Journal of Engineering in Industrial Research

2026, Volume 7, Issue 3

Original Research Article

Monitoring Land Surface Temperature (LST) Changes in Northern Alaska's Permafrost Regions Using MODIS Data

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Citation M.A. Memis, S. Ulus Memis. Monitoring Land Surface Temperature (LST) Changes in Northern Alaska's Permafrost Regions Using MODIS Data. *J. Eng. Ind. Res.* **2026**, 7(3):91-99.

https://doi.org/10.48309/JEIRES.2026.561167.1325

Article info:
Submitted: 2025-11-19
Revised: 2025-12-13
Accepted: 2025-12-22
ID: JEIRES-2511-1325

Keywords:
MODIS; Land surface Temperature; Google earth engine; Permafrost; Remote sensing.

ABSTRACT

This study investigates multiannual variations in land surface temperature (LST) across four representative permafrost regions in northern Alaska—Prudhoe Bay, Barrow, the Brooks Range, and the Yukon Flats—to identify short-term surface warming trends. MODIS Terra MOD11A2 V6.1 data were processed using the Google Earth Engine (GEE) platform to compute annual mean LST values for the period 2020–2025. Warming rates (°C/year) were quantified through linear regression analysis. The results reveal a consistent regional warming pattern, with positive temperature trends observed at all sites. Among the studied regions, the Yukon Flats exhibited the most pronounced warming, reaching positive LST values of approximately +1 °C by 2025. Gradual warming was also detected in the coastal regions of Barrow (approximately −8 °C in 2025) and Prudhoe Bay (approximately −6 °C in 2025). These findings demonstrate that the integration of MODIS data with GEE provides an accurate and efficient framework for monitoring regional permafrost thermal dynamics and underscores the importance of remote sensing in evaluating climate change impacts on ground stability in Alaska.

Introduction

The Arctic is said to be one of the most severely affected areas by present-day climate change, exhibiting rates of surface warming that greatly exceed the global average [1,2]. This situation, better known as Arctic Amplification, exemplifies a combination of feedbacks, including sea-ice loss, albedo decrease, and alterations to atmospheric circulation, which conspire to increase temperatures in high-latitude areas [3,4]. Thus, even with relatively minor increases in surface temperatures, permafrost systems-the areas of ground that remain in a frozen state for 2 years or more-are undergoing rapid thermal destabilization [5], [6]. Permafrost thaw holds widespread implications for Arctic environments and human systems. Ground temperature changes can induce carbon release from the frozen soil, alter ecosystem processes, and further reduce ground stability, adding a layer of vulnerability to the existing infrastructure, transportation corridors, and energy developments in cold regions [6-8]. These implications are particularly acute in northern Alaska, where continuous and discontinuous permafrost zones overlap with increasing industrial activity and climate-sensitive communities. Direct in-situ

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monitoring of permafrost thermal conditions across the Arctic is inherently constrained by inaccessibility, scant station coverage, and excessive operational expenses. Therefore, satellite-based remote sensing is now a vital component in the large-scale and temporally consistent monitoring of surface thermal dynamics [9]. Of all available datasets, Land Surface Temperature (LST) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) has been most widely used to study surface energy balance, the seasonal freeze–thaw cycle, and permafrost-related processes on regional to continental scales [10-12]. MODIS LST products cover the Arctic continuously in space and time, which is why they are suitable for Arctic applications. The recent rise of cloud-computing geospatial platforms such as Google Earth Engine (GEE) has greatly enhanced the accessibility and efficiency of MODIS-based analyses by permitting the processing of large volumes of data and multi-year trend assessments in a single computational environment [13]. This drive has been the cradle for many studies on Arctic warming trends occurring in the long term; however, the focus of screening in most of the literature has been either on multi-decadal trends or pan-Arctic averages. Yet with these advantages, little is available that offers comparative as well as quantitative assessments on short-term LST trends in recent times across specific permafrost domains in northern Alaska from 2020 to 2025. This is a particularly relevant period, as it captures the recent acceleration in Arctic warming and infers insight into the near-term response of permafrost under the present climatic conditions. In addition, regional contrasts within Alaska, driven by differences in coastal influence, topography, and continental climate, are greatly underrepresented in short-term analysis. In an attempt to close that gap, the present study is centered on four representative permafrost regions of northern Alaska-Prudhoe Bay, Barrow (Utqiaġvik), the Brooks Range, and Yukon Flats. These regions were selected for studying a variety of permafrost types and environmental settings so that the regional surface temperature behavior could allow direct comparisons for the period 2020-2025. The principal guiding research question for this study is: What regional differences and linear trends characterize the annual mean land surface temperature across key permafrost regions of northern Alaska during 2020–2025? By providing an evaluation of short-term LST trends, resolved at the regional scale, this study advances understanding of short-term permafrost surface warming patterns, which can contribute to ongoing assessments of permafrost vulnerability across northern Alaska. The remaining paper is structured as follows: Section 2 provides a description of study areas and data-processing methodology; Section 3 presents results; Section 4 discusses implications of the findings in light of existing literature; and Section 5 concludes.

Materials and Methods

Study area

In total, there were four representative permafrost regions in northern Alaska: Prudhoe Bay, Barrow (Utqiaġvik), Brooks Range, and Yukon Flats (Figure 1).
These regions were selected to encompass a fair spectrum of permafrost types and climatic and geomorphological conditions representative of Alaska. Prudhoe Bay is characterized as an industrial continuous permafrost region; the extensive oil and gas infrastructure has created disturbances to the surface and accelerated the degradation of coastal permafrost [14]. Barrow (Utqiaġvik), the northernmost settlement in Alaska, represents a coastal tundra environment that is thus highly vulnerable to atmospheric warming and changes in sea ice extent [2]. The Brooks Range is a mountainous transition zone for permafrost, where thermal conditions vary greatly with respect to elevation, snow cover distribution, and topographic shading [15].

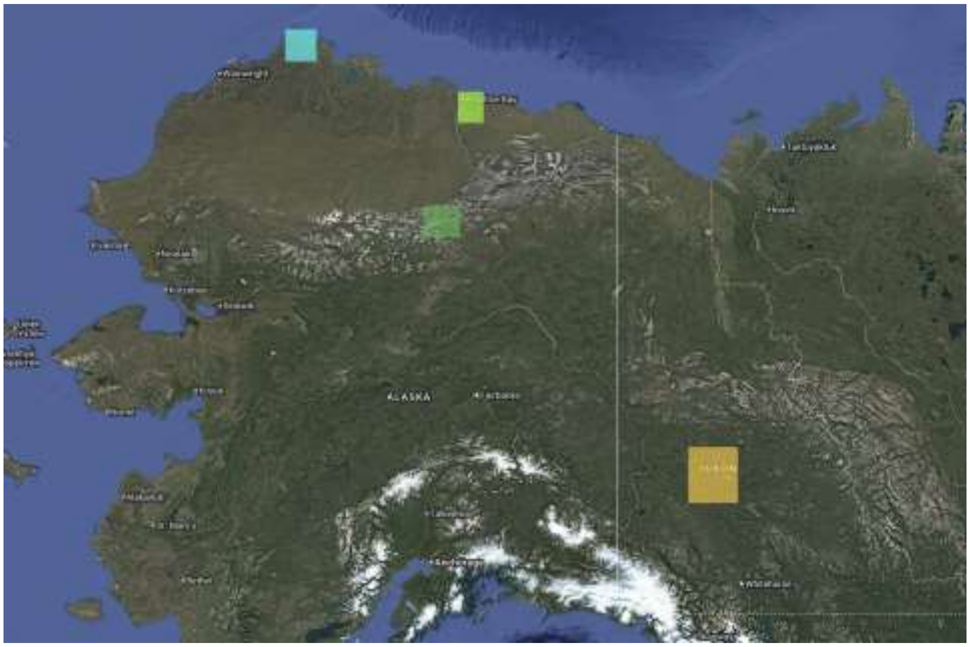

Figure 1: Map of the four study locations in northern Alaska: Prudhoe Bay, Barrow (Utqiaġvik), Brooks Range, and Yukon Flats. (Map compiled from MODIS data using the Google Earth Engine)

Yukon Flats is an interior basin characterized by discontinuous permafrost, having thermal regimes strongly influenced by seasonal freeze–thaw cycles as well as extensive thermokarst activity [16]. Thus, these regions provide a representative basis on which to observe scale variability in surface temperature trends across northern Alaska. The four study regions represent the dominant permafrost settings of northern Alaska (Table 1).

Prudhoe Bay is an industrialized continuous permafrost region characterized by extensive oil and gas infrastructure and coastal exposure, which contribute to surface disturbance and accelerated permafrost degradation [14]. Barrow (Utqiaġvik), the northernmost settlement in Alaska, represents a coastal tundra environment that is highly sensitive to atmospheric warming and variations in sea ice extent [2]. The Brooks Range constitutes a mountainous permafrost transition zone, where ground thermal conditions vary considerably with elevation, snow cover distribution, and topographic shading [15]. Yukon Flats is an interior lowland basin dominated by discontinuous permafrost, where surface thermal regimes are primarily controlled by seasonal freeze–thaw cycles and widespread thermokarst processes [16].

Data and processing

Land surface temperature data were obtained from the MODIS Terra MOD11A2 Version 6.1 product, which provides 8-day composite LST and emissivity measurements at a spatial resolution of 1 km [10]. LST values are retrieved from thermal infrared Bands 31 and 32 using the split-window algorithm [17]. All temperature values were converted from digital numbers to degrees Celsius using the standard scale factor of 0.02 [18]. Data processing and analysis were performed using the Google Earth Engine (GEE) cloud-computing platform, which enables efficient handling of large remote sensing datasets [9]. To ensure data quality, pixels affected by clouds or low-quality retrievals were excluded based on the MOD11A2 Quality Assessment (QA) flags [19]. For each region of interest (ROI), the following preprocessing steps were applied: 1) Application of QA-based pixel masking, 2) Temporal averaging of 8-day composite LST data, 3) Calculation of annual mean LST values, and 4) Extraction of annual means for the 2020–2025 period. This standardized workflow ensured temporal consistency across regions and enabled direct interregional comparison of LST trends (Table 2).

Table 1: Key characteristics of the four study regions

Region	Permafrost type	Dominant climate	Key features	Primary drivers of change
Prudhoe Bay	Continuous	Arctic coastal	Oil & gas fields, gravel pads	Coastal erosion, infrastructure loading
Barrow (Utqiaġvik)	Continuous	Marine-influenced tundra	Low relief, sea ice dependence	Sea ice loss, atmospheric warming
Brooks Range	Continuous/discontinuous	Alpine	High elevation, steep terrain	Snowpack variability, topographic shading
Yukon Flats	Discontinuous	Interior continental	Wetlands, flat basin floor	Freeze–thaw cycles, thermokarst

Table 2: Technical specifications of the MOD11A2 dataset used in this study

Attribute	Description
Product	MODIS Terra MOD11A2 V6.1
Spatial resolution	1 km
Temporal resolution	8-day composites
Variables	LST & emissivity
Bands used	TIR Bands 31–32
Algorithm	Split-window (Wan and Dozier, 1996)
Scale factor	0.02
QA filtering	MOD11A2 QA flags

Trend analysis

Temporal trends in land surface temperature were quantified using linear regression applied to annual mean LST values for each study region over the 2020–2025 period. The slope of the regression line represents the warming rate expressed in degrees Celsius per year (°C/year), while the coefficient of determination (R^2) was used to evaluate the goodness of fit of each model. Statistical analyses were conducted in a Python 3.10 environment using the *Pandas*, *NumPy*, and *scikit-learn* libraries [19]. The variables included in the regression analysis are summarized in Table 3. This approach facilitates comparison of short-term warming behavior among regions and supports interpretation of relative permafrost thaw susceptibility [20].

Results and Discussion

Prudhoe bay

Figure 2 presents the annual mean land surface temperature (LST) values for the Prudhoe Bay region between 2020 and 2025. Mean LST was approximately −10 °C in 2020, decreased to −11.8 °C in 2021, and then increased steadily, reaching −6 °C by 2025. Following the minimum observed in 2021, a consistent warming trend is evident through the end of the study period.

Table 3: Variables used in the trend analysis

Variable	Description	Units
LST_mean	Annual mean land surface temperature	°C
Year	Analysis period (2020–2025)	–
Slope	Warming rate from linear regression	°C/year
R^2	Model goodness of fit	–

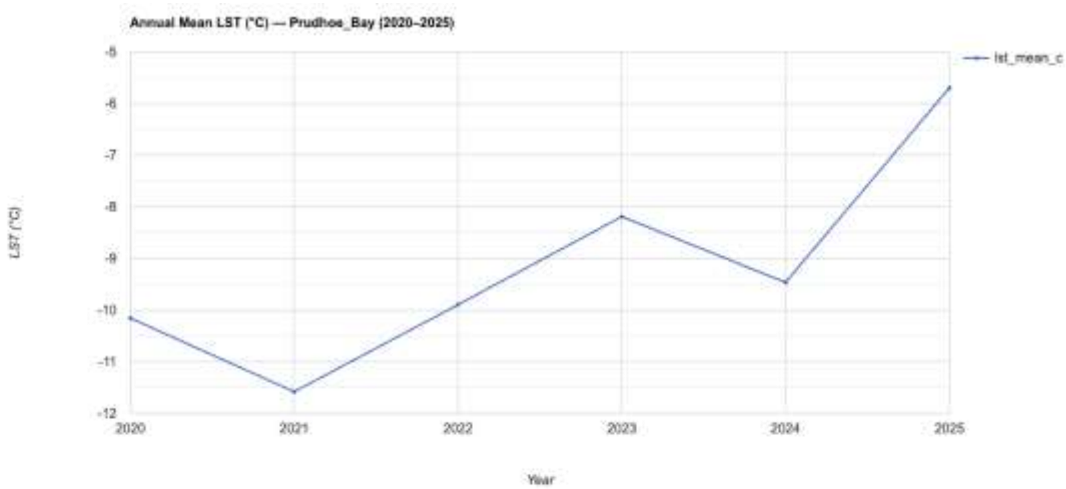

Figure 2. Annual mean land surface temperature (°C) trend for Prudhoe Bay (2020–2025)

Barrow (utqiaġvik)

Annual mean LST values for the Barrow region are shown in Figure 3. Temperatures remained near −12 °C during 2020–2021, followed by a gradual increase after 2022. By 2025, mean LST reached approximately −8 °C. Although interannual variability is present, the overall trend indicates a clear warming tendency during the latter half of the analysis period.

Brooks range

Figure 4 illustrates annual mean LST changes in the Brooks Range. This region exhibits the highest interannual variability among the four study areas. The lowest mean LST (approximately −10 °C) occurred in 2021, followed by progressive warming to −7 °C in 2023 and −4 °C in 2025. Despite year-to-year fluctuations, the overall trend indicates increasing surface temperatures over the study period.

Yukon flats

Annual mean LST values for Yukon Flats are shown in Figure 5. Between 2020 and 2024, mean temperatures ranged from approximately −4 °C to −3 °C. In 2025, LST increased sharply to positive values, reaching approximately +1 °C. Among all study regions, Yukon Flats exhibited the highest mean LST values and the strongest warming signal.

Interregional comparison

Figure 6 compares annual mean LST trends across all four study regions from 2020 to 2025. All regions display a consistent warming pattern over the analysis period. Yukon Flats shows the highest temperatures and the most pronounced increase, while Prudhoe Bay and Barrow remain the coldest regions. The Brooks Range exhibits intermediate temperatures with notable variability.

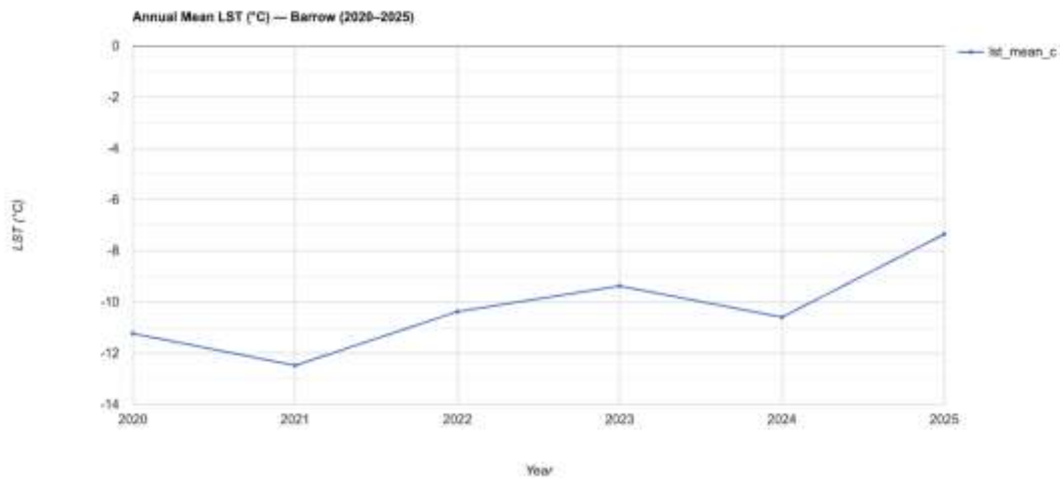

Figure 3: Annual mean land surface temperature (°C) trend for Barrow (2020–2025)

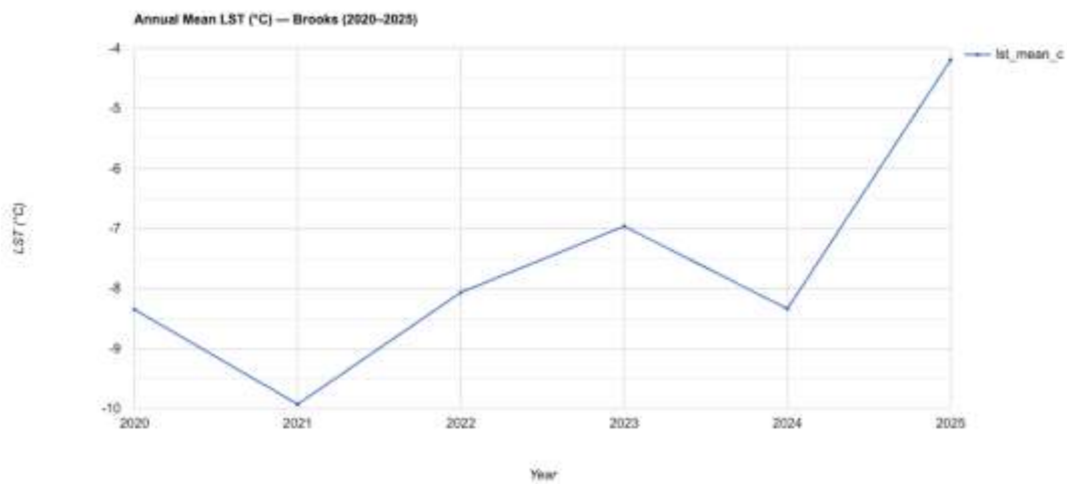

Figure 4: Annual mean land surface temperature (°C) trend for the Brooks Range (2020–2025)

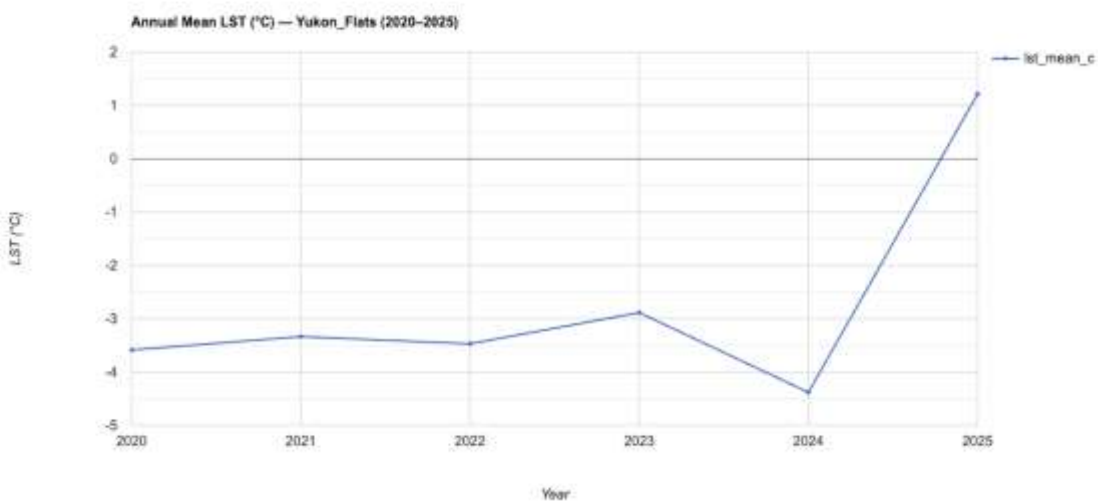

Figure 5: Annual mean land surface temperature (°C) trend for Yukon Flats (2020–2025)

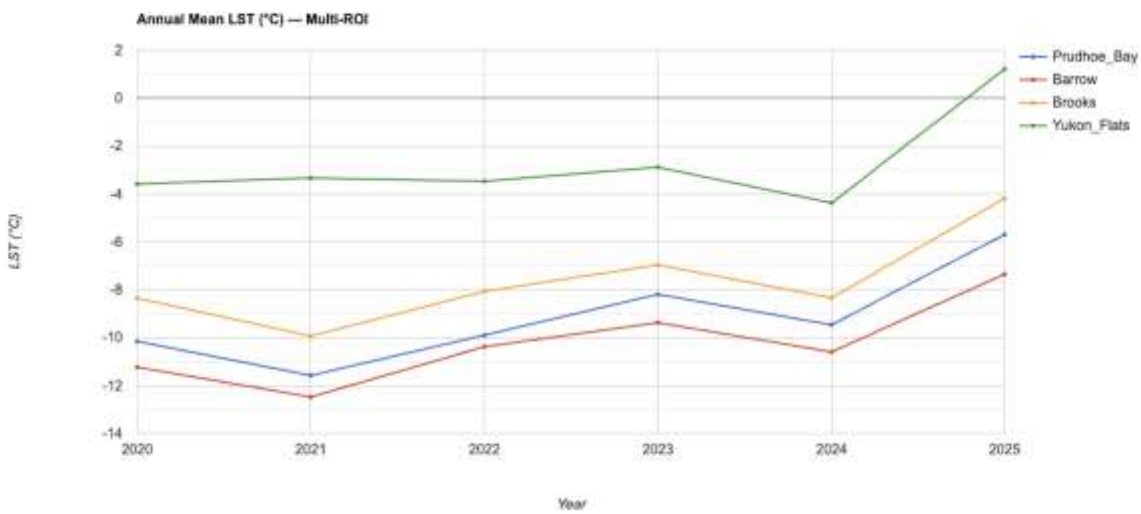

Figure 6: Comparison of annual mean LST (°C) across the four study regions (2020–2025)

Discussion

The results reveal a spatially coherent warming trend across northern Alaska during the 2020–2025 period, consistent with broader observations of accelerated Arctic surface warming [5,21]. However, the magnitude and temporal evolution of warming differ substantially among regions, reflecting contrasting climatic controls and permafrost settings. Yukon Flats experienced the most pronounced warming, including a transition to positive annual mean LST values by 2025. This behavior is characteristic of interior continental basins, where strong land–atmosphere coupling, lower surface albedo, and enhanced summer heat accumulation promote rapid surface warming [16,22]. The discontinuous permafrost conditions of Yukon Flats further increase susceptibility to thaw-related processes. In contrast, Prudhoe Bay and Barrow exhibited lower absolute temperatures throughout the study period. The more moderate warming observed in these regions is consistent with the influence of coastal conditions, where maritime effects partially buffer surface temperature increases [3,4]. Nevertheless, the steady post-2021 warming trend observed at Prudhoe Bay suggests increasing sensitivity of industrialized coastal permafrost to combined climatic forcing and surface disturbance [14]. The Brooks Range displayed the greatest interannual variability, reflecting the influence of elevation, topographic shading, and snow cover dynamics on surface thermal regimes [15,23]. Despite this variability, the long-term trend indicates progressive warming, consistent with previous observations of elevation-dependent temperature sensitivity in mountainous permafrost regions [24,25]. Overall, the interregional comparison highlights the importance of regional setting in controlling short-term permafrost surface temperature responses. While Arctic warming is widespread, inland basins such as Yukon Flats appear to respond more rapidly than coastal or high-elevation environments. These findings emphasize the need for region-specific assessments when evaluating near-term permafrost vulnerability under ongoing climate change.

Conclusion

This study evaluated short-term land surface temperature (LST) trends across four representative permafrost regions in northern Alaska—Prudhoe Bay, Barrow (Utqiaġvik), Brooks Range, and Yukon Flats—during the 2020–2025 period using MODIS Terra MOD11A2 data processed through the Google Earth Engine platform. The results demonstrate a consistent warming signal across all regions, with clear regional contrasts in both magnitude and temporal behavior. Yukon Flats exhibited the strongest warming response, including a transition to positive annual mean LST values by

2025, indicating heightened vulnerability of interior discontinuous permafrost to recent climate forcing. The Brooks Range showed moderate but persistent warming accompanied by higher interannual variability, reflecting the influence of elevation and terrain-related controls. In contrast, Prudhoe Bay and Barrow remained colder throughout the study period but displayed steady post-2021 warming trends, suggesting increasing sensitivity of coastal permafrost systems despite maritime moderation. The interregional comparison confirms that while Arctic surface warming is spatially coherent, its expression is strongly conditioned by regional climatic settings, topography, and land surface characteristics. Overall, this study demonstrates that the integration of MODIS LST data with cloud-based analytical workflows provides a robust and efficient framework for detecting short-term permafrost surface warming and for assessing near-term permafrost vulnerability in northern Alaska. The findings offer a valuable reference for anticipating future thaw-related risks to ground stability and Arctic infrastructure under continued warming.

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