High-Resolution Data from Integrated Micrometeorological and Geophysical Studies within an Arctic City: Preliminary Results from Utqiagvik, Alaska

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Abstract

The Arctic is a highly dynamic and extreme environment at the forefront of accelerated climate change. Situated on the coast of northern Alaska, 330 miles north of the Arctic Circle, the city of Utqiaġvik is built entirely on continuous permafrost with varying ice content. Since the 1970s, critical infrastructure, including water and electrical utilities, gravel roads, sanitation facilities, snow fences, schools, housing, and other government buildings were built. Most of these structures are on raised pilings driven into the underlying permafrost to mitigate heat transfer to the ground. Due to anthropogenic heat and a warming climate, Utqiaġvik faces challenges from destabilized permafrost, causing structural deformation of buildings and infrastructure. Although there are numerous studies on permafrost, less has been done on how urbanization and land use contributes to permafrost degradation. As part of a five-year study in partnership with the city of Utqiaġvik, this NSF-funded project has established an array of micrometeorological and ground-based sensors at five study sites: a residential building, a public utilities complex, a new hospital, a gas line node, and a tundra control site. The data from the sensor arrays, combined with geophysical measurements of subsurface permafrost conditions will provide constraints for the development of resilient design strategies. Repeat LiDAR surveys identify changes in structures and land surface over time. Preliminary results from the micrometeorological sensor installation in the summer of 2022, combined with geophysical surveys from 2021-2022, indicate highly variable urban microclimate, surface and subsurface ground conditions. Localization of snow and surface water accumulation due to disturbed natural surface drainage and/or presence of human-made structures plays a key role in destabilizing the thermal regime of the underlying permafrost. However, reduced solar insolation beneath raised structures with adequate thermal isolation decreases the depth of the active layer and enhances permafrost stability. These competing effects reveal the complexity of interactions within an Arctic urban environment and the importance of integrated studies to monitor changing conditions for future development and adaptation strategies for Utqiaġvik.

Overall Research Project Objectives

Three key objectives for this research:

1) The deployment of an array of micro-meteorological and aquatic sensors and geotechnical surveys throughout Utqiaġvik that will measure the interactions among infrastructure, buildings, and nearby landscapes, providing data on how urban system components interact with the surrounding air, ground, and water conditions.

2) The application of sensor data to generate environmental design analysis and design guidelines to address how current and future managements of Utqiaġvik's built environment can be improved; and

3) The study of how our research team and Utqiaġvik residents communicate across disciplines and cultures to co-produce knowledge that is useful for residents and that informs science and social science.

Design and Planning-Related Research Questions

Design Analysis and Strategies toward Resilient Buildings and Infrastructure:

1) How can high resolution sensor-based environmental data inform future best practices for design of buildings and infrastructure in an Arctic city?

2) How can environmental design guidelines be evaluated and enriched by incorporating qualitative data and community input from local and Inupiaq residents?

3) How can the future design and planning in Utqiagvik occur in a way to minimize environmental impacts on the landscape and increase the resiliency of the community?

Design Problems in the Arctic: A Brief Background

In the Arctic, climate extremes and geographic remoteness necessitates a critical dependence on buildings and infrastructure. Despite this the design and planning of the built environment in the Arctic is either poorly lacking due to imported practices from temperate latitudes, or places a singular emphasis on engineered solutions that seek to solve immediate environmental or structural problems. **What is long overdue is incorporation of a more holistic approach for the design of the built environment that meets the social and cultural needs of the residents as well as the environmental specificity of the northern latitudes.** The relative absence of integrated design practice in the Arctic has resulted in compromised living conditions, an absence of culturally specific design, adverse environmental impacts within and around communities, maintenance challenges, poor quality and organization of interior and exterior living space, energy inefficiency, and over-reliance on excessive fossil fuel energy sources. Furthermore, the high cost of logistics, short construction and repair seasons, and increasing impacts of climate change have resulted in a plethora of structural vulnerabilities and planning uncertainties, and the ability of communities to address these complex challenges through design and planning strategies is critical.

In order to develop a holistic framework for future design practices in Utqiaġvik, we will use the micro-meteorological, surface/subsurface ground and aquatic data to initially characterize two and three dimensional spatial patterns and variability of the environment. This will allow us to **assess the relative significance of architectural and urban design variables** (e.g., form/organization/materiality/orientation, infrastructure height/depth) **at multiple spatial scales in relation to the urban environment**, for example, perturbations to local weather patterns by disrupting prevailing wind patterns, modified solar radiation and surface albedo, redistribution of precipitation, and introduction of anthropogenic sources of heat and water to the exterior atmosphere and ground. Key questions we will address are, for example, the relative importance of building height, materiality, and foundation type on active layer thickness; the effect of horizontal spacing, built form, and height on generating significant localized environmental conditions that deviates from areas outside of the city; and the impact of building albedo on local snow surface cover. The results of these analyses will provide dense design data for the creation of an Arctic Design Guideline Database (ADGD), an index of design parameters and best practices based on quantifiable observational data from this study.

Research Sites and Future Development Plan of Utqiaġvik, AK

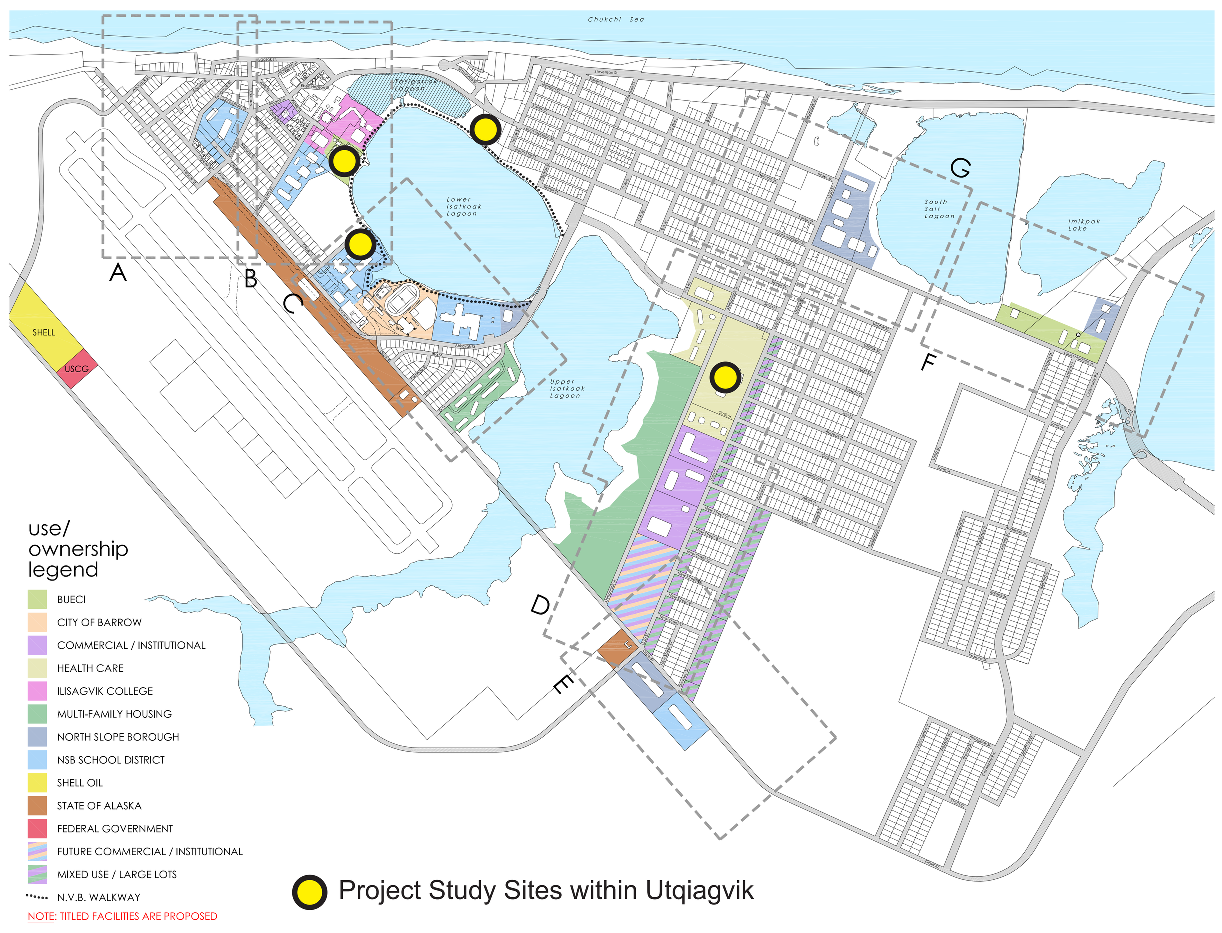
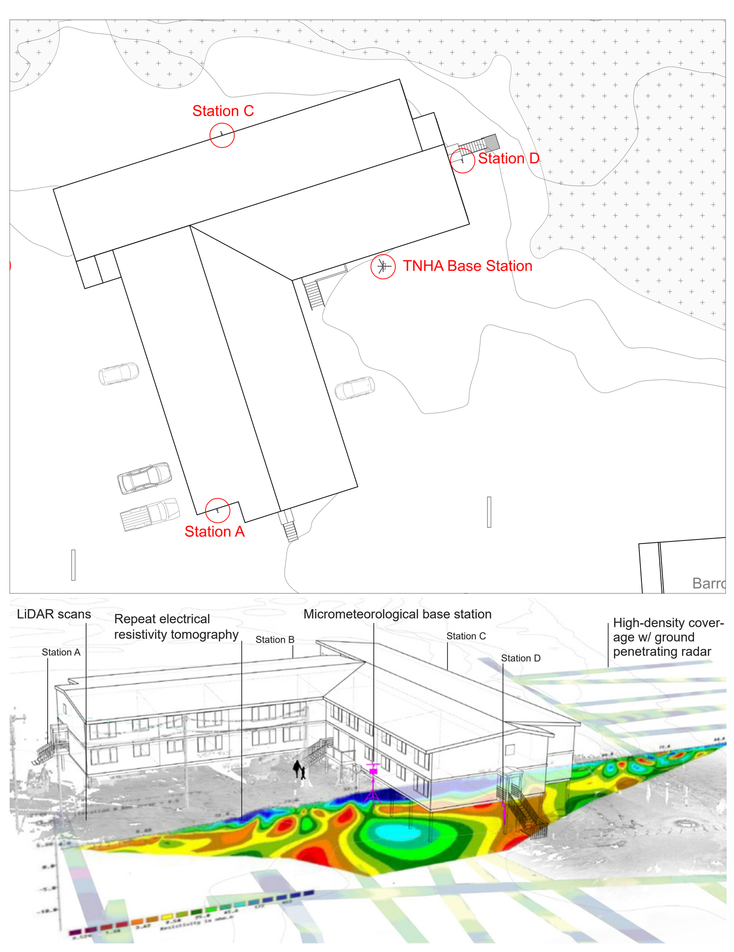
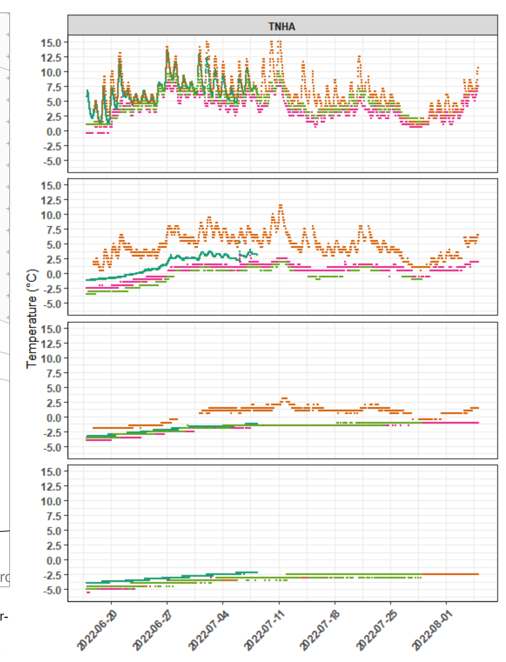


Image: *Barrow Comprehensive Plan 2015-2035*

TNHA Study Site: An Example and Preliminary Results





Air temperature, ˚C (TNHA)
(Table 1)

Sensor	Max	Min	Mean
BASE	22.51	-0.67	5.97
SA	25.16	-0.47	6.20
SB	21.62	-0.60	6.02
SC	19.32	-1.33	5.61
SD	20.1	-1.01	5.62

Instrumentation Sites, ERT and Data Stacking around TNHA Site.
Image: CRREL & M. Dawkins / UVA; Temperature Data + Graphs: M. Shaban.

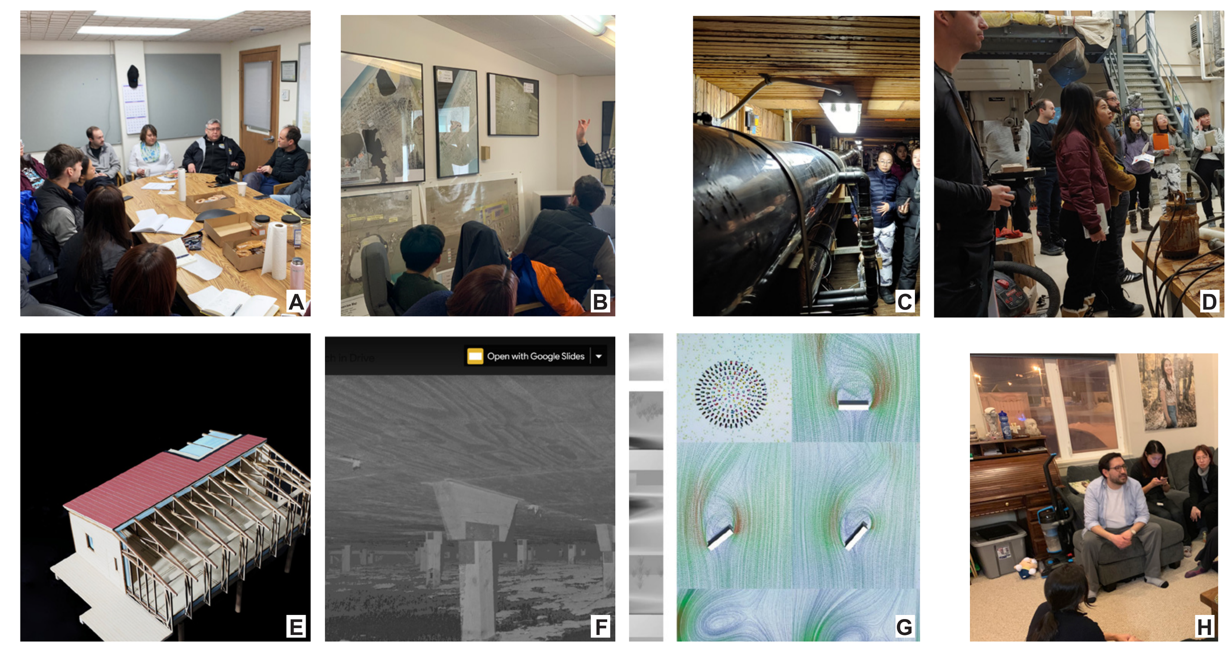
TNHA Site: Sensor Locations and Design Variables

TNHA Base Station

Sensor Locations Based on the Variability of Architectural and Microclimatic Conditions:

The TNHA housing site was recommended to the project team as one of potential study sites by the TNHA team and the NSB Department of Planning and Community Services in 2021. The building and its adjacent site further presents distinct urban and morphological conditions such as 1) the building's location within an older part of the city with a less orthogonal layout, 2) proximity to Lower Isatkoak Lagoon, and 3) presence of microclimatic variability unique to each facade orientation of the building.

Methods to Investigate Sensor-Generated Data and Design Linkages



In addition to investigating the natural-built interactions via micrometeorological sensors and geophysical surveys, the project team has organized a series of meetings with North Slope Borough to **A)** understand the city's future development directions and needs, **B)** learn about the history of urbanization, expansion and planning in Utqiagvik, **C)** visit critical community infrastructure facilities such as the underground utilidor to understand their functionalities, maintenance, current and future challenges, and **D)** learn about traditional and emerging building technologies in Arctic Alaska to guide the interpretation of environmental data that is specific to Utqiagvik and its community.

The project team is further utilizing **E)** physical models of buildings and infrastructural components within study sites, **F)** digital Building Information Modeling (BIM), **G)** Computational Fluid Dynamics (CFD) simulations as well as **H)** design idea exchange and charettes to produce action-oriented outcomes including the Arctic Design Guideline Database that will support future design and planning efforts of the city.

TNHA Site: Usign LiDAR Scanning to develop a Digital Model

LiDAR Scan of Building Structure and Raised Foundation Components
Image: K. Sparrman / UVA

Analysis of Surface Drainage Patterns in Utqiagvik

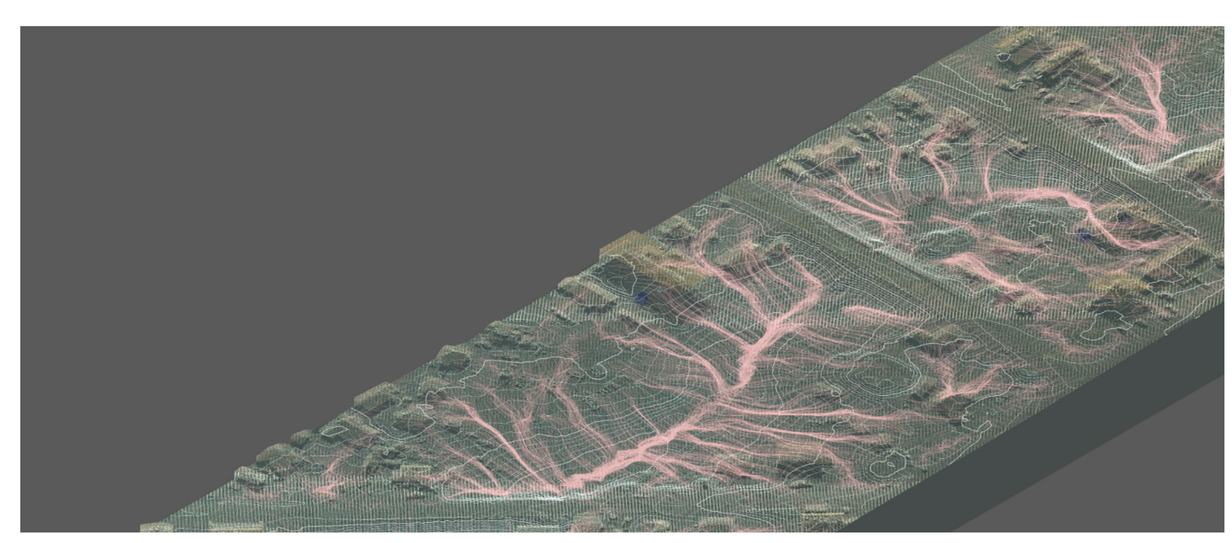


Image: K. Sparrman / UVA

Interdisciplinary Project Team and Project Partners

University of Virginia Co-PIs:

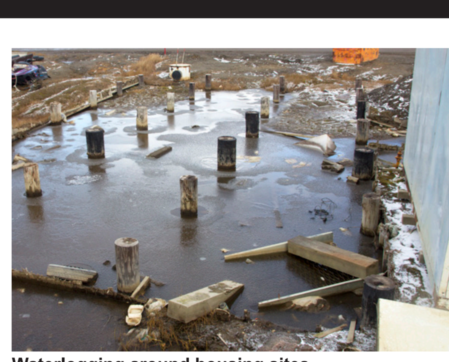
[1] College of Arts and Sciences (Department of Environmental Sciences), [2] School of Architecture (Department of Architecture, Department of Lanscape Architecture), [3] School of Engineering (Science, Technology and Society Program), [4] School of Data Science.

Research Collaborators:

[1] North Slope Borough (NSB) Department of Planning and Community Services, [2] Taġiuġmiullu Nunamiullu Housing Authority (TNHA), [3] TRIBN Consulting, [4] UIC Science, [5] Beaufort Lagoon LTER, [6] USACE Cold Regions Research and Engineering Laboratory (CRREL), [7] National Renewable Energy Laboratory (NREL)'s Cold Climate Housing Research Center (CCHRC).

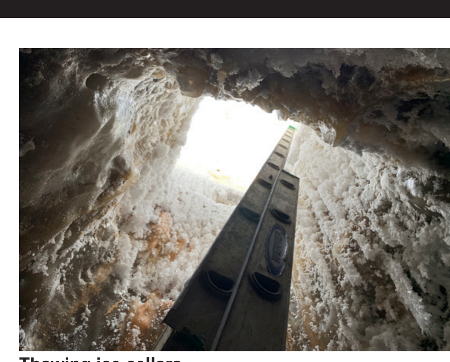
Key Challenges in the Built Environment of Utqiagvik, AK

Shoreline berm due to eroding coast in Utqiagvik.
Image: M. Jull

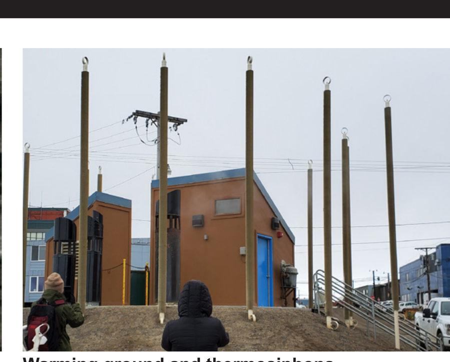


Waterlogging around housing sites.
Image: L. Cho

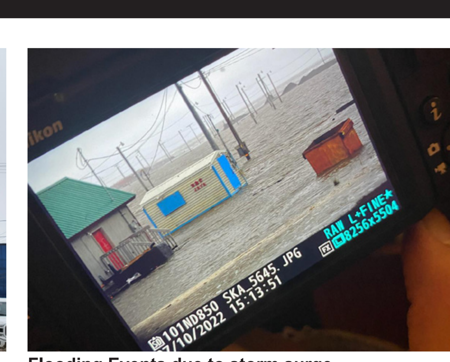
Building foundations and differential subsidence.
Image: M. Jull



Thawing ice cellars.
Image: C. Sha

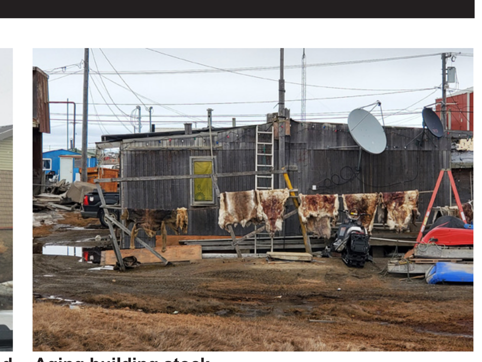


Warming ground and thermosiphons.
Image: M. Jull / UVA



Flooding Events due to storm surge.
Image: C. Charoonsophonsak / CCHRC

Surface water accumulation adjacent to roads and new construction. Image: M. Jull



Aging building stock.
Image: M. Jull