inst., Russia
5 ABR Inc, Environmental Research & Services, USA
6 University of Alaska Fairbanks, USA
7 Japan Agency for Marine-Earth Science and Technology, Japan
8 Arctic National Wildlife Refuge, USA
9 Komarov Botanical Inst., Russian Academy of Sciences , Russia
10 Southwest Research Institute, USA
11 Inst. of Arctic Biology, University of Alaska Fairbanks, USA
12 Geophysical Inst. , University of Alaska Fairbanks, USA
13 Hydrologic Software Consultant, Switzerland
14 Los Alamos National Lab., USA

ABSTRACT

Ice-wedges are common permafrost features formed over hundreds to thousands of years of repeated frost cracking and ice vein growth. We used field and remote sensing observations to assess changes in areas dominated by ice-wedges, and we simulated the effects of those changes on snow accumulation and runoff. We show that top melting of ice-wedges and subsequent ground subsidence has occurred at multiple sites in the North American and Russian Arctic. At most sites, melting ice-wedges have initially resulted in increased wetness contrast across the landscape, evident as increased surface water in the ice-wedge polygon troughs and somewhat drier polygon centers. Most areas are becoming more heterogeneous with wetter troughs, more small ponds (themokarst pits forming initially at ice-wedge intersections and then spreading along the troughs) and drier polygon centers. Some areas with initial good drainage, such as near creeks, lake margins, and in hilly terrain, high-centered polygons form an overall landscape drying due to a drying of both polygon centers and troughs.

Unlike the multi-decadal warming observed in permafrost temperatures, the ice-wedge melting that we observed appeared as a sub-decadal response, even at locations with cold mean annual permafrost temperatures (down to −14 °C). Gradual long-term air and permafrost warming combined with anomalously warm summers or deep snow winters preceded the onset of the ice-wedge melting.

To assess hydrological impacts of ice-wedge melting, we simulated tundra water balance before and after melting. Our coupled hydrological and thermal model experiments applied over hypothetical polygon surfaces suggest that (1) ice-wedge melting that produces a connected trough-network reduces inundation and increases runoff, and that (2) changing patterns of snow distribution due to differential ground subsidence has a major control on ice-wedge polygon tundra water balance despite an identical snow water equivalent at the landscape-scale. These decimeter-scale geomorphic changes are expected to continue in permafrost regions dominated by ice-wedge polygons, with implications for land-atmosphere and land-ocean fluxes of water, carbon, and energy.

LONG-TERM CLIMATE & PERMAFROST

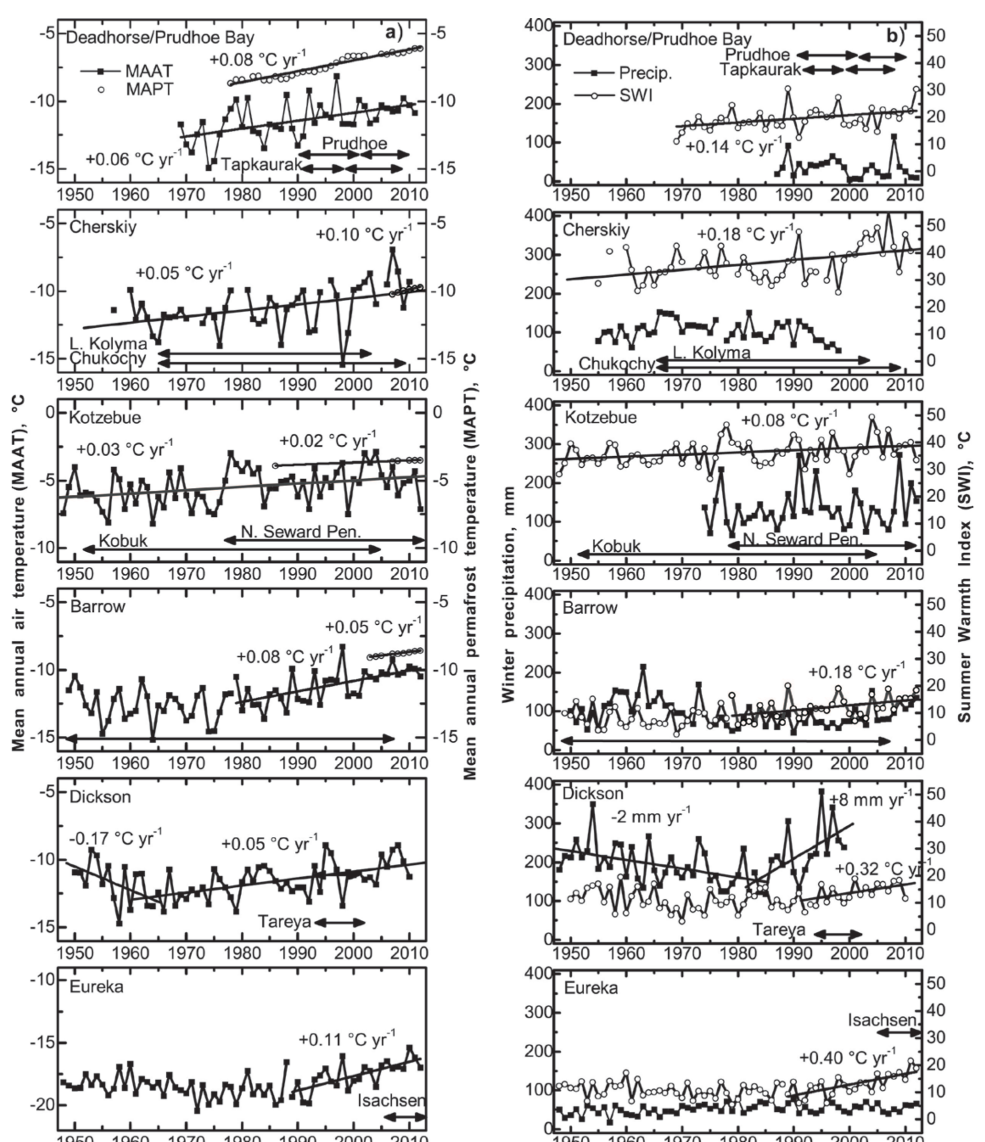


Figure 1. *Long-term winter precipitation, air and permafrost temperatures, Mean annual air (MAAT) and permafrost temperatures (MAGT) since ~1950 through 2012 (a) and total winter precipitation (Precip.) and Summer Warmth Indices (SWI), which is the sum mean monthly air temperatures above 0 °C. The arrow-ends represent time of field, aerial photo or satellite imagery observations, which constrain onset and duration of ice-wedge degradation. Also included are statistical significant trends (P-value < 0.01). Precipitation values were not corrected for undercatch.*

OBSERVED ICE-WEDGE DEGRADATION

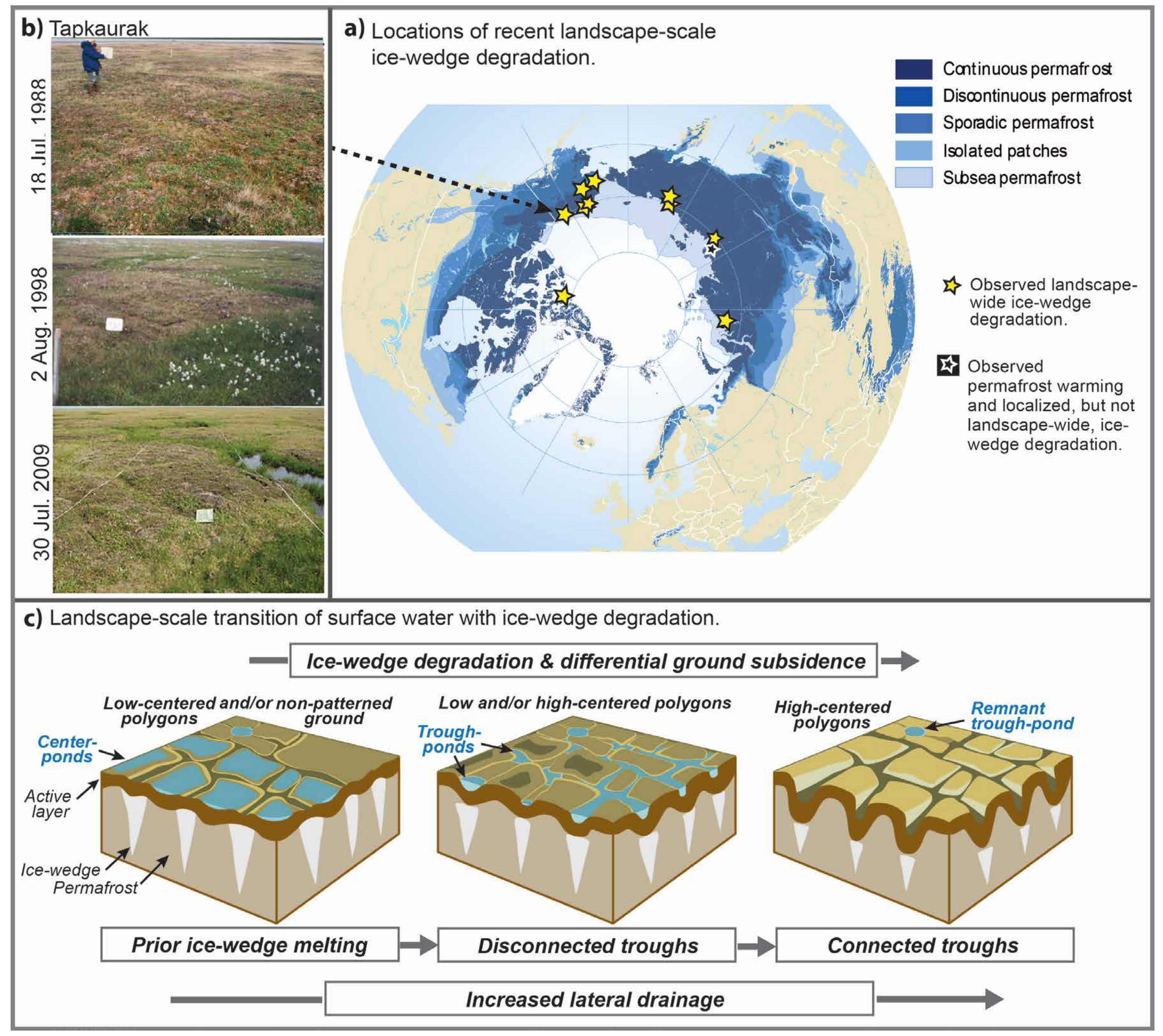


Figure 2. Observed recent ice-wedge degradation and its hydrological impacts. *The presented sites in the continuous permafrost region of North American and Eurasian Arctic lowlands (a). A field photo time series show ground subsidence and the subsequent changes in surface water and vegetation at Tapkaurak, North Slope, Alaska (b). A schematic representation of the observed morphological and hydrological changes, where the melting of the top of the ice-wedges result in a landscape transition of surface water from "center-ponds" (a landscape dominated by non-patternd ground or low-centered polygons) to "trough-ponds" (a network of disconnected troughs that surrounds low-/flat or high-centered polygons) to ultimately a laterally connected, well-drained trough-network and mounds (c).*

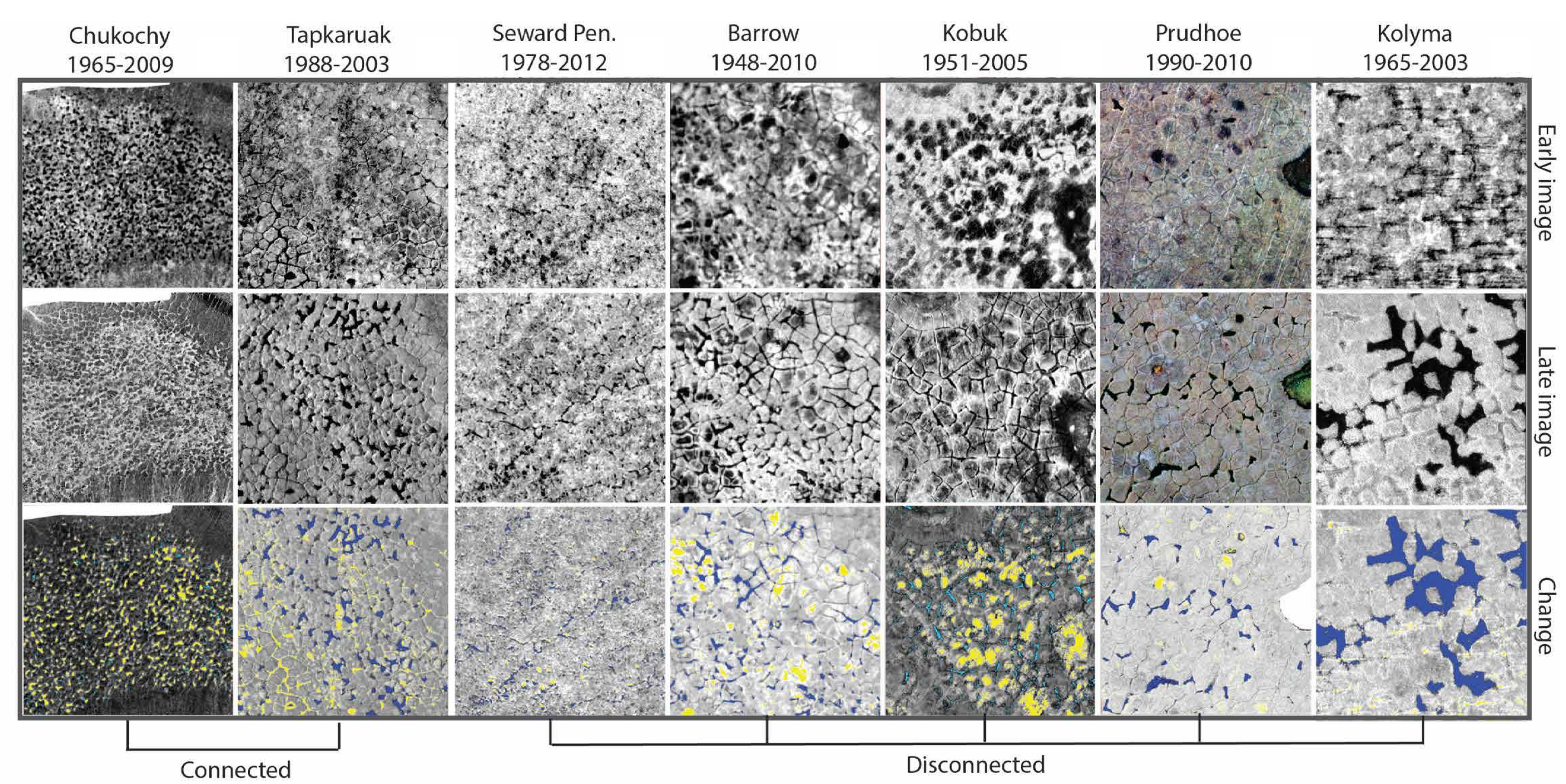
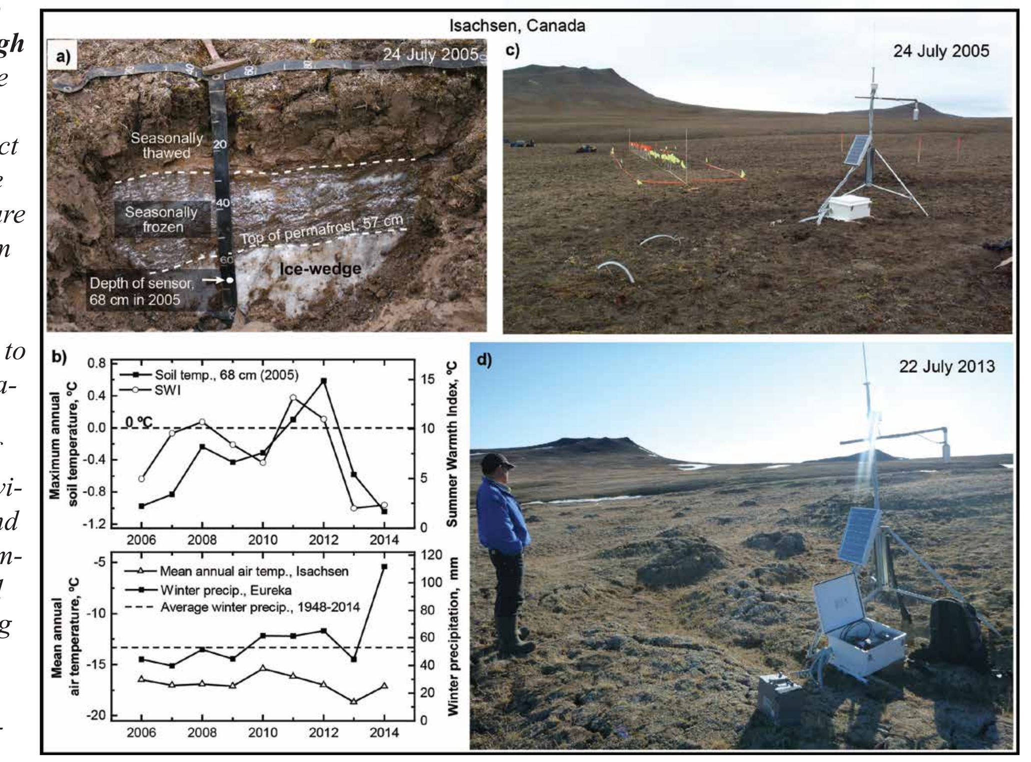


Figure 3. Observed recent ice-wedge degradation via aerial photos and satellite imagery from Alaska and Russia. *The early (top panel) and late images (middle panel) represents the landscape prior and after the landscape-wide differential ground subsidence, i.e. trough-formation. The change in surface wetness (bottom panel) show wetting (blue) and drying (yellow). Also highlighted are the two hydrological stages related to surface water connectivity (disconnected and connected). All frames have 250 m sides, except Seward Peninsula and Chukochy that are 500x500 m.*

Figure 4. Melting of the top of ice-wedges, Isachsen, High Canadian Arctic. *Soil profile photo showing the partially thawed active layer in contact with the top of the ice-wedge in 2005 (a). A soil temperature sensor was installed at 68 cm depth in 2005 (b). In 2013, this sensor was only 44 cm from the ground surface due to subsidence as ice-rich permafrost had thawed and due to some frost heave. Melting of the top of the ice-wedge is evident through observed ground subsidence (c, d) and soil temperatures above 0 ºC in 2011 and 2012. The above freezing soil temperatures coincides with high Summer Warmth Index (SWI) and above average winter precipitation.*



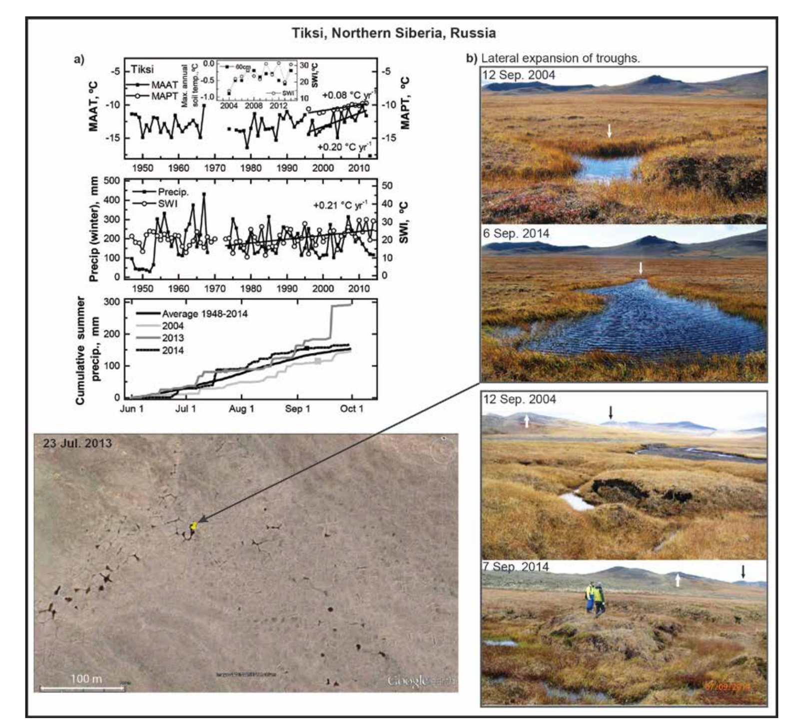


Figure 5. Ice-wedge degradation at Tiksi, Sakha (Yakutia) Republic, Russia. *Tiksi has experienced warming long-term trend in Summer Warmth Index (SWI), and mean annual air (MAAT) and permafrost temperatures (MAGT) (a). Trough-ponds and ground subsidence above ice-wedges were observed in 2004 and a visit to the same sites ten years later show a widening and lateral expansion of the troughs (b). Arrows indicate common reference points between photos. Cumulative summer precipitation during days of imagery was near-typical (a).*

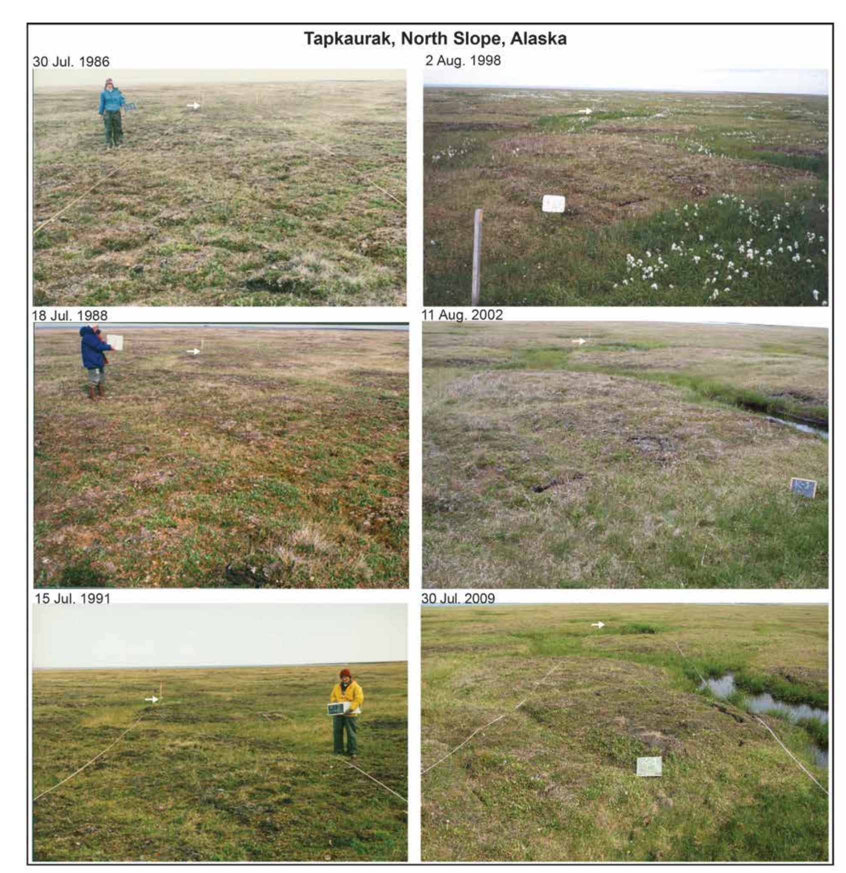
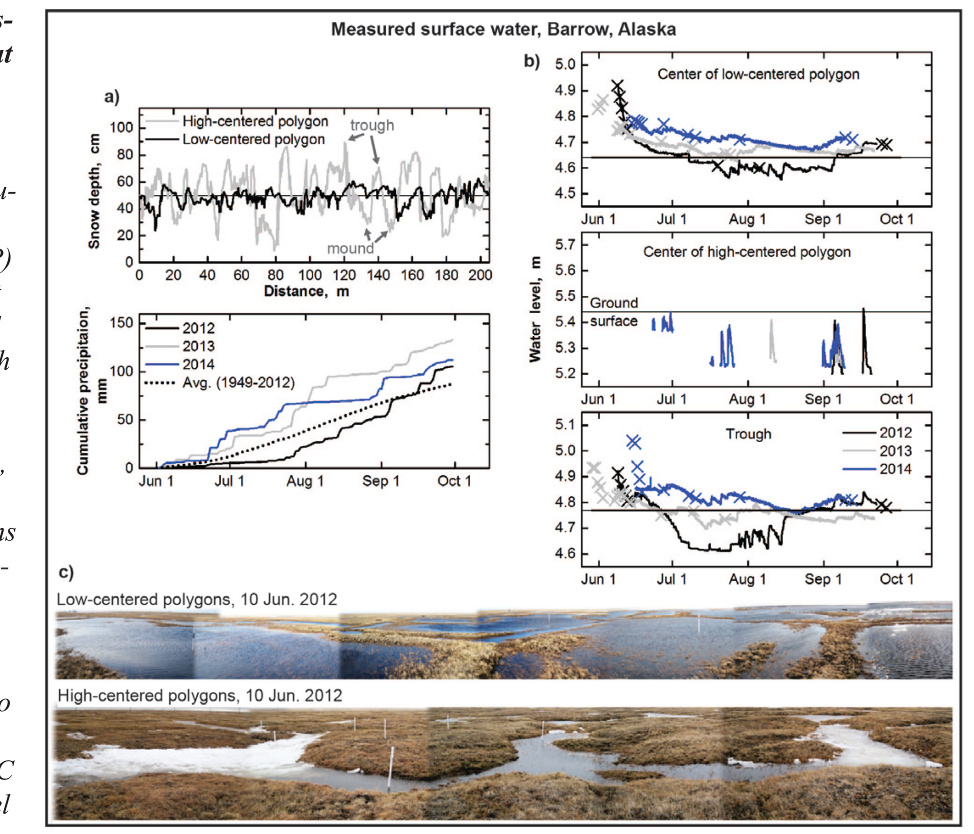


Figure 6. A 25-yr photo time series of ground subsidence and trough-pond formation at Tapkaurak, North Slope, Alaska. Subsidence of ground above melting ice-wedges and the subsequent altered vegetation (between 1988-1991 and onwards) and development of inundated troughs (1998-onwards). The white arrow is added to aid orientation

MEASURED & SIMULATED EFFECTS ON HYDROLOGY

Figure 7. Measured snow distribution and surface water at differing ice-wedge polygon types, Barrow, Alaska. *Averaged end-of-winter landscape-scale snow accumulation at low- (LCP) and high-centered polygons (HCP) was not significantly different (t-Test at the 0.05 level, equal variance not assumed) as both presented an average of 50±6.8 and 50±15 cm (standard deviation included), respectively, where the presence of well-developed troughs increased variability (a). Continuously measured water levels at the centers of low- and high-centered polygon and in troughs (b) and a photo of the sites near peak snowmelt runoff (c). The white PVC pipes represent the water level monitoring wells.*



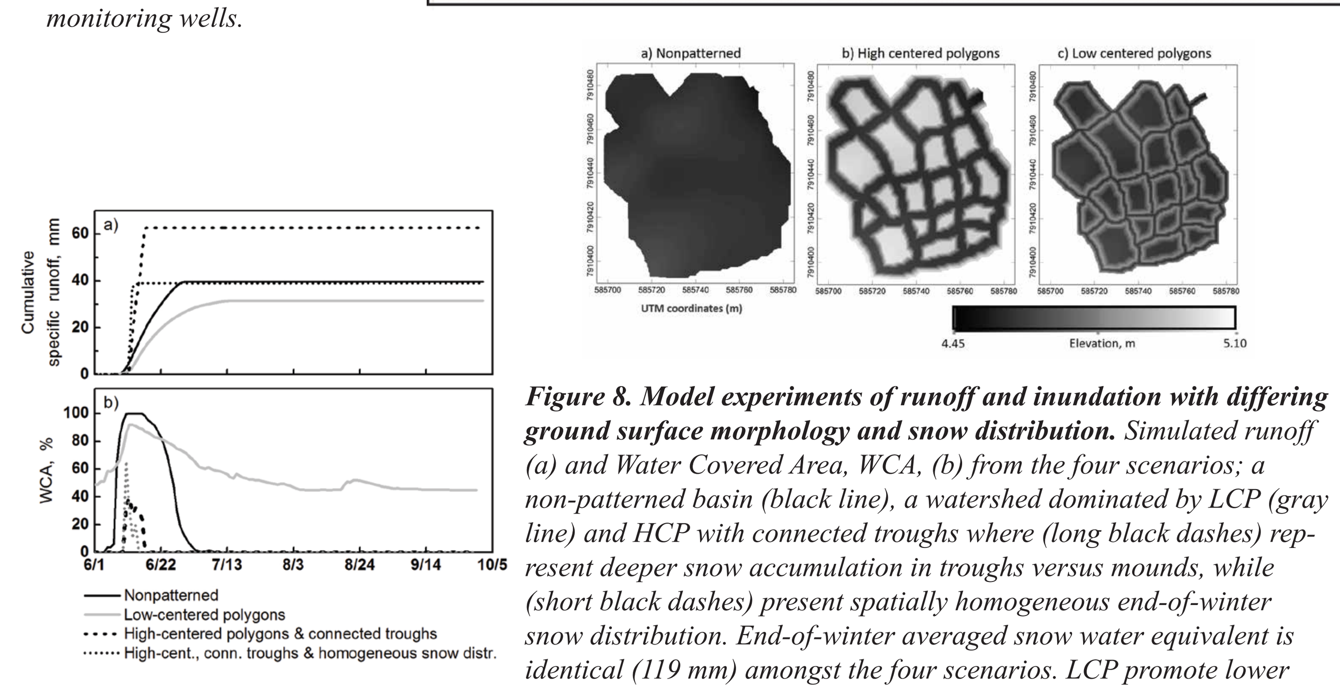


Figure 8. Model experiments of runoff and inundation with differing ground surface morphology and snow distribution. *Simulated runoff (a) and Water Covered Area, WCA, (b) from the four scenarios; a non-patterned basin (black line), a watershed dominated by LCP (gray line) and HCP with connected troughs where (long black dashes) represent deeper snow accumulation in troughs versus mounds, while (short black dashes) present spatially homogeneous end-of-winter snow distribution. End-of-winter averaged snow water equivalent is identical (119 mm) amongst the four scenarios. LCP promote lower runoff and extensive inundation, while the development of troughs and the subsequent increased spatial variability in snowcover increase runoff and decrease WCA.*

CONCLUSIONS

* Top melting of ice-wedges and subsequent ground subsidence is a widespread and recent phenomenon across the Arctic.

* Field and remote sensing observations document extensive ice-wedge degradation, which initially has resulted in increased wetness contrast across the landscape and an overall drying in later stages.

* Our coupled thermal and hydrological model experiments suggest that a connected trough-network reduces inundation and increases runoff and that changing patterns of snow distribution due to the differential ground subsidence play a crucial role in altering lowland tundra water balance.

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