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The capillaries of the Arctic tundra

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For millennia, permafrost landscapes have gradually grown the foundation for a capillary hydrologic system. It is now being activated by unusual warmth.

Much of the Arctic tundra is underlain by a network of ice wedges that formed during millennia of repeated frost cracking on cold winter days and later infilling of snowmelt water. Growing ice wedges push the soil upwards, forming connected ridges on the ground surface and the ubiquitous ice-wedge polygon tundra. Melting of the top of the ice wedge causes the ground surface to collapse with the rims transforming into snow- and water-collecting troughs – a phenomenon observed at multiple sites across the Arctic tundra in a decade or less[1,2]. Continued melt establishes a new drainage network only a metre or two wide and less than a half-metre deep[3], where a doubling of runoff and reduced surface water storage is possible without changes in precipitation[1]. Across the Arctic, lakes are disappearing[4], while precipitation[5] and river runoff are increasing[6]. So far, the sub-metre microtopographical changes have not entered the scientific analyses encompassing regional and pan-Arctic hydrology. The data and technology are now here to quantify the network of ice wedges across large regions and, though individually small, the ice wedges add up to large numbers. What at first may appear as contradicting hydrological change (for example, shrinking lakes despite increasing precipitation) could be explained by a sudden evolution of the stream network where the new channels are narrow but bountiful: the capillaries of the Arctic tundra hydrological system.

Thanks to recent technological advances, we can detect individual ice-wedge polygons across the treeless Arctic landscape using artificial intelligence and high-performance computing applied to sub-metre-resolution satellite imagery (Fig. 1a). Over a billion ice-wedge polygons have been outlined, each with its own identification number and statistics in geospatial data format (see the Permafrost Discovery Gateway). The total count is likely a major underestimate because the presence of ice wedges are not always evident on the ground surface, whether it is because of spruce trees hovering over the patterned ground in Interior Alaska or limited recent ice-wedge activity (growth or degradation) relative to soil accumulation. New or enlarged pond detection from satellite imagery is a method that scientists often used to identify thawed ice-rich permafrost, for example, ice-wedge degradation[7]. Conversely, in landscapes with a slope, ice-wedge degradation can also cause abrupt drainage of surface water bodies when troughs expand along the ice-wedge network and connect.

A common sight in recent years on Banks Island, Canadian Arctic Archipelago, are small metre-wide trough-ponds, the appearance of which are a tell-tale sign of ice-wedge degradation linked to warmer air temperatures[8]. At least 29% of the Bernard River watershed (10,543 km^2) on Banks Island is covered by ice-wedge polygons, resulting in a total length of ice wedges (1,129,327 km) that is 450 times longer than its existing streams (2,505 km). Assuming that all mapped ice wedges would become part of the drainage system, the troughs would represent 99.8% of the watershed's total stream length or a distance from the Earth to the Moon times three. Observations in northeast Alaska show the total area of ice wedges that were degraded increased from 7% (1950) to 66% (2018) with a noticeable acceleration between 1988 and 2000[3].

The significance of ice-wedge drainage networks to water-scale hydrologic flux is analogous to the role of capillaries in the circulatory system of humans (the length of all the capillaries within the human body adds up to 80,000 to 100,000 km). Both systems are organized in hierarchal, tree-like structures carrying nutrients, oxygen, and so on. Arteries and veins flow only through our muscles, while capillaries are found inside tissues throughout our body. Similarly, creeks, streams, and rivers flow at the bottom of Arctic valleys, while ice wedges occupy valley bottoms, slopes, uplands, and plains. For millennia, permafrost landscapes have gradually grown the foundation for a capillary hydrologic system and, at Banks Island and beyond, it is being activated by unusual warmth.

Establishing a completely new first-order stream class, known as 'tundra capillaries' or trough-drainage networks, which also exceeds the higher-order streams by magnitudes in its total length, shortens the retention time of water on the landscape while also enabling more water to reach the typical stream network. Stream channels, ranging from trough-drainage networks to large rivers, trap more snow than the surrounding tundra, effectively increasing the portion of snow within a watershed exported as runoff in spring[1]. There is a limited amount of total snowfall in winter, so an increasing portion of snow stored in drifts along drainage networks will reduce the amount of upland snowmelt water stored or lost to evapotranspiration in summer. Accordingly, a capillary hydrological system leaves less water on the tundra landscape as runoff is determined by the amount of precipitation that the landscape cannot hold.

The capillary system not only expands but it also reorganizes itself over time[3] due to the differing evolution of soils, vegetation, and water above ice wedges within a watershed. The trough-drainage networks are a mesh of a greener landcover compared to the surrounding drier tundra (Fig. 2). Aquatic mosses, which can inhabit trough-ponds, are as productive in generating biomass as tall shrubs[9]. As a consequence, the sediment cools and permafrost can reform[3]. The accumulating organic soil and the upward-advancing permafrost-table gradually elevate the surface, halting the evolution of the trough to connect into the capillary hydrologic network while adding to soil carbon stores above ice wedges[3]. At first, ice-wedge degradation increases the variability and contrasts in moisture and vegetation within the tundra landscape, while subsequent ice-wedge stabilization or the evolution of a capillary system somewhat reduces the contrasts[3]. What we come to find is that, in our time, the tundra ice-wedge polygon landscape appears to be evolving, as you can find actively degrading ice wedges and aggrading permafrost (beneath troughs) within the same watershed[3]. What we have yet to discover is the relative permanence of the capillary system once established. Individual capillaries may reorganize over time, while others may remain as permanent features in the landscape.

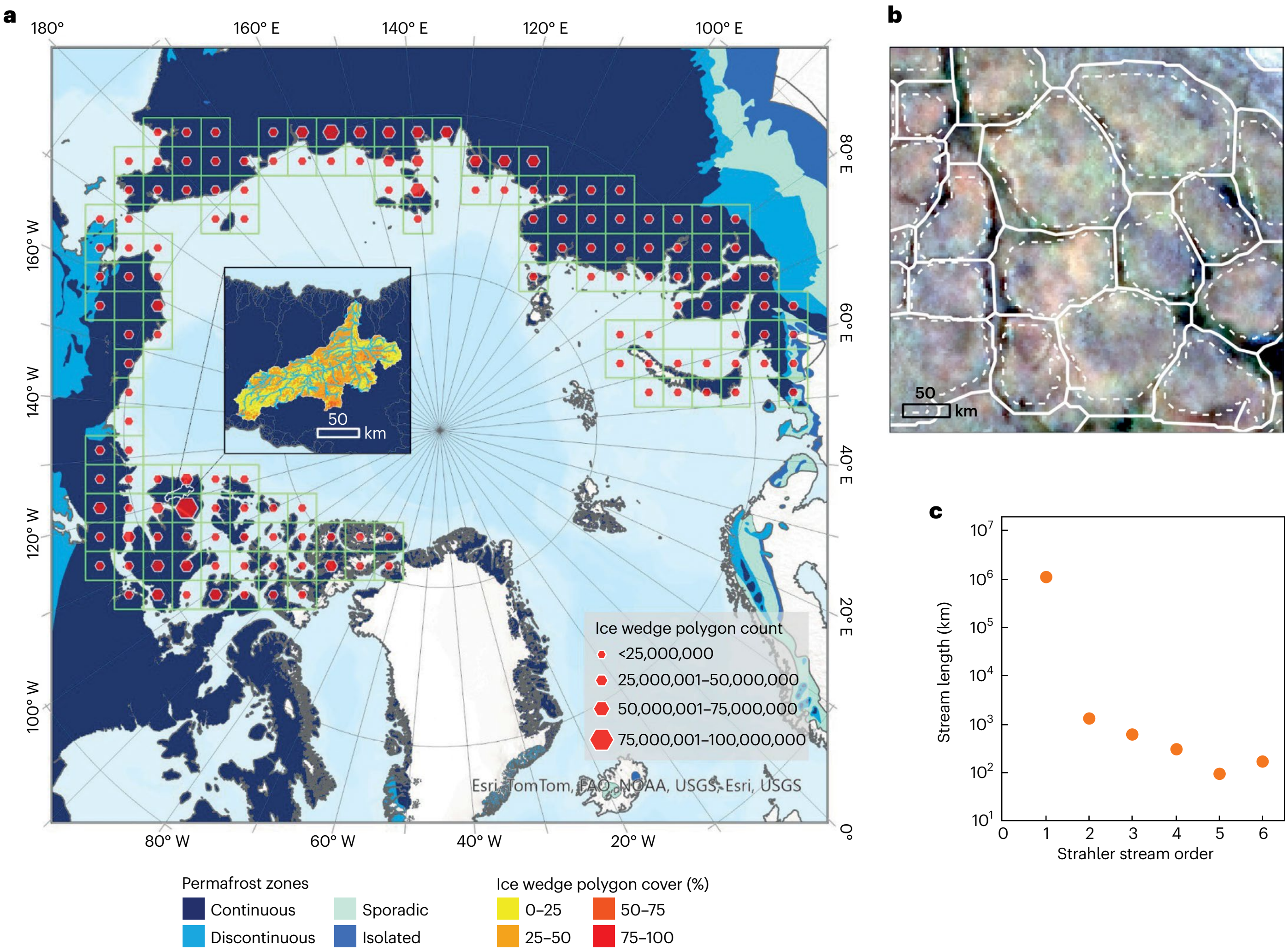

Fig. 1 | Abundance of ice-wedge polygons and the subsequent network of ice wedges. a, Over one billion ice-wedge polygons have been mapped from sub-metre-resolution imagery across the Arctic tundra, here represented as the total count of ice-wedge polygons within a 200 × 200 km grid. **b**, Each ice-wedge polygon is outlined (dotted lines) and the centre line of the ice wedge has been estimated via spatial analysis techniques (solid lines). The Bernard River watershed (10,540 km^2) on Banks Island (inset in **a**) shows an average ice-wedge coverage at of 29%. **c**, If all the mapped ice wedges where to degrade and form a connected network of trough channels (a capillary hydrological system), the total length of the tundra capillary system (Strahler stream order 1) would exceed one million kilometres, which is orders of magnitude larger than the typically outlined stream network. Data obtained from refs. 18–20.

The long-term evolution of the ice-wedge polygon tundra depends on whether a capillary system has become established or not. The slope of the landscape may be key in establishing a trough-drainage network as sloping landscapes offer more opportunities to concentrate flow. Perhaps a watershed, such as Bernard River will see the permafrost alternate between degrading and aggrading in the more upstream portions, while the troughs below are more likely to remain in the stream network. It is possible that the establishment of a capillary system includes processes that sustain its presence, altering the landscape in the long term. For example, rapidly growing aquatic mosses only thrive in trough-ponds, which is an environment that a well-drained trough does not offer. Continued field and remote sensing efforts are a necessary first step in exploring how permanent the tundra capillary hydrologic system is and, more specifically, what is shaping its evolutionary trajectory.

The establishment of troughs and an Arctic hydrological capillary system leads to a landscape-wide transformation that extends beyond water – and the Arctic. Several field studies offer descriptions of stark variability in vegetation, water, soils, and biogeochemistry between ice-wedge polygon types, including at varying stages of ice-wedge degradation and stabilization[10]. These plot-scale field studies are commonly designed as snapshot-in-time assessments where changes over time are substituted for changes across space. Here, findings tend to converge on a net (vertical) carbon loss in landscapes affected by degraded ice wedges[10,11]. However, when the same ice-wedge location is monitored over a decadal time scale or longer (beginning prior to the onset of degradation and lasting through the ice-wedge stabilization phase), the above- and below-surface carbon storage has increased[3]. Modelling suggest the trough-drainage system increases carbon exports mainly through runoff extending beyond snowmelt[12]

Fig. 2 | A tundra capillary at Prudhoe Bay, Northern Alaska, in July 2019. At least 0.5 m of ice-rich permafrost has thawed and formed a steep, relatively narrow, trough. The ice wedge is actively degrading as evident by the cracks along the channel sides where soil is slumping down because it has lost some of its original ice support. The vegetation is lush green at the bottom of the trough as the thawing permafrost is delivering solutes, which are also sourced from further upstream in this new miniature stream channel. Water is surfacing (lower centre of photo) between mosses and flowering sedges, while edges and centres of the high-centred ice wedge polygons are relatively dry and less productive.

with measured lateral exports represented by fresh carbon that is prone to degradation[13]. In an ice-wedge polygon delta landscape (that is, a low-gradient watershed), the vertical carbon fluxes dominated over the later exports[14]. It is clear that we need to acquire more insights from the field where a site is monitored over a decade or more and from landscapes with differing slopes to fully grasp the impact of trough-network evolution on carbon fluxes.

Climate models do not address the unique processes of landscapes underlain by ice wedges. Climate models that include permafrost assume the thaw is a gradual homogenous deepening of the active layer (the seasonally frozen ground above the permafrost), while differential ground subsidence and its connections to hydrology, vegetation, and soils are missing. Here, significant computational roadblocks have included: (1) the magnitude-sized differences in spatial scales between observed processes (via field or remote sensing studies) and the coarse-resolution climate model; and (2) the lack of fine-resolution geospatial data across the permafrost-affected region to inform the climate models. The Arctic climate modelling community are aware of their models' limitations and large uncertainties in estimating carbon fluxes[15] – at least when accounting for existing field-based knowledge. Field studies are the foundation for effective remote sensing and modelling efforts. Therefore, to remain connected to the real world, for every dollar spent investing in the virtual world (that is, models including remote sensing), we need at least a dollar to support field studies.

We are at a time where we can bring sub-metre-scale processes to the climate models. To do so we need to: (1) integrate several tools (field observations from multiple sites and years, remote sensing analyses across the Arctic down to the sub-metre scale, and numerical models) to identify key processes and how to represent them in the climate models; (2) explore the use of artificial intelligence in connecting traditional approaches and in mining the data; (3) automate the processing and analyses of big geospatial data to free-up time for Earth scientists; (4) optimize workflows to produce timely remote sensing monitoring of permafrost thaw features and permafrost aggradation to support the collaboration between the real and virtual worlds; and (5) move towards a community where sharing of data both before and after publication is encouraged and celebrated. In return, the science is likely to become more collaborative, groundbreaking, and relevant to society as a whole.

Individually, the relatively narrow ice-wedge polygon troughs may seem insignificant to the bigger picture. Yet, observations of abrupt-thaw ice-wedge degradation and its transformation on landscapes deserves continued and increased attention. The Arctic tundra landscape, from the sub-metre to watershed scale, can change within a heartbeat of a permafrost-lifetime due to the abundance and connectedness of ice wedges.

Data availability

The data collection of ice-wedge network and ice-wedge polygon coverage is derived from the pan-Arctic map of ice-wedge polygons[16], which used Maxar satellite imagery from 2010–2020 for the Bernard River watershed. The ice-wedge network and ice-wedge polygon coverage datasets are available for download at the Arctic Data Center[17] and it is available to visually explore in the Permafrost Discovery Gateway. The Bernard River watershed boundary was obtained from ref. 18. Stream order length (except the ice-wedge network) was obtained from ref. 19. The permafrost zones map was obtained from ref. 20.

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