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Frozen infrastructures in a changing climate: Transforming human–environment-technology relations in the Anthropocene

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The study of infrastructures has seen a growing interest in recent years across academic disciplines and global regions. The role of infrastructure as a critical component of social-ecological-technological systems (SETS), which interconnect people and nature to facilitate various human activities, has generated heated debates around its impacts on both humans and the environment. The understanding and examination of infrastructures is increasingly expanding and now includes not only traditional built structures, but also natural objects (Carse 2012), people (Simone 2004), social relations (Star 1999), ideologies (Humphrey 2005), institutions and processes (Anderies et al. 2016), and so on. Thus, infrastructure is located at the intersection of human and natural systems, necessitating comprehensive enquiries from both social and physical sciences to better understand its spatial and temporal characteristics.

Infrastructure reflects histories and geographies of specific locations, and cold regions are not the exception. The presence of snow, ice, and permafrost creates an intricate environment that uses the cold as a resource to develop unique forms of infrastructures. However, these infrastructures are hypersensitive to changing climatic conditions. The combined presence of snow, ice, and permafrost, as stand-alone phenomena or coupled with the built environment, define *frozen infrastructures*. The conceptualization and examination of frozen infrastructures expands upon previous research on green and blue infrastructures (e.g., Kazmierczak and Carter 2010; Frischmann 2012; Gunawardena et al. 2017). Water in its frozen state, known as the cryosphere, garners considerable attention in global climate and research (ACIA 2005; AMAP 2017; Constable et al. 2022). It is increasingly recognized and appreciated as a provider of significant contributions to human well-being (Su et al. 2019; Wang et al. 2019). Prominent examples of services provided by frozen infrastructures include bearing services provided in the form of snow and ice roads, airports, and subsistence trails; building foundations on permafrost; food and water storage; supporting services for snow shelters and animal habitats; as well as cultural services for identity or recreation.

In the Arctic, while most of the population is in urban communities and industrial centers, frozen infrastructures are integral parts of the daily lives, mobilities, livelihoods, and worldviews of Indigenous communities (Krupnik and Jolly 2002; Aporta 2004; Cruikshank 2005; Kuklina et al. 2021). Over a thousand settlements, housing approximately 5 million people in the Arctic regions, depend on the stability of permafrost (Ramage et al. 2021). Lake and river ice provides seasonal transportation and infrastructure for isolated communities, remote industrial development, and trail access to hunting, fishing, herding and trapping areas, thereby supporting traditional subsistence-based livelihoods (e.g., Vuglinsky et al. 2002; Prowse et al. 2011). Winter roads make about 8.6 million km^2 of the Arctic accessible (Stephenson 2017).

The urgency to study frozen infrastructures is raised by their vulnerability in the face of rapidly changing climatic conditions. As white reflective surfaces associated with the presence of ice and snow are replaced by darker surfaces associated with water, soil or vegetation, the albedo feedback accelerates atmospheric warming. As atmospheric temperatures rise, the decrease in duration and severity of the cold season results in a shorter season for the use of lake and river ice as winter roads, thereby threatening the accessibility of remote communities and industrial centers (Ford et al. 2019; Baskov et al. 2021; Gadeke et al. 2021). In regions located on permafrost, rising soil temperatures, increased thaw depth, and melting of ground ice can lead to a decrease in the lifespan or direct damage to infrastructure

(Shiklomanov et al. 2017; Suter et al. 2019; Hjort et al. 2022). Recent studies show that permafrost degradation poses a significant threat to built infrastructure (Hjort et al. 2022), resulting in substantial costs (Streletskiy et al. 2019, 2023). In many cold regions, communities rely on ice cellars dug into permafrost for food storage. However, with the warming climate or land use changes, these cellars may be impacted, threatening food security of remote communities (Nyland et al. 2017; Maslakov et al. 2020). As the natural availability of snow, ice and permafrost as means of transportation, construction, and storage may diminish in a changing climate, many artificial techniques have been developed to preserve the cold. These include construction methods on permafrost using various types of passive and active cooling devices, spraying of water to create roads and airfields on ice, storing ice underground, and the use of stupas in high mountain environments (Palmer 2022).

Social studies are necessary for understanding the choices and decisions involving where and how these frozen infrastructures develop and persist, and how they interact with power dynamics between multiple stakeholders, growing wealth, natural forces, and technological advances. With the growing complexity of infrastructural development and stakeholders involved in the Arctic and other cold regions, it is important to study how people design, construct, own, maintain, use, and govern frozen infrastructures. Related questions also include who benefits from the functions of these frozen infrastructures and where those benefits are distributed, as well as how stakeholders could be negatively affected.

The interrelation between physical and social science questions becomes crucial when considering the effects of climate change on diverse social groups in particular places, devising specific adaptation strategies, and looking for sources of resilience and sustainability. As such, the study of frozen infrastructure is an emerging domain of inter- and transdisciplinary research, and an area of concern that is likely to produce significant advancements in understanding the dynamics of SETS. This topic is highly relevant to science, policy, and communities, as it sheds a new light on the complex processes and interactions within SETS that arise from concurrent climate and societal change.

The papers in this special section come from a broad range of disciplines (including physical science, social science, and interdisciplinary studies) that critically examine frozen infrastructures as part of evolving human–environment-technology relations under rapidly changing climatic conditions. The geographic scope of the special section encompasses permafrost regions, both rural and urban areas, including Indigenous communities dependent on ice and snow for maintaining traditional cultures and subsistence activities. It also includes communities that devise new specific technological solutions or preserve traditions for building and maintaining the built environment.

The special issue contains the following articles: Waite et al. (2023) summarize existing methods of assessing impacts of changing climate and socioeconomic conditions on Arctic transportation systems that are significantly shaped by snow, ice and permafrost conditions. It identifies data and information in existing research using a systematic literature review. Snow, ice, and permafrost are among the most important variables that studies take into account for the assessment of adaptive capacity and vulnerability to climate change.

Landers and Streletskiy (2023) provide important insights into permafrost management from the perspective of construction regulations across the Arctic. The article traces the emergence and evolution of construction codes and principles in Russia, Canada and Alaska, and evaluates their role and potential effectiveness in building infrastructure on permafrost. They discuss the strengths and limitations of diverse approaches these countries developed to ensure the stability and resilience of infrastructure on permafrost.

Bennett (2023) focuses on gravel as a replacement for ice as an infrastructure material in a transition from subsistence to extractive industry-based livelihoods. It shows how settler colonialism transformed Indigenous peoples' relations with, and views on, land and ice through differing land claims settlements and politicized geology.

Kuklina et al. (2023) continue the conversation about use of granular materials, using examples of sand use in the Arctic city of Nadym. However, in contrast to gravel, sand is not as widespread. In this location, sand serves as an alternative to frozen water and as an additional stabilizer for foundations when mixed with water.

Povoroznyuk and Schweitzer (2023) focus on a paradox observed on the Bykovskiy island in the northern Republic of Sakha, where collapsing coastlines and diminishing fishing quotas coexist in local communities that seem to be unconcerned with climate change as a driver of frozen infrastructure collapse. The paper examines this paradox, concluding that (post)-Soviet legacies and pressing socioeconomic issues overshadow other concerns. The authors caution researchers against assuming people's perceptions of climate change, even if they are directly affected by its impacts.

Campbell and Ablazhey (2023) discuss the future imaginaries of Indigenous communities under the threat of dam construction which would drown villages, reindeer pastures, cemeteries, and other places of cultural and ecological significance. Moreover, it would impose risks of degradation of permafrost, which currently protects local communities from nuclear and chemical contamination that would be brought by the Yenisei river, the largest river to drain into the Arctic Ocean.

The articles featured in this special section highlight the crucial role of snow, ice, and permafrost in building, maintaining and sustaining human–environment relations in cold environments, particularly in the Arctic. Frozen infrastructures are multifaceted and complex, with dynamic interactions that hold economic, social, cultural, and spiritual importance across cold regions. Indigenous frozen infrastructures have been in operation for millennia and underpin the livelihoods of the Indigenous People in the Arctic. Modern frozen infrastructures are rapidly emerging and evolving in response to increasing industrial development and the impacts of climate change in cold regions. However, despite recent progress encapsulated in this special section, the phenomena of frozen infrastructures and their dynamics are still not fully understood and remain insufficiently explored. Further research will focus on not only unveiling the roles and characteristics of these frozen infrastructures within SETS, but also at understanding their dynamics in terms of sharing, management, impacts on multiple stakeholders, monitoring through multiple knowledge systems, and their collective governance as the planetary and regional commons to ensure their sustainability for this and future generations.

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